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Relocating the Wallace Desert Gardens

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Stinknet, A New Invasive, Non-native Plant in the Southwestern United States

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Abstract Stinknet (*Oncosiphon pilulifer*) a recent invasive, non-native species in the southwestern United States might become one of the worst invasive plants in the region. It is a winter annual, originally from South Africa, that has invaded Southern California since the 1980s and Arizona since the 1990s. The distribution of stinknet is expanding quickly and it is colonizing many different habitats. It might only be limited by winter cold and areas with reduced winter moisture. Stinknet readily colonizes open or disturbed areas, whether they are natural or human created, and often favors disturbed areas and spreads into adjacent wildlands. Several of its life history characteristics contribute to its great potential for spread, including the very high seed production with many thousands of small seeds per plant, the potentially long-lived seed bank, and the high dispersal in some cases. Stinknet can cause a number of problems. It can reach very high densities where it outcompetes native winter annuals and impacts perennial vegetation. These dense stands can also change the habitat for animals, such as birds, reptiles, and mammals. Stinknet can also extend fire to brush and trees and creates acrid, irritating smoke when burned. Stinknet could be another invasive plant that increases the number and extent of fires resulting in a positive feedback cycle. Control of stinknet has focused on herbicides and pre-emergent herbicides because patches of stinknet quickly increase beyond what manual or mechanical control is capable of limiting.

Introduction

Invasive, non-native plants can have many negative impacts on natural plant communities and they can greatly decrease native plant diversity by dominating resources and space (Simberloff et al. 2013). The environment in the southwestern United States, particularly in the Mohave and Sonoran Deserts, is extreme in many ways but plants from other parts of the world with somewhat similar extreme temperature and rainfall have become invasive in the southwest (Hedrick et al. 2019). In addition, there are extensive human-impacted disturbed habitats in the southwest, where some invasive, non-native plants are able to become established and spread (Tellman 2002

One of the most recent invasive, non-native plants to become established in the southwestern United States is stinknet (*Oncosiphon pilulifer* (L.f.) Källersjö: Asteraceae), a small winter annual native to South Africa. Stinknet was first found in southern California in 1981 and continues to spread to a number of counties in the state, mostly in Southern California and a few in central and northern California. Stinknet was first recorded in Arizona in 1997, and in recent years has rapidly spread in the Phoenix area and to the Tucson area (SEINet 2020).

There are relatively few publications on stinknet ecology and evolution from its native South Africa. In addition, while stinknet is invading Western Australia, it has only recently been recognized in Australia as a problem species. Research on these topics, and on the control of stinknet, is only in its early stages in the United States and Australia. As a result, some of the information here is summarized from the grey literature, research in progress, and personal observations or communications.

General Background

The unusual common name for this invasive plant, stinknet, means "stink only" in Afrikaans because of the plant's strong odor from its volatile oil; because it is useless for stock feed, it only stinks (Landrum et al. 2005). Another name for the plant in Afrikaans is stinkkruid, which means "stinkweed," referring to the strong, unpleasant odor, especially when crushed, or "stink herb" because in the past the plant was used medicinally (Landrum et al. 2005). It has also been sometimes called globe chamomile but we think this name should be discouraged because it makes this noxious weed appear to be related to a desirable herb. The specific epithet *pilulifer* is used here (H. Glen, pers. comm; L. Landrum, pers. comm.) and following the IPNI (International Plant Name Index from Kew Gardens), although the spellings *piluliferum* and *piluliferus* (Kolokoto & Magee 2018) are also used elsewhere. There are also several synonyms for the species including *Matricaria globifera* and *Pentzia globifera,* but *Oncosiphon pilulifer* is the currently accepted scientific name (although perhaps not the most commonly used).

Stinknet is a small winter annual in the southwest, only a few inches to over two feet (10 to 70 cm) in height. It is easily recognized by its many small (about 0.4 inch (1 cm) in diameter), round, globe-like yellow flower heads (inflorescences) which lack ray petals (Figure 1) and its strong, pungent odor. It can form dense stands of many hundreds of plants each with many distinctive yellow flowers (Fig-

Figure 1. Single stinknet plant showing flower heads (Photo courtesy of Chris McDonald)

Figure 2. Stand of stinknet in southern California at the University of California, Motte Rimrock Preserve in an undisturbed patch of sensitive species habitat, formerly dominated by native wildflowers and invasive grasses and forbs (Photo courtesy of Chris McDonald)

Figure 3. Foliage of a small stinknet plant, as viewed from above on left and as viewed from below on right (Photo courtesy of Chris McDonald)

ure 2). It has small bipinnate, dark green leaves which can vary from 1 to 2 inches long (2.5 to 5 cm) (Figure 3) (See also Chamberland 2020). Stinknet can be difficult to detect from a distance before it is in flower and after desiccated flowers have fallen off the dead plant, but its pungent odor is helpful in identification if the plant is close by. A detailed morphological description and the taxonomy of the species in the genus *Oncosiphon* has been given by Kolokoto & Magee (2018).

