REVIEW

GLYPHOSATE USE IN FOREST PLANTATIONS

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ABSTRACT

Under Chilean conditions the lack of weed control at forest tree establishment results in an average of at least 60% less biomass accumulation during the first year of growth of radiate pine or eucaliptus, and glyphosate offers a series of advantages in forestry weed management because its activity in both herbaceous weed groups, monocots and dicots, as well as annuals, biennials and perennials. Also, its efficacy in woody undesirable vegetation makes glyphosate a very important herbicide that can be applied to control herbaceous and woody weeds as pre-planting and during the second or third years of trees growth as strip applications. The aim of this review is to discuss the main uses of glyphosate in reforestation worldwide, during the first 2 yr after tree establishment, as broadcast application over the top of the forest trees and the most important factors that could affect glyphosate efficacy as a forest herbicide, like weed growth stage, application technique, volume and water quality, rainfastness, dew effect and the use of extra adjuvant with formulated glyphosate.

Key words: Pine, eucalyptus, rainfastness, woody plants.

INTRODUCTION

Weed management in forest crops has been applied for more than 40 years. Presently, it is widely recognized that all forest plantations should be sustainably managed. To achieve this goal, site management practices should consider several fundamental principles, like protecting the soil from erosion and loss of fertility, and at the same time give appropriate inputs to reach the desired level of annual growth rate (Nambiar, 1995). Plant growth can be improved substantially with appropriate management practices such as site preparation, fertilization and weed control.

The influence of weed control on productivity can be mainly explained in relation to competition for site resources, especially, water and nutrients (Nambiar and Sand, 1993). Weeds adversely affect N-uptake by trees, and thereby aggravate N-deficiency (Smethurst and Nambiar, 1989).

Under Chilean conditions after completing 17 field experiments established from Bío Bío Region to the Los Lagos Region (36° S, 72° W to 42° S, 73° W) it was demonstrated that lack of weed control at establishment resulted in an average of 60% less biomass accumulation

during the first year of growth of radiate pine (*Pinus radiata* D. Don). Also, it was clearly documented that total area pre-plant herbaceous weed control produced larger increase in biomass index than the conventional spot gun application (Kogan and Figueroa, 1997).

The length period of time required to convert a forest site back to timber in Chilean forestry, is influenced by the Mediterranean climate, which is characterized by two primary seasons: cold and rainy condition in winter and dry and warm weather in summer. During dry period most weeds and other undesirable vegetation compete with young forest plants. It is a prudent measure to continue controlling weeds until canopy closure starts to occur and trees start to dominate or suppress weeds growth and establish a woodland environment (Haig *et al*., 1990; Willoughby and Dewar, 1995). The time needed to achieve that condition will depend on tree species, space between rows, site characteristics and initial starting tree growth. The critical advantage in establishing trees free of weed competition compared with no vegetation management may be that canopy closure will occur several years earlier (Harmer and Kerr, 1995). Also reducing competition from undesirable vegetation, thereby allowing the young tree to get adequate moisture and nutrient, can considerably shorter the time required to bring a new forest into production, whichever the management objectives are (Marer *et al*., 1995).

A "good starting" is essential to maximize forest plant growth. Total weed control with herbicides is desirable

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for plantation in areas likely to encounter severe summer drought (Newton and Knight, 1981), being soil moisture the most limiting factor. Under Mediterranean conditions weeds that growth during winter and spring will deplete soil moisture causing serious deficiency during late spring and summer if rainfall was poor during the warmer season.

It has been normally considered that it is not necessary to undertake herbaceous weed control for more than 1 yr and the first two seasons of forest trees without moisture stress are enough to assure the plantation. Others insist a third year of weed control is required. However, it is not only a matter of knowing how many years of weed control are required, but also the intensity of this practice should be considered. Increasing the width of the weed control strip (spanning the tree row) increased N-uptake by trees. Because of this in a high N supply conditions (fertile soils), intense weed control is being unnecessary in plantations beyond second year of age and strip weed control could be a better option than complete weed control in managing weeds in young plantations of radiata pine. Weed control

in a 1 m-wide strip is sufficient to relief water stress in trees during the initial 2-3 yr after planting. Undoubtedly, this cannot be considered as a recipe (Kogan *et al.*, 2002). Thus, Balneaves and Henley (1992) found the largest increases in radiate pine diameter, height, stem volume and volume per hectare were obtained 7 yr after planting by weed control over the entire area. Nevertheless there is no doubt that under dry summers and non-fertile sites weed control intensity (WCI) should be a striking factor. Kogan *et al.* (2002) after conducting a field experiment to quantify the effect of different WCI during the first three growing season in a radiate pine plantation, found stem volume index of check trees was similar to plants received spot application in the first and second year. On the other hand, when plots were treated with herbicide spot applications (first year) plus band or total area applications (second year), the stem volume index was twice larger, respectively (Table 1). However, if the first year WCI consisted of total area application the second and third year treatment had less effect on trees growth. The largest biomass yield was obtained when plot were

