INTERNATIONAL JOURNAL OF AGRICULTURE & BIOLOGY
1560–8530/2004/06–1–209–212
http://www.ijab.org

Review

Herbicide Tank Mixtures: Common Interactions

CHRISTOS A. DAMALAS
Laboratory of Agronomy, University of Thessaloniki, 54124 Thessaloniki, Greece
E-mail: damalas@weedmail.com

ABSTRACT

Tank mixing two or more herbicides is a useful practice that is extensively used in intensive agriculture aiming to broaden spectrum of weed control, to improve efficacy of the combined herbicides, to delay herbicide resistance development in weed populations, or to reduce herbicide rates and consequently to reduce the cost of weed control. In many cases, however, this practice may result in modified activity of the herbicides in the mixture due to interactions which often occur prior, during, or after application of the mixture. The type and the extent of interactions between companion herbicides depend primarily on properties of each herbicide in the mixture including chemical family, absorption, translocation, mechanism of action and pathway of metabolism as well as on weed or crop species involved. Antagonism (reduced activity), which is generally observed more often than synergism (increased activity), occurs more frequently in grass weeds rather than broadleaf weeds and also in mixtures where the companion herbicides belong mainly to different chemical families. On the contrary, synergism occurs more frequently in broadleaf weed species and in mixtures where the companion herbicides belong mainly to the same chemical family.

Key Words: Antagonism; Herbicides; Interactions; Synergism; Tank mixtures

INTRODUCTION

Applying two or more herbicides simultaneously, either using prepackage mixtures or by mixing different herbicide products before the application, is a very common approach in intensive agriculture (Hatzios & Penner, 1985; Green, 1989; Zhang *et al.*, 1995). This is because the application of a single herbicide, even though may provide good control of certain weeds, is often inadequate for satisfactory and cost effective weed control. Furthermore, many herbicides have a narrow spectrum of weed control; whereas, other herbicides do not show the same efficacy against all weeds of their spectrum of control when applied at the recommended rates. Given that weed flora normally consists of many species with varying levels of herbicide sensitivity, more herbicide applications should be often performed or additional measures for weed control should be additionally adopted. This, however, increases the cost of weed control and consequently the cost of crop production.

Mixtures of selected herbicides offer several advantages over the use of a single herbicide, including (a) a reduction in production cost by saving time and labour, (b) a reduction in soil compaction by eliminating multiple field operations, (c) an increase in the spectrum of weeds controlled or an extension of weed control over a longer period of time, (d) an improvement in crop safety by using minimum doses of selected herbicides applied in combination rather than a single high dose of one herbicide, (e) a reduction in crop or soil residues of persistent herbicides by using minimum doses of such herbicides, and (f) a delay in the appearance of resistant weed species to selected herbicides (Hatzios & Penner, 1985).

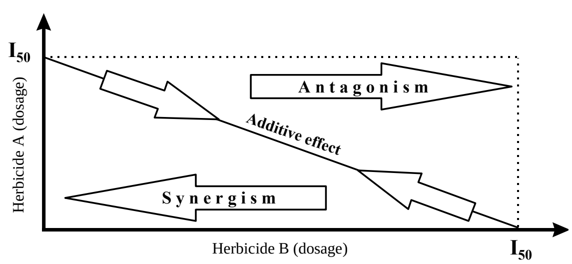
The use of tank mixtures with two or more herbicide partners presupposes that the combined herbicides behave and act independently (the presence of each one does not affect the activity of the other). In this case, the activity of the applied combination can be easily predicted as the sum of activities of each single herbicide of the mixture when these herbicides are applied separately. In some cases, however, interactions between companion herbicides may significantly modify the biological behaviour of each single herbicide in the mixture. These interactions often result in a reduction or an increase of the activity of the combined herbicides compared with activities when each one of them is applied alone. Practically, the optimum herbicide combinations would be those that exhibit enhanced activity on target weed species and decreased toxicity on crops (increased selectivity). This, however, is difficult to predict since the behaviour of each single herbicide in the mixture is often affected by the presence of the other(s) and the activity of the mixture may also vary considerably depending on plant species, growth stage, and environmental conditions.

The objective of this paper was to summarize important aspects on the most common interactions that take place between herbicides from the use of tank mixtures. Thus, the most important types and mechanisms of interactions as well as various factors that may affect the behaviour of herbicide mixtures are discussed.