Stinknet has been recognized for herbal remedies in South African ethnobotany by van Wyk (2008), and has been used to "treat a variety of ailments, including typhoid fever, rheumatic fever and influenza, and as a general tonic, anthelmintic and diuretic as well as a poultice for scorpion stings" (Kolokoto & Magee 2018). However, when stinknet was examined for anti-malarial activity, the extracted compounds were found to have high general toxicity (Pillay et al. 2007). A search online found that stinknet was for sale for $4.99 per 0.5 oz of flower heads claiming that the flowers could be used for a variety of medical ailments, such as convulsions, fevers, malaria, typhoid, gynecological issues, a cold remedy and heart conditions. Overall, the validity of the claims of stinknet as either an herbal or medicinal remedy appear scientifically unsubstantiated. More importantly, these advertisements point to a mechanism of spread by gardeners and users of herbal remedies if ripe seed is sold.

Another species (*O. suffruticosum*) closely related to stinknet, which is also native to South Africa, has become invasive in Australia, where it is found in coastal, arid and Mediterranean climates. It is not known in the southwestern United States but has been introduced along the Columbia River in Oregon and could possibly spread further if populations in Australia are indicative of potential habitat. Other closely related plants that have become invasive in the United States are pineappleweed (*Matricaria discoidea*), which is native to northeast Asia, and brass buttons (*Cotula coronopifolia*) from southern Africa. While they both look similar to stinknet, there are distinct differences. They both have conical-shaped yellow flower heads, but in a hemisphere, rather than the spherical shape of stinknet. All three species have dissected leaves, but pineappleweed and brass buttons are somewhat smaller and tend to be more prostrate than stinknet, which grows more upright. Most tellingly, pineappleweed and brass buttons do not have a largely unpleasant smell like stinknet and pineappleweed has a "pineapple" odor. Pineappleweed and brass buttons are uncommon in desert settings; pineappleweed, known as a turf and landscape weed, is typically found in riparian or wet habitats, while brass buttons is a perennial weed found in moist habitats near wetlands and marshes. Pineappleweed can be found in forest and montane habitats, while stinknet currently does not invade those habitats.

Distribution

Present Distribution

In its native range, stinknet is widely dispersed over the drier parts of South Africa, but is mainly found in the winter-rainfall Cape region (southwest section roughly W of longitude 24° E in Figure 4). The widespread locations of the 80 samples examined by Kolokoto & Magee (2018) in their taxonomic treatment are indicated in Figure 4 (east-west distance of this sampling area is about 700 miles, or 1200 kilometers). A. E. van Wyk in Landrum et al. (2005) suggests that the present distribution of stinknet in South Africa might not be its native range because it exists in many different habitats and shows weedy tendencies by mainly invading disturbed and agricultural areas, especially cultivated land receiving irrigation in winter. A. E. van Wyk (pers. comm.) found that in such localities (especially in the mainly summer-rainfall part, E of longitude 24° E, of its range) stinknet was completely absent from adjacent areas where there was undisturbed natural vegetation.