Table 1. Weed control intensity (WCI) based mainly in glyphosate and its effect on radiata pine stem volume index (dgh^2 h^{-1}) during trial (planting 28 June 1996) (adapted from Kogan *et al.*, 2002).

1996/1997		1997/1998		1998/1999	
June 1996	320 DAP	July 1997	680 DAP	July 1998	1040 DAP
WCI	dm³	WCI	dm³	WCI	dm³
No control	0.013a	No control	0.64d	No control	4.4g
Spotgun appl.[1]	0.061b	No control	0.9d	No control	3.3g
-	-	-	-	Spotgun appl.	3.5g
-	-	Spotgun appl.	1.6cd	No control	5.5g
-	-	-	-	Spotgun appl.	5.3g
-	-	Band appl.[2]	3.04c	No control	9.4fg
-	-	-	-	Band appl.	11.4fg
-	-	Total area appl.	4.91b	No control	16.0ef
-	-	-	-	Total area appl.	17.1def
Total area appl.[3]	0.31c	No control	5.61b	No control	23.0cde
-	-	-	-	Total area appl.	31.1bc
-	-	Spotgun appl.	5.82b	No control	26.1cd
-	-	-	-	Spotgun appl.	30.2bc
-	-	Band appl.	6.58ab	No control	30.0bc
-	-	-	-	Band appl.	36.3ab
-	-	Total area appl.	8.21a	No control	44.4a
-	-	-	-	Total area appl.	39.7ab

DAP = days after planting.

Means of a given column by the same letter are not significantly different (P = 0.05) according to Duncan multiple comparison test.

[1]Spotgun treatment (1 m² around each pine tree) in June 1996 corresponded to hexazinone 2.0 kg ha⁻¹ applied 45 DAP. In the second and third year spotgun treatments corresponded to glyphosate 0.87 kg ai ha⁻¹ around each tree, avoiding to make contact with them.

[2]Band application was carried out applying glyphosate in a strip 2 m wide (1-m to each side of the trees), also avoiding to contact the trees.

[3]Total area application at the first year corresponded to glyphosate 1.0 kg ai ha⁻¹ applied 1 wk before planting. In the second and third year this WCI corresponded to glyphosate applied to the whole area, avoiding spray pine trees.

submitted to total area WCI during the first and second year, independent of weed management during the next 2 yr. On the other hand, considering slope erosion, it appears reasonable according to these data giving to radiate pine the best conditions for establishment, which means total area weed control in the first season, and just a band treatment (1 m-wide strip) during the second year to avoid or decrease risk soil erosion. Under Chilean conditions, if these first 2 years weeds are killed at the right time, it is highly probable that a third year of chemical weed control could be unnecessary.

Glyphosate as a forestry worldwide herbicide

Of the different alternatives for vegetation management, progressively more attention has been focused on chemical weed control and actually the use of herbicide is intensive for forest establishment. The phenoxyacetic acids, 2,4-D and 2,4,5-T, served for this purpose for more than 30 yr, until 2,4,5-T was banned in several countries in the early 1970s. At this time, glyphosate (*N*-(phosphonomethyl) glycine) appeared as the alternative. This herbicide offered a series of advantage, because its activity in both weeds groups, monocots and dicots, as well annuals, biennials and perennial herbaceous species. Also, its efficacy in some woody undesirable vegetation makes glyphosate a very important herbicide. Also its effect on stump-sprouting species (*Fraxinus excelsior* L., *Betula* spp.) after the cutting and the sprouting of *Eucalyptus* stump can be highly reduced applying to the cut surface glyphosate from 10 to 50% in water. This is also true after cutting brushwood on trees to eliminate or reduced their growth capacity.

Glyphosate can be applied to control herbaceous and woody weeds as pre-planting to establish forest trees in ex-arable and improved grassland site and reforestation conditions after timber production. Also, can be applied during the second or third years of trees growth as a strip applications and to control selectively: cut stumps, frill-griddle for large undesirable trees and less common glyphosate tree injection.

