HOW *AMARANTHUS PALMERI* EVOLVED FROM AN OBSCURE NORTH AMERICAN PLANT TO BECOME THE BIGGEST WEED PROBLEM IN THE US CORN AND SOYBEAN BELT

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The success of *Amaranthus palmeri* in US row crops resulted from a confluence of changes in productions systems, the dominance of herbicide resistant forms over its susceptible counterparts, the release of glyphosate transgenic crops, a one herbicide fits all mentality, and perhaps a touch of negligence.

Amaranthus palmeri is perhaps the most troublesome weed in US row crops. It is one of several closely related *Amaranthus* species, collectively and individually referred to as pigweeds, some of which bear close resemblance to *A. palmeri*. There are several traits of *A. palmeri* which have led to it becoming a huge weed problem but perhaps none was more important than evolving resistance to the herbicide glyphosate. Other species attributes that favor *A. palmeri* are that it grows quickly, produces high numbers of seed, causes severe interference with crops, can acclimate to many environments, and has evolved resistance to several major classes of herbicides. In some cases, the resistant type is so prevalent that it is difficult to find glyphosate-sensitive plants.

The first record of *A. palmeri* in the US was in 1834 (Berlandier 1834) where it was collected along the banks of the Rio Grande and then again in the San Diego area in 1877 (Palmer 1875). Thereafter, many collections were made throughout the southwestern US and Mexico. However, specimens were also collected in Massachusetts in 1886 (Pease 1912) in disturbed areas and farms, but these were thought to be introductions from the southwest. So, for over one hundred years *A. palmeri* has slowly been gaining a foothold and spreading across the US.

So how did *A. palmeri* become one of the most troublesome weeds? Did rising glyphosate-resistant populations go unnoticed? Were there no past experiences of hard to control weeds or weeds out of control to draw upon? Of course not! *A. palmeri* has been on the weed control radar since records of the most troublesome weeds were initiated. It was reported as a troublesome weed and was #6 out of 10 listed (Buchanan 1974) in the south. In 1987, it ranked #7 out of 10 (Webster & Coble 1987) and moved up to #4 by 2009 (Webster & Nichols 2012). Glyphosate-resistant *A. palmeri* was listed as #1 in 2013 and was distinguished from susceptible pigweeds in four of eight states reporting (Webster 2013). The change in ranking represents a weed shift, that is, one weed displacing another in abundance and importance over time. Morning glories (*Ipomeae* spp.) and nutsedges (*Cyperus* spp.) have remained high on these lists over years whereas contrary to the rise in *A. palmeri* and horseweed (*Erigeron canadensis* (synonym *Conyza canadensis*)) in importance to farmers, weeds such as prickly sida (*Sida spinosa*), cocklebur (*Xanthium* spp.) and goosegrass (*Eleusine indica*) have fallen off the list. *A. palmeri* is likely to remain in its pre-eminent position in weed surveys in years to come because it is developing multiple resistances to several herbicides.

A. palmeri has several traits which contribute to it becoming a dominant weed problem. Its produces massive quantities of small seed with high germinability and the amount of seed produced is dependent on the biomass of the plant. The larger the plant the more seed is produced. Seed estimates have been as high as 600,000 seeds plant^{-1} for plants grown without other plant interference (Keeley *et al*. 1987). A study of *A. palmeri* growth in competition with soybean determined from 1,011 to 796,135 seeds per plant were produced with averages of 13,384 ± 27,363 to 60,221 ± 21,991 (Schwartz *et al*. 2016). Equally important was that most *A. palmeri* seeds were retained on the plant at harvest (Schwartz *et al*. 2016) which means they are scattered during harvest, renewing the soil seed bank. *A. palmeri* seed may be viable in the soil for a few years. The seed can germinate on the soil surface and its long germination period increases the likelihood of germination throughout the growing season. The small size (1 mm in

Figure 1. *A. palmeri* emerging between the rows of corn and exceeding 8 feet in August. Note pigweeds growing at the end of the rows in various early growth stages. These young pigweeds are also capable of producing seeds.

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Figure 2. Mature soybean field with *A. palmeri* emerging through the canopy as the crop matures and the canopy thins due to leaf drop.