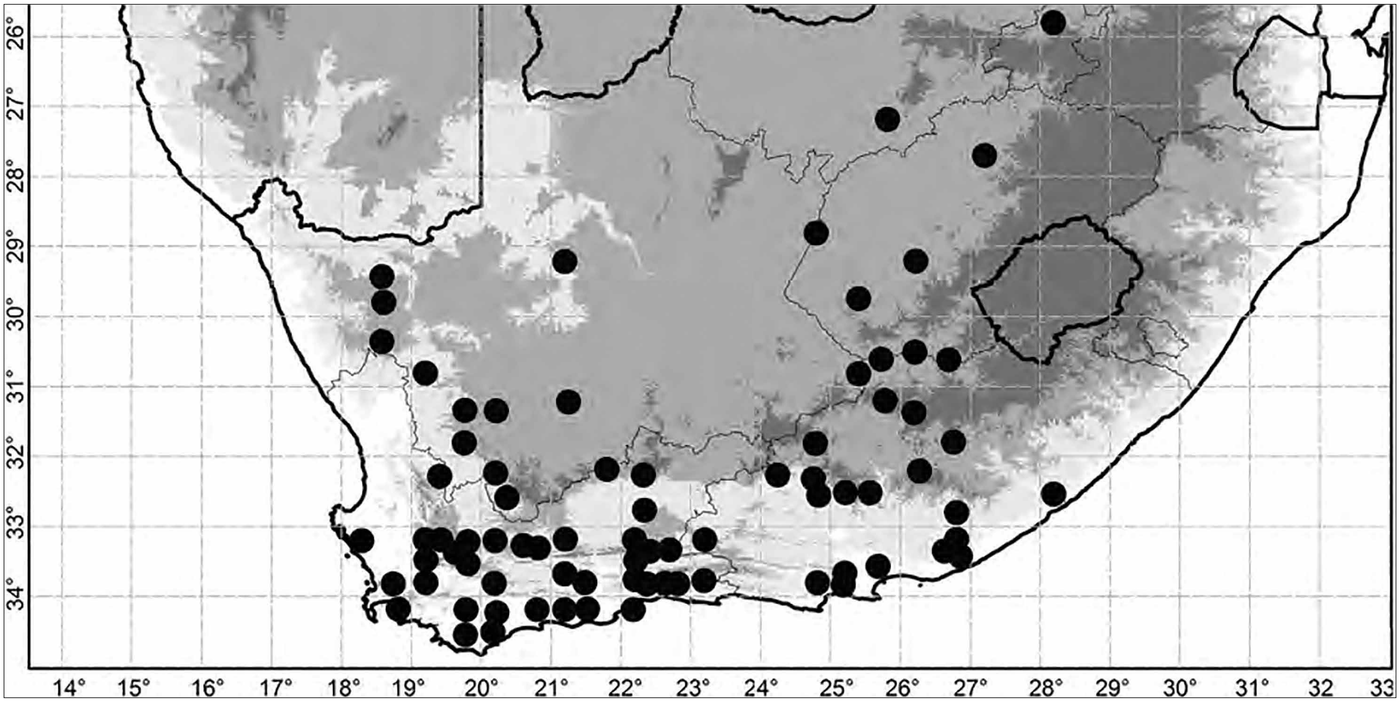

Figure 4. The distribution of stinknet in South Africa, its native range, based on 80 herbarium samples examined by Kolokoto & Magee (2018) where the darkest shading with a number of samples indicates areas between 900 m (3000 ft) and 1500 m (5000 ft) in elevation and no shading indicates areas less than 300 m (1000 ft) in elevation.

Stinknet is invasive in Australia and North America. In Australia, it has been found in both Western Australia and Victoria, on opposite sides of the country. In North America, stinknet has been recorded in Arizona, California, and Nevada, and in the Mexican state of Sonora. In the western Cape region, where stinknet is found in South Africa, forage crops such as wheat and oats are grown. It is likely that stinknet was introduced accidentally to Australia as a seed contaminant. Stinknet is thought to have been introduced to Western Australia in contaminated fodder from South Africa during the drought of 1922 (A. Douglas, pers. comm.). The first record in Western Australia was in 1939 with many more records in the 1960s and 1970s (Australasian Virtual Herbarium 2020). There are herbarium collections before 1920 in an area of Melbourne, Victoria, suggesting that the introduction to Victoria was earlier than that to Western Australia and likely independent. However, it is likely that the Victoria populations have been extirpated as stinknet has not been recorded there for over 50 years (Australasian Virtual Herbarium 2020).

Stinknet was first found in the United States in Southern California at a state preserve in Riverside County (Lake Perris State Recreation Area) in 1981 where it was apparently accidentally introduced. It was possibly introduced as seeds lodged on clothing or boots from someone returning from an overseas trip, although other explanations are

Figure 5. Distribution of stinknet in southern California (Calflora 2020). Blue shading indicates counties for which specimens have been deposited in an herbarium, purple shading indicates there are reports of this species in the county.