Types of herbicide interactions. The result of an interaction between two or more herbicides after their application in mixture may be additive, synergistic, or antagonistic (Fig. 1). In the first case, the activity of the mixture is equal to the sum of the activities of all herbicides in the mixture when these herbicides are applied separately. In the second and the third case, however, the activity of the mixture is greater or lower, respectively, than the sum of the activities of all herbicides in the mixture when these herbicides are applied separately (Hatzios & Penner, 1985; Green, 1989). It is obvious that in the case of antagonism, where the activity of the mixture is reduced, greater application rates of the affected herbicide are required, whereas in the case of synergism, where the activity of the mixture is enhanced, application rates can be reduced.

Antagonistic interactions in herbicide mixtures often cause significant problems in weed control. For example, the application of pyrithiobac in mixture with fluazifop-P has been reported to reduce the efficacy of fluazifop-P on large crabgrass (*Digitaria sanguinalis*) (Ferreira *et al.*, 1995). Similarly, the application of tribenuron in mixture with diclofop has been reported to reduce the efficacy of diclofop on wild oat (*Avena fatua*) (Baerg *et al.*, 1996). It is obvious that such herbicide combinations should be avoided. Antagonistic interactions, however, may be considered beneficial when they reduce herbicide activity on crops. For example, according to Deschamps *et al.* (1990), mixtures of fenoxaprop with MCPA showed reduced toxicity of fenoxaprop on wheat and barley compared with fenoxaprop applied alone. Furthermore, mixtures of thifensulfuron with bentazon showed reduced toxicity of thifensulfuron on soybean compared with thifensulfuron applied alone (Hart & Roskamp, 1998; Lycan & Hart, 1999). Therefore, such herbicide combinations appear desirable unless antagonism on weeds also occurs.

Fig. 1. Schematic presentation of herbicide interactions (ID_{50} = rates of herbicides, applied alone or in mixture, for a 50% weed control) (modified from Green, 1989)



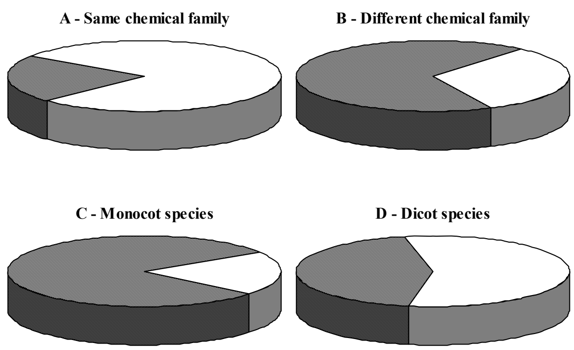
Synergistic interactions may be particularly beneficial when they result in more effective control of troublesome weeds. For example, Flint and Barrett (1989a) found that mixtures of glyphosate with 2,4-D were more effective on field bindweed (*Convolvulus arvensis*) compared with separate applications. Similarly, Scott *et al.* (1998) found that mixtures of sethoxydim with dimethenamid were more effective on johnsongrass (*Sorghum halepense*) compared with separate applications. It is obvious that such herbicide combinations are particularly useful for more effective weed control. Synergistic interactions, however, may cause significant problems when they result in increased herbicide activity on crops. For example, mixtures of ethametsulfuron with haloxyfop, fluazifop, fluazifop-P, quizalofop, and quizalofop-P may cause phytotoxicity and yield losses in *Brassica napus* and *Brassica rapa* (Harker *et al.*, 1995). Furthermore, mixtures of thifensulfuron (sulfonylurea) with imazethapyr (imidazolinone) may cause phytotoxicity in soybean resistant to sulfonylureas (Simpson & Stoller, 1996).

Mechanisms of herbicide interactions. Interactions in herbicide mixtures can occur prior, during, or after application of the mixture. This means that herbicides may interact physically or chemically in the spray solution or biologically in the plant. Mechanisms of interactions in herbicide mixtures can be broadly grouped into four categories: biochemical, competitive, physiological, and chemical (Hatzios & Penner, 1985; Green, 1989; Zhang *et al.*, 1995). According to this classification, interactions between herbicides in mixtures may be attributed to a) changes in the amount of an herbicide that reaches its site of action through absorption, translocation or metabolism caused by the presence of the other herbicide, b) interaction at the site of action between the combined herbicides where one herbicide of the mixture affects the binding of the other at its site of action c) interaction between combined herbicides that produces opposite effects on the same physiological process of the plant or synergizes the overall effect, and e) chemical reaction between the combined herbicides that leads to formation of inactive complex or an increase in the rate of metabolism (Hatzios & Penner, 1985; Green, 1989; Zhang *et al.*, 1995). The aforementioned mechanisms have not been fully documented in many cases. This is because of the great complexity in the study of such interactions since the occurrence of interactions may be a result of two or more mechanisms.