Figure 3. *A. palmeri* in a cotton field growing faster than and overtopping the cotton.

diameter) also allows it to move during excessive rain events or in irrigation streams.

A. palmeri has a competitive advantage when present in crops. *A. palmeri* exhibits very rapid growth with stem elongation as high as 2.25 inches per day (Molin & Nandula 2017). It can grow from 2 to 7 feet when not in competition with other plants (Schonbeck 2014). These heights easily exceed the crop canopy of cotton and soybean, and when present in corn may exceed the final corn height (Figure 1). *A. palmeri* also competes efficiently for nutrients, especially nitrates, and has high water use efficiency, allowing it to tolerate droughty conditions. It has C_4 type of photosynthesis and is adapted to high light and high temperatures. It is dioecious, an obligate out crosser, making gene transfer inevitable. It can survive shading and grow through the crop canopy at the end of the growing season (Figures 1 and 2). *A. palmeri* becomes large quickly (Figure 3), and mature plants are difficult to remove because of large stem and root diameters. Hoeing stalks if not taken below the soil line will allow regrowth (Sosnoskie *et al*. 2014). *A. palmeri* also demonstrates environmental adaptability as it is found in many of the 50 US states, and its distribution includes all southern states and many throughout the northeast and north central states as far north as Minnesota and Ontario, Canada (Heap 2019). *A. palmeri* has a discontinuous emergence pattern, being able to germinate and establish new plants across the entire growing season (Figure 1: note the emerging *A. palmeri* in the forefront compared to the *A. palmeri* in the mature August corn).

Is *A. palmeri* more problematic to control than other weeds? Timely applications of treatments, both herbicide-based and mechanical, are essential to efficient weed control. Many of the methods used to control *A. palmeri* available today are just as good as they were prior to glyphosate resistance. However, several changes in agronomic practices occurred from the 1970s to 1990s which supported greater *A. palmeri* survival and germination. Conservation tillage programs had been gaining favor through the 1970s and 1980s due to development of herbicides and advances in planting and soil manipulation machinery. Further strength for conservation tillage programs were enabled by the Farm bills of 1985 and 1990 which had provisions for mandatory compliance with conservation tillage programs. This allowed *A. palmeri* seed to remain on the soil surface where it germinates best. In addition, in 1996 transgenic soybeans were released permitting the use of glyphosate applied postemergence over-the-top of the crop, a method consistent with the concepts of conservation tillage. In fact, the adoption of herbicide-resistant tolerant crops benefitted the environment directly by reducing herbicide use and by increasing conservation tillage (Fernandez-Cornejo 2012). This made economic sense because, basically, glyphosate killed just about everything in the field except glyphosate-resistant plants. The strategy was to plant the transgenic soybeans, apply glyphosate postemergence a few times, and Voila! no more weeds. It worked wonderfully (for a few years). This led to a decrease in herbicide diversity (Table 1), a rise in the singular use of glyphosate after 1996 and fewer herbicide mixtures going out on the soil. Glyphosate resistant cotton and corn followed shortly after herbicide tolerant soybeans, resulting in large acreages of crops in which a single herbicide might be used for weed control. The one-herbicide-only approach was enhanced further by a decrease in the price of Roundup (glyphosate) and development of low-cost generic glyphosates. Other companies began making glyphosate because the exclusive rights to make glyphosate by one company had expired.

To make matters worse, eight years after introduction of glyphosate-resistant soybean *A. palmeri* evolved resistance to high rates of glyphosate (Culpepper 2006) and resistance cases have expanded to six other classes of herbicides (Heap 2019). *A. palmeri* is present in 39 states (Kniss 2018) and glyphosate-resistant *A. palmeri* has now spread to 28 (Heap 2019). *A. palmeri* with multiple resistances has made control choices ever more difficult. Most cases of multiple resistance are to glyphosate or the herbicide class known as acetolactate synthase (ALS) inhibitors (Heap 2019). Twelve states have reported resistance to two herbicides, and two states have reported multiple resistance to three and five herbicides from different classes (Heap 2019). Furthermore, no significant fitness costs

Table 1. The average soybean acreage for the years listed for the state of Mississippi was 1,929,000 ± 5,000,000. Herbicide values are in thousands of pounds applied for the state of Mississippi. Note the shift in product diversity and pounds used for glyphosate following the introduction of Roundup Ready soybeans in 1996. Herbicides with applications of less than 50,000 pounds are not shown and had patterns like bentazon. New on the scene in 2017 and 2018 were dicamba with applications of 174,000 and 625,000 pounds, and glufosinate with 110,000 and 67,000 pounds. Data source: USDA-NASS 2019.