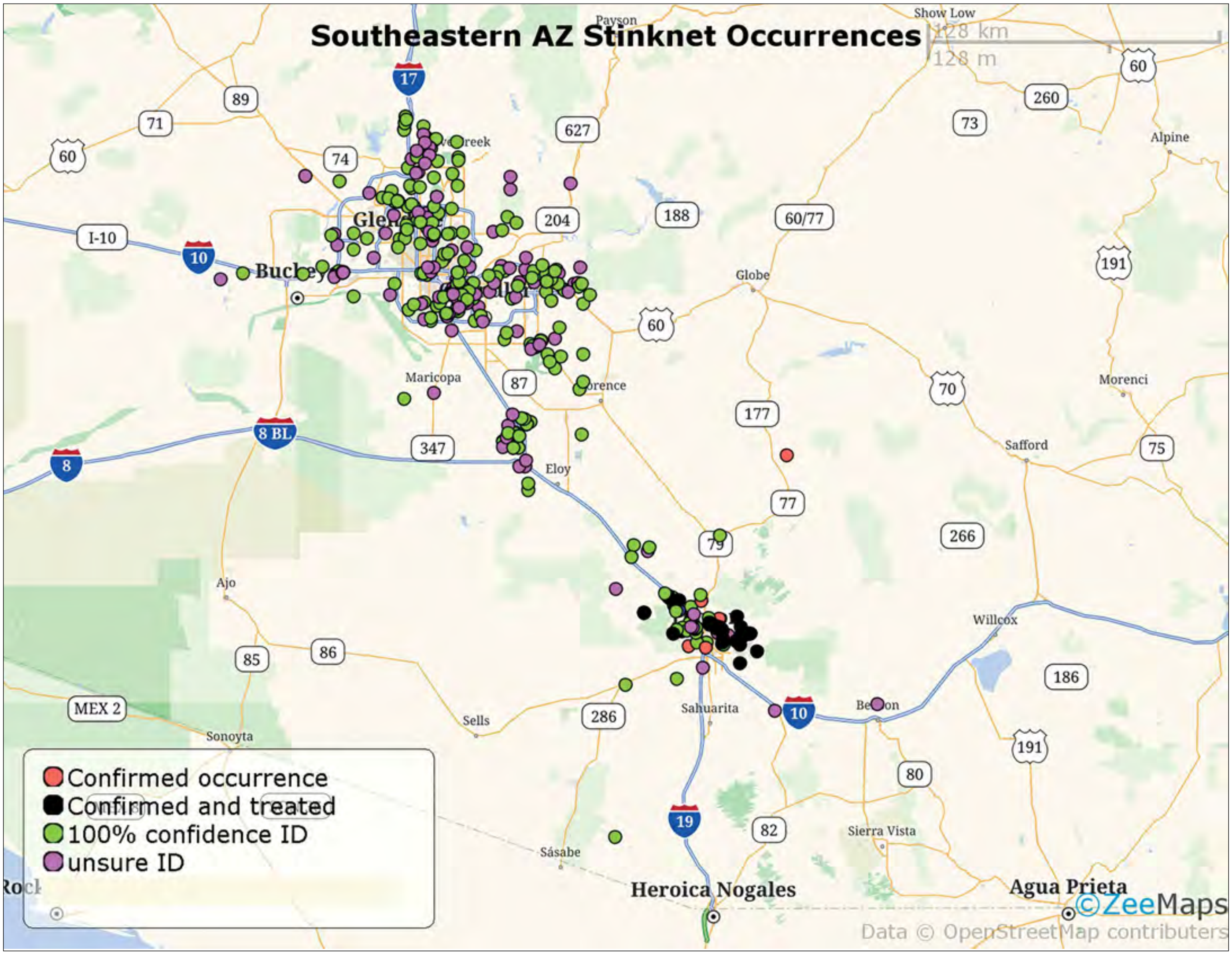

Figure 6. Distribution of stinknet in Arizona (Horst, 2020) where the Phoenix area is in the upper left and the Tucson area is in the lower middle (Photo courtesy of Jonathan Horst)

also possible. All early collections of stinknet were found in other locations near the park, further supporting that this area was the site of the founder invader population (Calflora 2020). Stinknet was subsequently recorded in San Diego County in 1997, Orange County in 2003, is now spreading to other Southern California counties, and has been documented in Santa Clara County in Northern California (Figure 5). Multiple populations have recently been found in Las Vegas, Nevada, and stinknet is spreading in Mexico.

Stinknet was thought to be introduced into Arizona in Maricopa County in the 1990s (Landrum et al. 2005). No details of its introduction are known but it is presumed to have been accidentally introduced. The earliest records in Arizona are in suburban areas, which indicates it was likely not introduced as an agricultural seed contaminant. Similar to Southern California, stinknet has rapidly spread in Maricopa County (Phoenix). It was first found in Pima County (Tucson) in 2015. As a result of this rapid spread and its impact, stinknet was listed as an Arizona Noxious Weed as of January, 2020. Figure 6 gives the present locations of stinknet in Arizona as reported to the Audubon Survey, and concentrates on urban sightings. SEINet also has a map of the geographic distribution of stinknet which appears to have a wider distribution.

For understanding the invasions into Australia and the United States, knowing the source of invasions from South Africa and how they were transported is important. With this information, any connection between the invasions into Australia and the United States and any connections between the invasions into California and Arizona, to see if California was the source of the Arizona invasion, or between Western Australia and Victoria, could potentially be identified. Because there does not appear to be historical information to make these connections, genetic markers could provide information about these connections. Importantly if the infestations in Australia and the United States were started from very different source populations in South Africa, then different ecotypes may well be involved. This might potentially explain the difference in invasiveness in stinknet in the two countries and suggests that caution should be used when relying on experimental results from Australia because they might not be transferable to the United States, and vice versa.

Future Distribution

Stinknet appears to have been quickly spreading in recent years in the United States. Stinknet fills in open areas, prefers sunny, open habitat, and is particularly abundant in disturbed areas and washes, often along roadsides, field edges, and into the edges of riparian areas. Stinknet also appears to be spreading somewhat as a roadside weed, presumably because of the disturbed roadside habitat, potential dispersal mechanisms, and the higher runoff along roads. Stinknet can also be seen spreading into wildlands adjacent to roadsides. If the distribution in South Africa can be used as a guide, where stinknet appears to cover a fairly wide climate gradient, it is likely to spread much further than the present range. Because stinknet appears somewhat frost-sensitive, it could be limited by extreme cold because it prefers a more temperate climate, although there is evidence that it can withstand below freezing winter temperatures in South Africa quite well (A. E. van Wyk, pers. comm.). Another important limiting factor is the amount of winter moisture. In South Africa, it can survive in areas with cool to cold winters when there is irrigation but does not do well with lower winter moisture (A. E. van Wyk, pers. comm.).

In general, stinknet is quickly spreading in the Sonoran Desert and new populations are being discovered in the Mojave Desert. It is likely to spread throughout the southwestern United States and Mexico where there is adequate winter and spring moisture and winter temperatures are not well below freezing. Given that it has done well in a recent winter drought in California in 2018, it might also be able to expand into the Chihuahuan Desert as well where the environment is similar to that where it has already successfully established. In addition, stinknet has invaded annual grasslands in California, suggesting that it could also invade semi-arid grasslands in Arizona and New Mexico. Because it also grows well in riparian areas in California and next to the Pacific coast, it could invade riparian areas in Arizona. In addition, livestock generally do not eat stinknet, unlike some invasive plants, such as buffelgrass (*Pennisetum ciliare*), which eliminates herbivory as a factor in reducing it.

