Ke, L.S. and W.D. Wang. 1997. J. Agric. Assoc. China. 179:15-29.

Khayyat, M., E. Tafazoli, S. Eshghi, M. Rahemi, and S. Rajaee. 2007. Amer. Eurasian J. Agric. Environ. Sci. 2:539-544.

Lester, G.E., J.L. Jifon, and W.M. Stewart. 2007. Better Crops. 91:(1)24-25.

Lester, G.E., J.L. Jifon, and D.J. Makus. 2006. HortScience. 41:741-744.

Lester, G.E., J.L. Jifon, and G. Rogers. 2005. J. Amer. Soc. Hort. Sci. 130:649-653.

Lester, G.E., Arias L. Saucedo, and Lim M. Gomez Lim. 2001. J. Amer. Soc. Hort. Sci. 126:33-36.

Li, R.H., D.B. Xu, and Q.W. Huang. 2008. China Vegetables. 6:17-20.

Li, S., Y. Xu, W.S. White, S. Rodermel, and H. Taber. 2006. FASEB J. 20(5, Part 2):A1059.

Lin, X.Y, Y.S. Zhang, M.Z. Cai, Y.P. Zhang, G. Li, and X.E.Yang. 2006. Plant Nutr Fertilizer Sci. 12:82-88.

Locascio, S.J. and G.J. Hochmuth. 2002. HortScience. 37:322-324.

Magen, H., P. Imas, Y. Ankorion, and A. Ronen. 2003. Proc International Fer-tiliser Soc. (524):13-24.

Marschner, H. 1995. Functions of mineral nutrients: macronutirents, p. 299-312. In: H. Marschner (ed.). Mineral nutrition of higher plants 2nd Edition. Academic Press, N.Y.

Muthumanickam, D. and G. Balakrishnamoorthy.1999. South Indian Hort. 47:152-154.

Naresh, B. 1999. Bioved. 10:39-42.

Nava, G., A. Roque-Dechen, and G. Ribeiro-Nachtiga. 2008. Communications Soil Sci. Plant Analysis. 39:96-107.

Ni, W.Z., J.S. Liang, and R. Hardter. 2001. Pedosphere. 11:251-255.

Perkins-Veazie, P., W. Roberts, and K. Perez. 2003. Hortscience. 38:816-817.

Pettigrew, W.T. 2008. Physiol. Plant. 133:670-681.

Rebolledo-Martinez, A., A. Lid-del-Angel-Perez, and J. Rey-Moreno. 2008. Interciencia. 33:518-522.

Rengel, Z., P.M. Damon, and I. Cakmak. 2008. Physiologia Plantarum 133:624-636.

Shawky, I., A. Montasser, M. Nageib, L. Haggag, and M. Abd-El-Migeed. 2000. Effect of fertilization with potassium and some micronutrients on Navel orange trees. II - Effect on yield, fruit quality and juice mineral content. In El-Sawy M, Francis RR, El-Borollosy MA, Hosni AM (ed) Annals Agric Sci Cairo. 3(Special): 1215-1226.

Shinde, A.K., D.J. Dabke, B.B. Jadhav, M.P. Kandalkar, and M.M. Burondkar. 2006. Indian J. Agric. Sci. 76:213-217.

Si, S.K.G., M. Bellal, and F. Halladj. 2007. Acta Hort. (758):269-274.

Simoes, Ado-N, J.B. Menezes, S.E.V.D. Lima, J.F. Medeiros, G.F. Silva, D.F. Freitas. 2001. Caatinga. 14:31-35.

Singh, H.K., K.S. Chauhan, and B.P. Singh.1993. Haryana J. Hort Sci. 22:276-279.

Sipiora, M.J., M.M. Anderson, and M.A. Matthews. 2005. Proc. Soil Environment Vine Mineral Nutr. Symp. San Diego, CA, 29-30-June,-2004. pp 185-192.

Skogley, E.O. and V.A. Haby. 1981. Soil Sci. Soc. Am. J. 45:533-536.

Srivastava, A.K., A.D. Huchche, R. Lallan, and S. Shyam. 2001. J. Potassium Res. 17:93-97.

Suresh C.P. and M.A. Hasan. 2002. Res Crops. 3:398-402.

Taber, H., P. Perkins-Veazie, S.S. Li, W. White, S. Rodermel, and Y. Xu. 2008. HortScience. 43:159-165.

Tisdale, S.L., W.L. Nelson, and J.D. Beaton. 1985. Soil and Fertilizer Potassium. Ch. 7 in S.L. Tisdale, W.L. Nelson, and J.D. Beaton (eds). Soil Fertility and Fertilizers, 4th ed. Macmillan, New York. 249-291.