Factors affecting herbicide interactions. The type and the extent of interactions depend primarily on properties of the combined herbicides (chemical group, absorption, translocation, mechanism of action, pathway of metabolism). In general, antagonism has been found to occur three times more often than synergism regardless of the species or the herbicides in which is recorded (Zhang *et al.*, 1995). Synergism has been found to occur more frequently in mixtures where the companion herbicides belong to the same chemical group (Fig. 2A). These herbicides normally have similar chemical structure, the same mechanism of action, and similar pathway of metabolism. The high frequency of antagonism in such herbicide mixtures could be attributed in plant inability to metabolize simultaneously two or more herbicides. Antagonism, unlike synergism, has been found to occur more frequently in mixtures where the companion herbicides belong to different chemical groups (Fig. 2B). These herbicides normally have different chemical structure, different mechanism of action, and different pathway of metabolism. This is because these herbicides probably have a greater chance to interact at the site of action (enzyme or physiological process) or to react chemically and form an inactive complex.

The point of entrance and the mobility of the combined herbicides into the plant may affect significantly the behaviour of the herbicide mixture. In particular, when the combined herbicides enter into the plant through the same point (root or foliage) then the presence of one herbicide in the mixture may reduce the absorbed amount of the other and consequently can reduce its efficacy (Flint & Barrett, 1989b; Wanamarta *et al.*, 1989; Hart & Wax, 1996; Culpepper *et al.*, 1999; Damalas & Eleftherohorinos, 2001). Furthermore, the translocated amount of an herbicide to its site of action can be reduced by the presence or the concomitant translocation of another herbicide into the plant (Aguero-Alvarado *et al.*, 1991; Hart & Penner, 1993; Ferreira *et al.*, 1995, Baerg *et al.*, 1996; Hart, 1997; Damalas & Eleftherohorinos, 2001). On the contrary, the chance of such interaction is significantly reduced when only one herbicide in the mixture is translocated; whereas, the other is not (Zhang *et al.*, 1995). A similar trend with aryloxyphenoxypropionate and cyclohexanedione herbicides was observed using data from previous studies; members of both herbicide families were found to be affected more when mixed with systemic rather than contact broadleaf herbicides (Damalas & Eleftherohorinos, unpublished data).

Fig. 2. Frequency of antagonistic (●) and synergistic (○) interactions after simultaneous application of herbicides belonging to the same (A) or different (B) chemical groups and applied either on monocotyledons (C) or dicotyledons (D) (modified from Zhang *et al.*, 1995)



Antagonistic interactions may sometimes be attributed to increased metabolism of an herbicide because of the presence of another herbicide. For example, studies of Jacobson *et al.* (1985) and Shimabukuro *et al.* (1986) showed that the reduced efficacy of diclofop on various species after application with hormone herbicides such as 2,4-D resulted from an increase in its metabolism (formation of complex in the carboxylic group) because of the presence of 2,4-D.

The type of interactions between companion herbicides may depend on target plant species. For example, the combination of acifluorfen and bentazon showed an increased efficacy against common lambsquarters (*Chenopodium album*) and velvetleaf (*Abutilon theophrasti*) but reduced efficacy against jimsonweed (*Datura stramonium*) and red root pigweed (*Amaranthus retroflexus*) (Sorensen *et al.*, 1987). Moreover, the combination of herbicides that inhibit acetolactate synthase (ALS) (e.g. imazaquin, chlorimuron) with herbicides of the diphenyl-ether group (e.g. acifluorfen, fomesafen) showed increased efficacy on prickly sida (*Sida spinosa)* but reduced efficacy on common cocklebur (*Xanthium strumarium*) (Wesley & Shaw, 1992).