To add to this complexity, stinknet has been present in southwestern Australia for 80 years, yet its distribution in Western Australia is much less than in North America. Until 20 years ago, it was not recognized as a problem weed in Australia, but recently it has been spreading rapidly (Lee 2017; A. Douglas, pers. comm.). This increased spread might be from environmental changes, such as changing climate patterns or differences in agricultural practices (A. Douglas, pers. comm.), or potentially from genetic changes that have increased invasiveness. The local level of infestation appears to be significantly greater in the United States than Australia, as evidenced by the apparently larger fields and stands of stinknet in both California and Arizona than in Australia. This difference might be due to more suitable soils or climate in the United States, or a more invasive ecotype in the United States.

In California, stinknet has not been found above 3500 feet (1000 m), but it has been found above this elevation in Arizona at up to 4200 feet (1280 m) (SEINet 2020). Stinknet might well grow in some locations at high elevations and this paucity might be from lack of sampling or a limited time to colonize higher elevations. Stinknet is limited and often absent under dense shady canopy cover in California, such as under large dense chaparral shrubs (e.g. *Malosma laurina*) as well as dense riparian forests or oak forests. Although these conditions appear to limit the site-specific distribution of stinknet at this point, it is not clear how much they will limit its eventual distribution.

An eventual potential invasive distribution of stinknet could be constrqucted using climate information from the distribution in South Africa and the geographic distribution of comparable data in the United States. However, there might be some other factors, such as soil type, that could limit the invasive distribution or, because stinknet is successful in disturbed and agricultural habitats and without possible natural biotic suppressing factors, its invasive distribution might be expanded beyond that predicted from climate information. In addition, stinknet is not a strictly winter grower in South Africa and is perhaps more responsive to rainfall than to season (S. Neser, pers. comm.). In California, stinknet can germinate in the spring and flower during the summer, where soil moisture persists, extending the limits on its growing season (C. McDonald, pers. obs.).

Table 1. Different life history traits and information about them in stinknet.

Life history trait	Stinknet
Germination and growth	Germination within 10 days, has a long germination period from November to April, has a long flowering season
Reproduction	Sexual with a high likelihood of self-fertilization and self-compatibility, does not appear to be wind pollinated and significant insect pollination appears unlikely
Seed production	Very high, a single flower head has about 250 seeds and a single plant can produce thousands of seeds
Seed bank	Seed bank viability of at least several years, in Australia it is at least 4 years
Dispersal	Very small seeds (< 1 mm in length) are spread by wind, vehicles, water, equipment, people (on clothing, shoes, camping equipment, or purposely), and wildlife.

Life history Characteristics

Germination and Growth

Stinknet can germinate quickly (less than 10 days after rain) and germinates over a long period from November to April (C. McDonald, pers. obs.)(see summary of life history traits in Table 1). Seed ripening starts in March and sometimes continues until late May. In riparian areas, stinknet can continue to flower into the summer (C. McDonald, pers. obs.). This is a particularly long flowering season for a winter annual in the southwest and, as a result, stinknet can continue to flower later than most native wildflowers. Several cohorts of germinating seeds can be triggered by rainfall throughout the winter and spring. However, in California the largest cohort of seedlings is produced by the first large precipitation event of the season (C. McDonald, unpub. data). For successful control, it is necessary to return to the same site over several months to treat newly germinating plants. This extended germination period can be considered a kind of "bet-hedging strategy" within a growing season, that is, by delaying some germination to other time periods, it is more likely that some germinated plants will encounter a beneficial environment. In Australia, some plants that germinate in late winter can continue to grow and produce seed during the summer if the conditions are favorable (A. Douglas, pers. comm.). Stinknet appears to have only one generation per year, that is, seeds that mature in a single year appear to germinate the next year or in subsequent years from the seed bank.

Douglas & Nicholson (2017) and Douglas (unpub. data) experimentally examined the effect of several factors on germination, including the effects of burial, as a proxy for tilling, on the reemergence of stinknet populations upon exhumation. They found that stinknet seeds did not germinate at 5 C or at 35 C or above, indicating stinknet germinates at moderate temperatures consistent with the fall, winter, and spring seasons. Stinknet appears to germinate well under light and hardly at all in the dark (averaging 40% in light vs. 1% in the dark). They found that buried stinknet seeds had a moderate germination rate (averaging 42%) when exhumed 3-12 months after burial. Buried seeds exhumed 24 months after burial, had a much lower germination rate (averaging 15%), potentially indicating this species may have secondary dormancy mechanisms for long-term dormancy. Stinknet seeds left on the surface had a low germination rate (averaging 7%) after 3-12 months and the germination rate increased (averaging 16%) upon exhumation after 24 months of burial, however some of these seeds on the surface might have germinated and died within the bags or degraded, confounding comparisons between buried seeds and those left on the surface.