Year	Acifluorfen	Bentazon	Clomazone	Fomesafen	Imazaquin	Metribuzin	Paraquat	Pendimethalin	Metolachlor	Trifluralin	2,4-D	Glyphosate
1990	71	120			66	149		288		723		
1991	70	121		46	48	155		245	118	616		164
1992	173	140	77	25	82	130	38	445		659		116
1993	191	332	69	61	87	190	166	327		714		144
1995	270	179	65	54	88	130	74	578	334	475		116
1996	162	151	93	33	71	149	39	140	355	619		302
1997	171	154	41	21	46	97	39	251	179	295		952
1998	115	120	153	43	42	93	160	307	246	330	48	1147
1999	88	86	77	43	39	110	47	215	380	381	59	1321
2000	28	13	12		17	45		108	116	278	55	1313
2002	26				8			50		42	78	2013
2006							58				194	3225
2012	27			103			242		681		277	3767
2015				155		119	446		1714		488	4381
2017						336	938		2258		835	3417
2018				196		194	894		1943		583	3568

were identified in plants with the resistance trait (Giacomini 2014). Resistance has also crossed species lines. An interesting case of resistance was discovered in Water Valley, MS. A farmer reported a glyphosate-resistant pigweed presumably *A. palmeri* that looked a lot like a rather tall *A. spinosus* (Spiny amaranth). These pigweeds were hybrids between *A. spinosus* and *A. palmeri* with retention of the spines of *A. spinosus* and height of *A. palmeri* and resistance to both glyphosate and ALS inhibitors from *A. palmeri* (Molin *et al*. 2016).

A. palmeri is highly competitive and, if left unchecked can cause catastrophic yield losses. A density of only eight *A. palmeri* plants m^{-1} of row, present at soybean or corn emergence, reduced soybean grain yield by 78% (Chandi *et al*. 2012) and by 91% in corn (Massinga *et al*. 2001). *A. palmeri* outgrows neighboring corn plants achieving heights of 8 to 10 metres (Figure 1). Figure 3 shows *A. palmeri* in a cotton field in which both species germinated at the same time. In addition, late emerging plants that have escaped herbicide treatment may grow up through the crop canopy (Figure 3) late in the season providing opportunity to produce added seeds. (Schonbeck 2014)

There has been a lack of adequate containment from contaminated equipment and grain shipments. *A. palmeri* seeds are difficult to remove from combines and other farm implements because they hang up in every nook and seam. Glyphosate-resistant seeds that dislodge from improperly cleaned equipment may move herbicide resistance to new fields. Cleaning equipment between fields is burdensome and delays field operations despite producer awareness. The seed are also small enough to spread by wind, water, animals and migrating birds, and be contaminants in grain, mulches and manures. Plants harboring resistant genes may also survive in field margins providing a source of pollen and seed.

Considering these concurrent changes in agriculture and the attributes of *A. palmeri* that led to its success in row crops, it is not surprising that it has become such a dominant weed problem. The quote "Nature abhors a vacuum", attributed to Aristotle, reminds us that nature fills a void when presented with the opportunity. The confluence of events including changes in agronomic practices and changes in measures of control of *A. palmeri*, have provided that opportunity. We have created the PERFECT *A. palmeri* (pigweed) STORM – THE PIG-NADO!

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William Molin has enjoyed a career in weed science, specifically herbicide mechanisms of action and herbicide resistance management, in both industry, academia, and government service. His latest research describes the basis for the amplification mechanism causing resistance to glyphosate in Palmer Amaranth.

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