Umamaheswarappa, P. and K.S. Krishnappa. 2004. Trop Sci. 44:174-176.

Usherwood, N.R. 1985. The role of potassium in crop quality. In Munson, R.D. (ed). Potassium in Agriculture ASA-CSSA-SSSA, Madison, WI. pp 489-513.

Wójcik, P. 2005. Proceedings International Scientific Conference: Environmental-ly friendly fruit growing, Polli, Estonia,-7-9-September,-2005. pp 44-50.

Yang, X.Y., Y.S. Bu, and X.Z. Duan. 2005. Xinjiang Agric Sci. 42:272-275.

Zhang, S.Y., J. Yang, and G.H. Liu. 2008. J. Anhui Agric. Univ. 35:289-292.

How Potassium Nutrition Can Suppress Soybean Aphids

Tom Bruulsema, Christina DiFonzo, and Claudio Gratton

The soybean aphid has become the most important insect pest of soybeans in the Northeast and Midwest regions of North America. It often damages soybean plants that are K-deficient more than those that are not. Recent research in Wisconsin and Michigan has found that K-deficient soybeans can in some, but not all, instances suffer more from aphids than soybeans without K limitation, and that the causes may be related to amino acid composition of the phloem sap.

The soybean aphid, Aphis glycines Matsumura, is an invasive species that was first discovered in the United States in 2000. On-farm visits and observations in Wisconsin and Michigan indicated that many of the soybean fields most heavily infested with soybean aphids were also exhibiting symptoms of K deficiency. This article summarizes results from recent research conducted to examine the association between

Abbreviations and notes: K = potassium; P = phosphorus; N = nitrogen; S = sulfur; ppm = parts per million; CEC = cation exchange capacity.

Table 1. Soybean leaf K and yield increased with increasing soil test K in a field experiment in Arlington, Wisconsin (means of 2 years, 2001-2002; adapted from Myers et al., 2005).

Soil test K[1], ppm	Soybean yield, %	Soybean yield, bu/A	
		Sprayed	Unsprayed
60	0.76	33	26
93	1.20	47	38
114	1.43	52	41

[1]Soil test K in Wisconsin is by the Bray-1 extractant. Values below 80 and above 100 are considered low and high, respectively.

Close-up photo of an individual aphid (Aphis glycines Matsumura).

aphids and K, in order to determine the appropriate role of plant nutrition in the management of the aphid pest.

Wisconsin, 2001-2002

In a controlled field experiment in which K fertilizer had been applied at different levels, soybean leaf K and yield increased with increasing soil test K (**Table 1**), but no differences were observed in aphid populations (Myers et al., 2005). Repeated foliar insecticide sprays reduced aphid populations and increased yields, but there was no interaction between spray and K on either parameter.

Yet, aphid populations were very high in both years in this experiment, substantially higher than those in farm fields. For example, in 2002 peak abundance in the unsprayed plots eclipsed 1,600 aphids per plant, compared to an average peak abundance of 280 in a survey of southern Wisconsin fields. It is possible that owing to the close proximity (< 3 ft.) and small size (10 by 23 ft.) of the plots, severe K deficiencies attracted and supported large aphid populations that led to colonization of plants both deficient and sufficient in K. Thus the design of this experiment may have hindered the ability to detect the observed effects that appear to be operational at the whole-field scale.

Wisconsin, 2003

A laboratory experiment examined performance of aphids on leaf material collected from healthy and visually K-deficient soybean plants growing in an experimental field in Arlington, Wisconsin, in 2003. The number of nymphs per adult and the population increase rate were substantially higher on the leaves low in K (**Table 2**). This effect indicates that K-deficient soybeans provide for greater potential expansion rates of aphid populations. These controlled laboratory conditions, however, do not allow expression of factors such as natural predators and parasites that would be operational in the field.

The mechanism for this effect was not identified, but others have noted that aphids are dependent on soluble amino acids for their nutrition, and that K deficiency can cause increased concentration of such amino acids in plant tissue.

Wisconsin, 2004

In 2004, a year with low aphid pest pressure, soybean aphid populations were monitored in 34 production soybean fields across Wisconsin, ranging in soil test K from 80 to over 200 ppm (Myers and Gratton, 2006). These fields included some soils of sandier texture, whose critical level for soil test K (upper limit of the "low" range) is as low

Potassium deficient (left); healthy leaf.

Aphid infestation on a soybean leaf.

Table 2. Aphids in a 2003 lab study grew more rapidly on soybean leaves with less K (adapted from Myers et al., 2005).