Reproduction and Seed Data

Stinknet is strictly a winter annual in the southwest with no known perenniality and no vegetative reproduction. Stinknet appears able to self-fertilize and is likely self-compatible but there are no direct data on either phenomenon. Although some insect visitation by bees, and less visitation by butterflies and beetles, has been observed, pollination might not depend on larger insects. However, there is a strong possibility that hardly noticeable small insects like usually ubiquitous flower-visiting thrips species may move between flower heads (S. Nesser, pers. comm.). Stinknet also does not appear to be wind pollinated both because pollen is not seen or found on windy days and the pollen appears to somewhat sticky and not readily dispersed by wind (C. McDonald, pers. obs.). Further investigation of the level and importance of self-fertilization, insect and wind pollination is needed.

Stinknet produces very large numbers of small (less than 1 mm long) seeds (technically cypselas, a type of fruit) per plant. A single seed head (capitulum) can have about 250 seeds. Because individual plants have dozens to hundreds of seed heads, individual plants can easily have many thousands of seeds. Douglas & Nicholson (2019) estimated that single plants averaged about 3,000 to 5,000 seeds and that single plants in ungrazed areas can have many more seeds.

It appears that seeds can remain viable in the soil for at least several years and research is under way to determine some of the characteristics of the seed bank (C. McDonald, unpub. data). Dodd & Lloyd (1988) found that 90% of fresh seed germinated, 2% was dormant, and 8% was inviable. They also found that 30-month old seed still had 85% to 88% viability, suggesting a long-lived seed bank, but these seeds had a much higher dormancy of 75% to 81% than fresh seeds. Douglas & Nicholson (2019) found that 10% of the seed retained in the seed head would still germinate after 9 months intact on the plant. In California, a small but significant portion of plants retain seeds on desiccated inflorescences for over a year (C. McDonald, pers. obs.). Dodd & Lloyd (1989) found that seedlings were still being produced five years after plants had last set seed in an area and that 77% of the seeds buried in packets for four years were still viable. From the information available, it is likely that the seed bank in the United States will last at least three years and possibly longer.

Dispersal

Stinknet seeds are both very small and very light and are potentially spread by wind, vehicles, water, equipment, people (on clothing, shoes, or camping equipment), and wildlife. New infestations scattered far from existing populations along highways suggest that vehicles can spread the seed great distances. The seeds remain tightly attached to the inflorescence, possibly as a partial serotinous dispersal mechanism, until they are disturbed by wind, vehicles, people, rainfall, or animals. When the dry inflorescence is disturbed, it can break apart and the seeds can attach to surfaces, more or less like large dust particles. Although the seeds appear to catch on clothing, they do not have any specialized mechanism of adherence.

The pappus is quite inconspicuous, suggesting that wind dispersal of the seeds is probably not very efficient, except during strong gusty winds or in a 'dust devil' when entire inflorescences can break off a plant and are carried by the air (C. McDonald, pers. obs., Douglas & Nicholson 2019). Dry inflorescences can remain intact on the plant for many months to over a year until disturbed, providing a long time period for seeds to eventually disperse.

Because stinknet has been recommended as a medicinal plant, a garden plant, or for producing a special kind of chamomile tea, it might have been distributed for these purposes by farmer's markets, by nurseries, or online. In one known infested site in eastern Pinal County, Arizona, stinknet was intentionally introduced by seed in 2015 because it was thought to be a native flowering desert plant (P. Hedrick, pers. comm.). In 2020, this infestation still appears localized on the property where it was introduced, suggesting that dispersal has not yet occurred for any significant distance. However, this lack of dispersal appears to be a rare occurrence, in most cases stinknet easily disperses to neighboring areas in just a few short years.

Table 2. Different problems and information about them in stinknet.

Problem	Stinknet
Allergenic	Can cause a skin rash and potential respiratory problems for some people handling it, odor is also very disagreeable
Plant density	Density can be very high (1 per square cm), excludes other native annual plants and potentially impacts other plants and animals such as birds, reptiles and mammals
Inedible	Appears generally untouched by herbivores and insects and livestock will not eat stinknet, presumably because of its odor and taste
Fire	Stinknet can extend fire from open areas between shrubs, trees and cacti and also creates acrid, irritating smoke, it can increase in number and distribution with fire, resulting in a positive feedback.

Problems and Control

Problems

Stinknet appears allergenic and can cause a skin rash and potential respiratory problems for some people handling it (see summary of problems in Table 2). As a result, gloves, long sleeves, long pants, eyewear, and possibly face masks are recommended when removing or mowing it. It is not clear whether stinknet pollen is allergenic. The odor of the whole plant is quite disagreeable and some people in prolonged close contact with stinknet report headaches after working with the plant for several hours, others report wheezing and other allergy-like symptoms after long exposures. It is unknown how common or rare these symptoms are for people with close contact to stinknet.