The growth stage of weeds may often affect the extent of interactions between combined herbicides. Liebl and Worsham (1987) observed that the postemergence application of chlorsulfuron and diclofop decreased efficacy of diclofop on italian ryegrass (*Lolium multiflorum*) and the effect was more severe when the application was performed at the three-leaf growth stage than at the two-leaf growth stage. This may be attributed to reduced detoxification ability from the younger plants and also to their thinner cuticle that probably allowed retention, absorption, and translocation of greater amounts of the applied herbicides.

The postemergence application of various graminicides in mixture with one or more broadleaf herbicides to broaden spectrum of control often results in reduced efficacy of graminicides (Vidrine, 1989; Holshouser & Coble, 1990; Grichar, 1991; Vidrine *et al.*, 1995; Damalas & Eleftherohorinos, 2001). This is the most common case of herbicide interaction reported in the literature and it has been observed in a great number of herbicide combinations on various grass species. Antagonistic interactions between graminicides and broadleaf herbicides are probably due to morphological and physiological differences between grasses and broadleaf weeds. Broadleaf weeds have meristems at the top of the plant; whereas, grasses have them at the base. This difference probably affects absorption and mainly translocation of the foliar applied herbicides particularly the systemic ones that are translocated and accumulated at the meristematic tissues of the plant where they act. Data of the literature show clearly that the simultaneous application of various graminicides with certain broadleaf herbicides limits considerably graminicide absorption by foliage and translocation to the meristematic tissues. This has been confirmed by the results of Zhang *et al.* (1995) who found that the frequency of antagonistic interactions was four times greater than synergistic interactions in grasses (Fig. 2C); whereas, the corresponding frequencies were almost equal in broadleaf weeds (Fig. 2D). It is worth mentioning that almost 80% of the interactions that has been observed in species of the family Poaceae (grasses) refer to cases of antagonism (Zhang *et al*., 1995).

It is evident from all the above that many factors may affect the behaviour of herbicide mixtures. Many of the observed interactions are not fully understood at the physiological and biochemical levels and it is possible that more than one mechanisms are involved.

CONCLUSIONS

Herbicide mixtures are considered powerful tools for cost effective control in intensive agriculture. A number of factors, however, may significantly modify the expected behaviour of herbicide mixtures in practice. The selection of the most appropriate combinations should be made taking into account the properties of the herbicides to be combined and the species to be controlled. Trends from previous studies may also provide good evidence for a successful selection of companion herbicides. Better efficiency in predicting herbicide interactions will come from a combination of using computer models and a better understanding of herbicide behaviour in plants when applied alone or in mixtures. Further research on the behaviour of herbicide mixtures will provide useful information in an effort to avoid undesirable interactions and select potentially useful mixtures for each particular case.

REFERENCES

Aguero–Alvarado, R., A.P. Appleby and D.J. Armstrong, 1991. Antagonism of haloxyfop activity in tall fescue (*Festuca arundinacea*) by dicamba and bentazon. *Weed Sci.*, 39: 1–5

Baerg, R.J., J.W. Gronwald, C.V. Eberlein and R.E. Stucker, 1996. Antagonism of diclofop control of wild oat (*Avena fatua*) by tribenuron. *Weed Sci.*, 44: 461–8

Culpepper, A.S., A.C. York, D.L. Jordan, F.T. Corbin and Y.S. Sheldon, 1999. Basis for antagonism in mixtures of bromoxynil plus quizalofop–P applied to yellow foxtail (*Setaria glauca*). *Weed Technol.*, 13: 515–9

Damalas, C.A. and I.G. Eleftherohorinos, 2001. Dicamba and atrazine antagonism on sulfonylurea herbicides used for johnsongrass (*Sorghum halepense*) control in corn (*Zea mays*). *Weed Technol.*, 15: 62–7

Deschamps, R.J.A., A.I. Hsiao and W.A. Quick, 1990. Antagonistic effect of MCPA on fenoxaprop activity. *Weed Sci.*, 38: 62–6

Ferreira, K.L., J.D. Burton and H.D. Coble, 1995. Physiological basis of antagonism of fluazifop–P by DPX–PE350. *Weed Sci.*, 43: 184–91

Flint, J.L. and M. Barrett, 1989a. Effects of glyphosate combinations with 2,4–D or dicamba on field bindweed (*Convolvulus arvensis*). *Weed Sci.*, 37: 12–8

Flint, J.L. and M. Barrett, 1989b. Antagonism of glyphosate toxicity to johnsongrass (*Sorghum halepense*) by 2,4–D and dicamba. *Weed Sci.*, 37: 700–5