Soil test K, ppm	Leaf K, ppm	Petiole sap K, ppm	Population growth rate	Population growth rate
60	0.55	1000	68	0.48
160	1.68	2493	49	0.42

Table 3. Leaf K and soybean yield were increased, and aphid infestations were decreased, by addition of muriate of potash to bring soil test K to 113 and 142 ppm, in an open field trial in 2004 in Arlington, WI. (adapted from Myers and Gratton, 2006).

Soil test K, ppm	Leaf K, %	Clip-cage aphids		Natural aphids/plant		Soybean yield, bu/A
		Population growth rate	Population growth rate	19-Aug	26-Aug	
60	1.50	42	0.31	107	251	24
113	2.40	27	0.28	56	72	47
142	2.40	26	0.27	54	72	46

as 60 ppm. Across these fields, aphid population growth rate was negatively correlated with soil K and P and leaf K, N, P, and S. However, peak aphid densities were positively correlated with the same suite of soil and leaf nutrients.

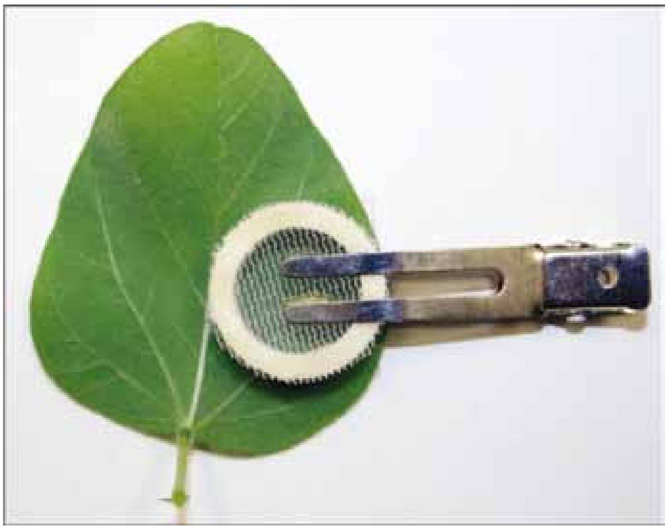
In the same year, a controlled K response trial in field plots showed that medium and higher soil test K levels decreased aphid reproductive rates, slowed rates of population increases, and lowered peak abundance of naturally occurring aphid populations (**Table 3**). Clip-cages placed on leaves of intact plants allowed the study of reproduction of single aphids placed on single leaves in a small enclosure, isolated from other aphids and protected from predators and escape, but in the field environment.

The reasons why aphid populations were reduced by higher K levels in 2004 (**Table 3**), but not in 2001 and 2002 (**Table 1**) are not clear. It may be related to the lower pest pressure in 2004 which made it possible for the effects of plant nutrition on aphids to be detected without high overall aphid numbers swamping out any effects. Plot size in 2004 was the same as in the earlier studies.

Michigan, 2003-2004

In mid-August of both 2003 and 2004, five to eight commercial soybean fields in southwest Michigan showing symptoms of K deficiency were surveyed (Walter and DiFonzo, 2007). Within each field, pairs of samples were selected such that one was in the center of an area of severe visual symptoms, and the other was in a nearby symptomless area. At each of the areas, soils, plant phloem, and aphid populations were sampled. Soil test K levels were found to be lower in areas showing symptoms in both years. In 2003, an outbreak year, aphid density was higher in the K-deficient sample areas (**Table 4**). In 2004, aphid populations were too low to detect differences in density.

Soybean leaves showing symptoms of K deficiency.



A clip cage to measure growth and development of single aphids.

In 2004, in a commercial soybean field with low soil test K in Van Buren County, Michigan, a field trial was established containing five plots, each 20 by 120 ft., with and without application of potash fertilizer at a rate of 140 lb of K_2O/A. Clip cages and exclusion cages were used to monitor reproductive performance of aphids. A clip cage was a small predator-proof enclosure clipped to a leaf to measure the growth and reproduction of individual aphids. Exclusion cages were 6 x 6 ft., covering 10 plants each, and prevented predation on the introduced aphids, but allowed escape of any aphids which morphed into alate (flying) form.

The first set of clip cages, installed on 10 June, showed no differences in aphid reproductive performance. The second set, installed 14 July, produced nymphs earlier and in greater numbers on soybeans that had not received K fertilizer (**Table 5**). In the exclusion cages, significantly higher populations of aphids were observed on the zero-K treatment from 30 June onward.

Samples of phloem sap were analyzed from all studies conducted in Michigan in 2003 and 2004. The sampling method measured the ratios of 18 common amino acids in the sap, but not the total amounts. The relative proportion of the amino acid asparagine was found to correlate negatively with soil test K, while the other amino acids showed no

Table 4. Surveys conducted in Michigan found higher numbers of naturally-occurring aphids in K-deficient field areas in 2003 but not in 2004 (Walter and DiFonzo, 2007).