Stinknet seedlings can grow in dense mats, sometimes so dense as small seedlings that they look like “moss” (J. Brock, pers. comm.), and can reach densities of 6 seedings per square inch (1 per square cm) (McDonald 2019). Because of these high densities, it appears to outcompete many native winter annuals and could potentially impact perennial vegetation. These dense stands can also potentially change the habitat for animals, such as birds, reptiles, and mammals.

Plants observed in California and Arizona show few if any signs of either herbivore or insect damage (C. McDonald, pers. obs.), suggesting that herbivores or insects in the United States will generally not eat it. Reportedly livestock will not eat stinknet (Rutherford & Powrie 2010), presumably because of odor and taste as suggested by its common name. Sheep have been known to eat it if they are starving and have very little other forage (A. Douglas, pers. comm.). This can result in a potential increase in the abundance of stinknet because most of its competitors will have been consumed first. From the perspective of providing forage for livestock, stinknet is detrimental both because it crowds out palatable native forage plants and covers areas with an unpalatable plant.

Stinknet can extend fire from annual plants to brush and trees and also creates acrid, irritating smoke when burned. Stinknet could be another invasive plant, like buffelgrass and red brome (*Bromus rubens*), that increases in number and distribution with fire, resulting in a positive feedback, unlike most native plants in the southwest deserts which are reduced or eliminated by fire (Stevens & Falk 2009). In addition, stinknet seeds have a higher germination rate when exposed to smoke (Perez-Ochoa & de la Rosa 2019). At Lake Perris State Recreation Area where there have been prescribed burns, stinknet has increased in abundance over time, suggesting that reduction in competition from more fire sensitive species may have provided an advantage for stinknet. In addition, although some stinknet seeds are probably killed by fire, the seeds in the center of an intact inflorescence might not be killed as numerous only slightly burned inflorescences can be found after a fire (C. McDonald, pers. obs.).

Control

There are only a limited number of options for land managers and property owners to efficiently and effectively control stinknet (see summary in Table 3, see also Chamberland 2020). Manual removal, with or without hand tools, can be effective in small patches, but is often not efficient. Removal and disposal of plants before flowering is best because no seeds are present on the plants

Table 3. The different types of potential control and that used for stinknet.

Type of control	Stinknet
Manual	With or without hand tools, manual control is only efficient in small patches, careful cleaning to prevent spreading seeds is important
Mechanical	Vacuuming seeds both from plants and ground is possible in small patches, mowing can be effective, but plants can resprout and flower so monitoring and additional treatments are essential
Chemical	Herbicides such as glyphosate, aminopyralid, and aminopyralid/triclopyr appear to control stinknet. Aminopyralid, indaziflam and isoxaben + dithiopyr appear effective as pre-emergents but more research on herbicide treatments is needed.
Biological	Little is known but one possible agent is a South African moth for which the host range is not known for native plants in the United States

but care should be taken to dispose of flowering plants appropriately. Removed plants that have flowers that might produce mature seed should be double-bagged. In addition, when pulling stinknet and seeds are mature, vacuuming the seeds that are dropped can reduce the number of seeds in the soil (J. Conn, pers. comm.). When plants are fully dried out and seed heads readily shatter upon disturbance in the collection process, vacuuming entire seed heads from standing plants reduces the number of seeds dispersed in the collection and removal process (J. Horst, pers. comm.). Seeds can also be vacuumed from the top layer of litter to remove mature seeds. When vacuuming, care must be taken not to move the small stinknet seeds to other sites in the vacuuming equipment. Vacuuming works best on small infestations.

Stinknet can form very dense stands with multiple cohorts flowering during the season, thus multiple removals will be necessary, reducing efficacy. Although at dry sites, or in years with a few precipitation events, these multiple cohorts may bloom in relative synchrony in the spring.

It is also extremely difficult to control medium-sized to large-sized patches with manual methods. Mowing can be efficient for small- and medium-sized patches although multiple treatments might be necessary. However, stinknet plants readily resprout after cutting, even late in the growing season, when there is adequate soil moisture. Because of this, mowing is only moderately effective and best late in the season, but before flowering, when plants are water stressed. Livestock grazing in areas with stinknet will very likely make the infestation worse (Rutherford & Powrie 2010). Prescribed fire may partially control stinknet in the short term, however stinknet appears to thrive in post-fire environments and fire may increase the population if used as a stand-alone treatment.

Herbicide treatments can be very efficient and effective at reducing small to medium-sized stinknet infestations. Few long-term, widespread and successful studies or management operations on herbicide effectiveness have been conducted. In some herbicide trails glyphosate, aminopyralid, and aminopyralid/triclopyr appear to control stinknet (McDonald 2019). Aminopyralid can also provide long-term control of stinknet patches (up to 12 months) as it also acts as a pre-emergent herbicide. While clopyralid has been highly effective in some years, in other years, it showed only moderate post-emergent control (McDonald 2020). Clopyralid and aminopyralid are similar compounds and it is possible that under some conditions aminopyralid might only show partial post-emergent control of stinknet, similar to what has been observed for clopyralid. In other preliminary studies, aminopyralid, indaziflam, and isoxaben + dithiopyr, provide a high level of control, with clopyralid showing good control if used as a pre-emergent herbicide, and not when applied post-emergent. However, more research is needed to verify these results (McDonald 2020, C. de la Rosa, pers. comm., and C. Rodriguez and L. Larios, unpub. data).