Use of glyphosate in ex-arable and improved grassland site. In this condition, soils are frequently more fertile compared with traditional replant forest sites and have large weed seed banks. Because of this, heavy weed infestations are common after preparing the site for planting, as well as numerous herbaceous weed species (annuals, biennials and perennials) will germinate, emerge and growth, competing from the beginning with forest plant seedlings. To prevent competition, a pre-planting treatment of glyphosate at relatively low rate (1.1 to 1.44 kg ai ha^{-1}) at early post weed emergence in mixture with the right soil-active herbicide will allow to control

perennial herbaceous weeds to obtain soil persistence effect on newly weed emergence from seeds. The main soil-active herbicides, at least in Chile, that have been used as glyphosate partners belong to the triazine group, mainly simazine, atrazine and terbutilazine. These three herbicides are very selective to pine, and eucalyptus is tolerant enough under agroclimatic conditions in the South of Chile. Nevertheless, simazine and atrazine have been lately banned as herbicide for those Forestry Companies that have certified their plantations through the Forest Stewardship Council (FSC). Other soil-active products like flumioxazin, diclosulam and isoxaflutole could be considered.

Glyphosate in the mentioned mixtures provides a wide spectrum of control, including herbaceous perennials that start growing as soon as site soil preparation takes place. These species are not controlled by Triazines or by most of the other soil-active herbicides. Examples of those species are: *Arrhenatherum elatius* var. *bulbosum*, *Agrostis* spp., *Achillea millefolium*, *Rumex acetosella*, *Chrysanthemum leucanthemum*, *Hypochaeris* spp. Also glyphosate would complement the soil active herbicides in controlling most of all grasses.

In the other countries where different species of the *Pinus* are planted (ex. *Pinus taeda*), there is also the possibility to use Imidazolinone herbicides, because those forest species are tolerant enough to that group of herbicides. Therefore some of the imidazolinone herbicides could also be used as a tank mix with glyphosate as pre-planting treatment.

Pre-planting treatment for herbaceous weed control can be applied to the whole area or just a strip application. Weed control intensity discussed before will depends on several factors, technical and economicals, but should be maintained at least the first 2 yr after planting to ensure tree growth.

Use of glyphosate in reforestation. Before the adoption of chemical weed control, brush control was carried out by hand method; cutting with specific tools ("knifes") those plants at the base. This operation was very difficult, labor demanding, and then highly expensive. Besides, most of the woody species re-growth later in the first year of the plantation making them a real problem because of the limited selective herbicide treatments available to be used in most forest trees.

Generally, foresters view brush weeds as the most difficult competitive plants to manage in reforestation programs. In this situation herbicide treatments can also carried out a pre-planting release, to control especially woody species (shrubs or brush). Domination by shrub and brushes hardwood tree species is the second successional stage following removal of a closed forest canopy by

logging or wildlife, but also grasses and other herbaceous dicots species will establish themselves. Table 2 shows a partial list of some common shrubs and trees weed species growing in productive forest sites in Chile.

Table 2. Important shrubs and tree weed species in forest sites in Chile.

Chile
Acacia dealbata
Cytisus scoparius
Cytisus striatus
Rosa rubiginosa
Rubus constrictus
Rubus ulmifolius
Teline monspessulana
Ulex europaeus
Several hardwood trees
(*Gevuina avellana*, *Nothofagus* spp., *Ulmus* spp.)

Source: Marer *et al.* (1995); Kogan and Figueroa (1999).

Because of the various shrubs and tree weed species, before recommending glyphosate as a pre-planting release treatment; oneself must be sure about glyphosate efficacy in the different species that can be present, as not all of them are equally susceptible to this herbicide. Moreover, complete brush control is seldom achieved with a single herbicide application because of the diversity of species and age at most sites. For that reason glyphosate at rate from 1.44 to 2.5 kg ai ha^{-1} is often applied as a tank mix with metsulfuron-methyl (Sulfonylurea), or with triclopyr, clopiralyd, fluroxypyr (Pyridines). Glyphosate is particularly effective against *Rubus* spp., *Laniova* spp., *Pueraria lobata*, *Acer saccharum*, *Rosa multiflora*, *Campsis radicans*, *Salix* spp. Some brush species cannot be effectively controlled with herbicides (e.x. *Diospyros* spp., *Sassafras albidum*), and addition management techniques are necessary (Table 3) (CPCR, 1987).