Within-field area surveyed	2003		2004	
	Soil test K[1], ppm	Aphids/leaf	Soil test K, ppm	Aphids/leaf
K-deficient	15-65	174	28-83	3
Symptomless	22-83	103	38-83	3

[1]Ammonium acetate extractable K; critical levels 75-100 ppm.

Table 5. Aphid populations in a K-deficient commercial soybean field in 2004. Exclusion cages were infested with one aphid per plant on 28 May. Initial soil test K was 67 ppm[1] (Walter and DiFonzo, 2007).

KCl applied, lb K_2O/A	Clip cage		Exclusion cage	
	14-Jul		30-Jun	15-Jul
	Age at first nymph	Nymphs /adult	Aphids/plant	
0	8.8	88	703	6858
140	11.0	71	233	2315

[1]Critical level for this soil (CEC of 8.6 meq/100g) is 96 ppm.

Predator-proof cages used to measure population growth rate of aphids on K-deficient and K-amended soybean, southwest Michigan, July 2003.

relationship. That is, asparagines levels in plant sap increased as soil K tests decreased: at a soil test K level of 120 ppm, asparagine comprised 3 to 10% of the total amino acids but increased to 8 to 20% when soil tests were at 20 ppm.

Asparagine may play a critical role in relieving N-limitation of aphids. Weibull (1988) noted that sap from the most aphid-resistant accessions of oat and barley contained relatively low levels of asparagine. Richards and Berner (1954) reported that K deficiency caused higher asparagine content in barley leaves. Barker and Bradfield (1963) reported that higher levels of K in a nutrient solution resulted in reduced concentrations of free amino acids, especially asparagine, in young corn seedlings.

Aphids are thought to obtain all of their dietary N from amino acids translocated in the phloem sap. Aphids are not known to use proteinases as part of their nutritional digestion, probably because high levels of proteinase inhibitors and extremely low protein concentrations in typical phloem sap make plant proteins a poor N source. Godfrey and Hutchmacher (1999) reported that K applied on California cotton at 100 to 200 lb K_2O/A had a "moderate negative effect on both the generation time and the fecundity of the aphid." So, as plants become more stressed due to K-deficient soils, their response is to release more free amino acids such as asparagine into the phloem to counterbalance osmotic imbalances in plants. However, aphids can take advantage of these free-flowing and easy-to-digest N-containing compounds to develop faster and produce more offspring per female. This results in faster aphid population growth and ultimately higher population densities on soybean which further exacerbates yield loss.

Conclusions

In both Wisconsin and Michigan, low soil K was associated with increased aphid populations only at the low end of the range of soil K in production fields, and well below the K levels recommended for soybean production. Soil test summaries conducted in 2005 for these two states indicate a median soil test K of 125 to 149 ppm, and that only about 10 to 15% of soils are expected to test below 80 ppm.

While these results from Wisconsin and Michigan show a strong "bottom-up" effect of soybean K nutrition on the soybean aphid, it does not imply that adequate K is a reliable control for aphids. Aphid populations are also affected by natural enemies such as Asian lady beetles, and by natural parasites. Both are examples of "top-down" factors that may be more or less important, depending on the year and the site, than "bottom-up" factors such as host plant nutrition. Aphid infestations can still occur when K nutrition is adequate.

However, preventing deficiencies provides at least one degree of protection or insurance against yield loss from these potentially damaging and disease-transmitting insects. From a practical standpoint, this means that soybean growers should manage soil K levels in their fields as part of their integrated pest management plan for the soybean aphid.

Dr. Gratton in Associate Professor in the Department of Entomology, University of Wisconsin, Madison.

Dr. DiFonzo is Professor in the Department of Entomology, Michigan State University, East Lansing.

Dr. Bruulsema is Director, Northeast Region, IPNI North America Program, located in Guelph, Ontario, Canada; e-mail: tom.bruulsema@ipni.net.

References

Barker, A.V. and R. Bradfield. 1963. Agron. J. 55(5): 465-470

Godfrey, L.D. and R. Hutchmacher. 1999. http://www.cdfa.ca.gov/is/fflders/completed_projects.html

Myers, S.W., C. Gratton, R.P. Wolkowski, D.B. Hogg, and J.L. Wedberg. 2005. J. Econ. Entomol. 98: 113-120.

Myers, S.W. and C. Gratton. 2006. Environ. Entomol. 35: 219-227.

Richards, F.J. and E. Berner, Jr. 1954. Annals of Botany 18: 15-33.

Walter, A.J. and C.D. DiFonzo. 2007. Environ. Entomol. 36(1)26-33.

Weibull, J. 1988. Phytochemistry 27: 2069-2072.