Douglas & Nicholson (2019) experimentally examined the impact of a number of herbicides and found that glyphosate also reduced seed set and seed viability on plants in early stages of flowering. Adding a methylated seed oil (MSO) or similar adjuvant may increase the effectiveness of glyphosate treatments especially late in the growing season (J. Scheuring, pers. comm.). In addition, when the plant is fully flowering, several herbicides including glyphosate and aminopyralid do not appear to stop the growth of stinknet or inhibit the seeds from ripening enough to become viable (C. McDonald, pers. obs.), however, more research is needed to further understand this result (Perez-Ochoa & de la Rosa 2019). For herbicide applications to be most effective, treatments need to be implemented before flowering. Post-treatment restoration, preferably by fast growing winter annuals or possibly mulch, may decrease the ability of stinknet to re-invade a treated site.

The best method of stinknet control is prevention, and after that early detection and rapid response. Stinknet spreads quickly and can be difficult to detect when not flowering, thus once a population is discovered when it is flowering, especially later in the growing season, it might be too late to stop seed production that growing season, unless plants can be hand pulled and double bagged. Because stinknet seeds are tiny, less than 1 mm long, in order to reduce the spread of stinknet all equipment, clothes and footwear need to be cleaned when leaving an infested site, and equipment and materials should be cleaned when entering an uninfested site.

Biological control for stinknet has not been investigated to any extent. One possible candidate is a South African moth species, *Loxostege frustralis* (Möhr 1982), that feeds on stinknet and related plants, and sometimes reaches outbreak proportions on degraded agricultural properties in the Karoo region of the Western, Eastern and Northern Cape Provinces (S. Neser, pers. comm.). However, this moth is not strictly host-specific (monophagous) in South Africa, and its potential host range and thus possible impact on native plants in the United States is unknown. Although biological control might be the only long-term control for stinknet, efforts for finding and evaluating control species have not even been initiated.

Conclusions and Potential Topics of Study

Stinknet is likely to become one of the most difficult of recent invasive, non-native plants in the southwest to control for several reasons, possibly more difficult than buffelgrass, red brome, or Sahara mustard (*Brassica tournefortii*). From consideration of its life history characteristics, the very high seed production with many thousands of seeds per plant, the relative ease of long-distance dispersal, the difficulty in detecting infestations before flowering, avoidance by native herbivores and livestock, and the potentially long-lived seed bank are perhaps the most problematic traits. In addition, the apparent ability to flourish in a number of different natural and disturbed environments is of great concern.

Because stinknet has not been the object of extensive research, there are a number of unanswered basic questions about stinknet, some of which we mentioned above and will highlight here.

(1) What factors can limit the distribution and spread of stinknet? We have discussed this above but both experimental and observational research should be undertaken to determine how niche modeling that includes climate, precipitation, soils, disturbances, habitat, shade tolerance, and other factors might limit stinknet distribution and spread.

(2) What are the best long-term approaches to control the spread including manual, mechanical or chemical treatments? In addition to research on cost-effective control methods, a combination of methods as recommended in integrated pest management programs, and timing of methods is needed. We have provided general information on control methods, and so far those few attempted methods are neither highly effective nor highly efficient. Without an effective and efficient method of control, land managers and property owners will have a difficult time stopping the spread. Further refinement of the success of these approaches would be useful.

(3) What is the possibility of biological control? Are there insects, pathogens, or other biological agents in the native and invaded ranges that might be considered for biological control? As basic information, what are the numbers and proportion of viable seeds in capitula in South Africa compared with those in the invaded environment?

(4) What is the longevity of the seed bank? Seed bank longevity is important for control and the number of years that an infested site would need to be monitored. Factors that limit the longevity of the seed bank, such as climate, fire, pathogens, and seed herbivory, should be investigated.

(5) How is stinknet pollinated and fertilized? For understanding the spread of stinknet, knowledge about pollination and fertilization is important, such as what is the relative importance of self-fertilization, self-compatibility, insect pollination, and wind pollination. One approach to determine the importance of different types of pollination is to use genetic markers, which then could also provide an estimate of the amount of genetic variation.

(6) What were the sources of invasions from South Africa to Australia and the United States? For understanding the invasions into Australia and the United States, knowing the source of invasions from South Africa and how they were transmitted is important. Given genetic markers, any connection between invasions into Australia and the United States could be determined. This information might also be of crucial importance in biological control studies. Ideally, matching should be done of possible host-specific "strains" of pathogens, and possibly "strain"-specific insects or mites as biological control candidates of target entities present in invaded areas (S. Neser, pers. comm.).

(7) How many founders contribute to an invasion? Given genetic markers, the number of founder individuals for these invasions could be estimated. For example, this might provide an estimate of whether populations can be started from single or very few founders and then spread with self-fertilization. We suspect, based on the large number of small and scattered stinknet sites, that populations can be initiated from very few founders, but further research is needed.

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