Glyphosate recommended rate for brush and trees control can vary according to the target species and stage of development. However, most of the time there is several species growing together. For this reason the rate can markedly vary according to species susceptibility to glyphosate from: a) 1.8-2.1 kg ai ha^{-1} (more susceptible species), b) 2.5-2.88 kg ai ha^{-1} (moderate susceptible species), and c) 3.3-4.0 ai ha^{-1} (more tolerant species). The highest rate should be preferred if plants are larger than the adequate size for optimum results or weed density is really high. This herbicide should be applied when woody plants are actively growing, after full leaf expansion or after regrowth (± 50 cm height). Table 4

Table 3. Response to glyphosate of woody brush and undesirable tress.

Susceptible	Moderate susceptible	Tolerant
Alnus spp.	*Acacia greggii*	*Diospyros* spp.
Acer saccharum	*Acer rubrum*	*Sassafras aibidum*
Baccharis consanguinea	*Acer circinatum*	
Cytisus scoparius	*Fraxinus* spp.	
Campsis radicans	*Gevuina avellana*	
Prunus emarginata	*Liriodendron tulipifera*	
Prunus serotina	*Mimulus guttatus*	
Prunus pensylvanica	*Nothofagus* spp.	
Pueraria lobata	*Oxydendrum arboreum*	
Populus tremuloides	*Polystichum munitum*	
Quercus palustris	*Parthenocissus quinquefolia*	
Quercus rubra	*Quercus velutina*	
Rhus radicans	*Quercus alba*	
Rosa multiflora	*Robinia pseudoacacia*	
Rubus spp.	*Rhamnus purshiana*	
Salix spp.	*Rhus copallinum*	
Teline monspessulana	*Rhus vernix*	
	Rhus glabra	
	Ulex europaeus	
	Ulmus spp.	

Adapted from CPCR (1987; 2001) and own data.

Table 4. Recommended pre-planting glyphosate treatments to control some brush and woody trees (adapted from Kogan and Figueroa, 1999).

Type of undesirable vegetation	Herbicide treatments
Teline monspessulana and *Aristotelia chilensis*[1]	Glyphosate 1.08 kg ai ha^{-1}
Rubus spp., *Rosa moschata* and *Cytisus scoparius*[1]	Glyphosate 0.9 kg ai ha^{-1} + Triclopyr 0.6 kg butoxyethyl ester ha^{-1}
Ulex europaeus and trees (*Ulmus glabra*, *Nothofagus* spp., *Gevuina avellana*, *Luma apiculata*)[1]	Glyphosate 1.4 ai ha^{-1} + Triclopyr 1.5 kg butoxyethyl ester ha^{-1} (add a non-ionic surfactant)

[1]Native species in some circumstances growth in forest sites. Unfortunately in those situations are considered as undesirable vegetation.

shows an example of brush and trees chemical control recommendation in Southern Chile (Kogan and Figueroa, 1999).

During the year of pinus establishment (after woody species were controlled) is common in Chile, before of the FSC certification, to apply a band treatment of hexazinone + atrazine or a mixture of haloxifop-methyl + clopyralid + atrazine or terbutilazine. In the case of Eucalyptus were normally applied glyphosate + simazine or glyphosate + fluroxipyr + simazine. All these treatments will control a wide spectrum of herbaceous weeds. Preventive measures should be taken to avoid contact of glyphosate or any other non selective product with forest trees. Actually other herbicides like isoxaflutole, flumioxazin and diclosulam have been introduced to replace herbicides like hexazinone and triazines.

Glyphosate uses during the first 2 years after tree establishment. The use of glyphosate in the second and third year after forest establishment will depends on weed species that will prevail. Authors experience indicates if pre-planting weed control was effectively done, most of weeds that will trait the plantation will be herbaceous weeds (monocot and dicot, annuals, biennials and perennials) and a minimum of brush and tree regrowth.

Herbaceous weeds will start emerging as soon as rains occur in the fall, and their growth rate will depend on temperature. Cold winters do not favor weeds growth. A new flush of herbaceous weeds will emerge from early spring throughout beginning of summer. These weeds could be mainly competitive in those cases which rains fail to occur at the end of spring. As a result of this there is no guaranty of water supply for forest trees summer growth. During the first 2 years after establishment all these weeds must be controlled to assure appropriate tree rate growth and get a quick soil cover (canopy).