Green, J.M., 1989. Herbicide antagonism in the whole plant level. *Weed Technol.*, 3: 217–26

Grichar, W.J., 1991. Sethoxydim and broadleaf herbicide interactions effects on annual grass control in peanuts (*Arachis hypogeae*). *Weed Technol.*, 5: 321–4

Harker, K.N., R.E. Blackshaw and K.J. Kirkland, 1995. Ethametsulfuron interactions with grass herbicides on canola (*Brassica napus*, *B. rapa*). *Weed Technol.*, 9: 91–8

Hart, S.E., 1997. Interacting effects of MON 12000 and CGA–152005 with other herbicides in velvetleaf (*Abutilon theophrasti*). *Weed Sci.*, 45: 434–8

Hart, S.E. and D. Penner, 1993. Atrazine reduces primisulfuron transport to meristems of giant foxtail (*Setaria faberi*) and velvetleaf (*Abutilon theophrasti*). *Weed Sci.*, 41: 28–33

Hart, S.E. and G.K. Roskamp, 1998. Soybean (*Glycine max*) response to thifensulfuron and bentazon combinations. *Weed Technol.*, 12: 179–84

Hart, S.E. and L.M. Wax, 1996. Dicamba antagonizes grass weed control with imazethapyr by reducing foliar absorption. *Weed Technol.*, 10: 828–34

Hatzios, K.K. and D. Penner, 1985. Interactions of herbicides with other agrochemicals in higher plants. *Rev. Weed Sci.*, 1: 1–63

Holshouser, D.L. and H.D. Coble, 1990. Compatibility of sethoxydim with five postemergence broadleaf herbicides. *Weed Technol.*, 4: 128–33

Jacobson, A., R.H. Shimabukuro and C. McMichael, 1985. Response of wheat and oat seedlings to root applied diclofopmethyl and 2,4–dichlorophe-noxyacetic acid. *Pestic. Biochem. Physiol.*, 24: 61–7

Liebl, R. and A.D. Worsham, 1987. Effect of chlorsulfuron on diclofop phytotoxicity to italian ryegrass (*Lolium multiflorum*). *Weed Sci.*, 35: 383–7

Lycan, D.W. and S.E. Hart, 1999. Physiological response of soybean (*Glycine max*) and two weed species to thifensulfuron and bentazon combinations. *Weed Sci.*, 47: 143–8

Scott, R.C., D.R. Shaw and R.L. Ratliff, 1998. Effect of SAN 582 on sethoxydim efficacy in johnsongrass (*Sorghum halepense*) and soybean (*Glycine max*). *Weed Sci.*, 46: 2–7

Shimabukuro, R.H., W.C. Walsh and R.A. Hoerauf, 1986. Reciprocal antagonism between the herbicides diclofop–methyl and 2,4–D in corn and soybean tissue culture. *Plant Physiol.*, 80: 612–7

Simpson, D.M. and E.W. Stoller, 1996. Physiological mechanisms in the synergism between thifensulfuron and imazethapyr in sulfonylurea–tolerant soybean (*Glycine max*). *Weed Sci.*, 44: 209–14

Sorensen, V.M., W.F. Meggitt and D. Penner, 1987. The interaction of acifluorfen and bentazon in herbicidal combinations. *Weed Sci.*, 35: 449–56

Vidrine, P.R., 1989. Johnsongrass (*Sorghum halepense*) control in soybeans (*Glycine max*) with postemergence herbicides. *Weed Technol.*, 3: 455–458

Vidrine, P.R., D.B. Reynolds and D.C. Blouin, 1995. Grass control in soybean (*Glycine max*) with graminicides applied alone and in mixtures. *Weed Technol.*, 9: 68–72

Wanamarta, G., D. Penner and J.J. Kells, 1989. The basis of bentazon antagonism on sethoxydim absorption and activity. *Weed Sci.*, 37: 400–4

Wesley, M.T. and D.R. Shaw, 1992. Interactions of diphenylether herbicides with chlorimuron and imazaquin. *Weed Technol.*, 6: 345–51

Zhang, J., A.S. Hamill and S.E. Weaver, 1995. Antagonism and synergism between herbicides: trends from previous studies. *Weed Technol.*, 9: 86–90

(Received 04 December 2003; Accepted 15 December 2003)