If brush and/or tree regrowth control is required glyphosate can be applied alone or in mixture with metsulfuron-methyl or Pyridine herbicides (triclopyr, clopiralyd, fluroxypyr), when regrows reach at least 1-m height. This application is locally oriented to any regrowth

on the bands or in the interrows. All precautions must be taken to avoid contacting forest trees with the spray or with drift. Using anti-drift nozzles and do not apply in windy days is a duty.

To control herbaceous weeds glyphosate plus soil active herbicide could be recommended to the band or total area, during the mid fall. The band has to be treated carefully, avoiding any contact of glyphosate with forest trees. Contractors work with specialized operator that most of the times are able to apply directing the spray, avoiding contacting the small trees. As a result a very limited damage can be produced that is largely compensated because of the plantation rate growth. The interrows, if they are treated, can be treated with a shielded boom sprayer, also equipped with anti-drift nozzles, if topography allows.

A second application, at the beginning of spring, in the same season may be required. This can be performed spraying just the plantation band with glyphosate. Doing this program most of the growing season can be cover and allow the forest trees to growth without competition for water and nutrient.

Use of glyphosate as broadcast application over the top of forest trees. Radiata pine and Eucalyptus spp. are susceptible to over the top glyphosate application. It is interesting to discuss this type of treatment performed in other countries. The most commercially important conifers in USA, like Norway spruce (*Picea abies*), Sitka spruce (*Picea sitchensis*), Shots pine and fir (*Pseudotsuga* spp.) are tolerant enough for standard glyphosate applications. Rate of glyphosate should be reduced at least by 10% under high temperature (> 24-25 °C) at application time and expected hot temperatures the first 24 h after applications to ensure sufficient tolerance to glyphosate by the conifers (Lund-Hoie, 1982 cited by Lund-Hoie, 1985). Radosevich *et al.* (1980) studied the selectivity of glyphosate applied at different phenological stages of development of six coniferous species (Ponderosa pine, Jeffrey pine, Sugar pine, Douglas-fir, White fir, and Red fir). All of them were more tolerant to glyphosate after

fall dormancy, and pine species were more tolerant to fall glyphosate applications. Unfortunately *P. radiata* is not tolerant to allow over the top applications of glyphosate.

Other uses of glyphosate in forest plantations. Stumps of many brushwood species may rapidly sprout after cutting. Glyphosate, at concentration of 8-10% in water, applied to the stump surface after cutting will eliminate or reduce sprouting of the most deciduous trees (Lund-Hoie, 1985). Also, after *Eucalyptus* timber (is being harvested) stumps rapidly regrowths. In these cases glyphosate at 50% in water will prevent re-growth from Eucalyptus stumps (Kogan, unpublished data). This treatment is most effective applied immediately after the tree or brush is cut.

Trunk injection often helps glyphosate to penetrate through the tree bank. In some cases the herbicide may serve as a chemical girdle. The frill treatment consist of a single line of overlapping downward ax cut around the base of the tree, then glyphosate is sprayed or squirted into the cut around the entire trunk of the tree. This method is being used for large trees. A program based in a solution 1-2 mL of 20% glyphosate in water per injection or on the ax cut with a frequency of 1 mL for each 5 cm of the steam diameter can offer very good results on most deciduous trees, especially in the early summer. Glyphosate can be applied alone or in mixture with growth regulator herbicides, according to tree susceptibility.

Some factors that could affect glyphosate efficacy as forest herbicide

Glyphosate is a fundamental herbicide for weed management in forest establishment and during the initials 2 or 3 yr of growth, because of a series of extraordinary and unique characteristics, among them its weed spectrum, its active translocation, almost no detectable soil activity, very low leaching because its strong soil adsorption, reduce soil half-life, and because is a herbicide with low environmental risk. However, there are some factors that could affect its efficacy. Application techniques, environmental conditions and weed stage of growth, volume and water quality, and use of coadjuvants can determine the success of glyphosate applications.

Weed growth stage. Most of annual weed species are very susceptible to glyphosate. However, there is a very specific response according to different weeds and growth stages. In general, glyphosate should be applied to actively growing grass and broadleaf weeds, and for maximum forestry benefit, it should be apply when weeds are 15 cm or less in height. Better results may be obtained when more of the weeds are exposed to glyphosate solution. Weeds not contacted by glyphosate will not be affected, as can occur in dense clumps (severe infestations) or when the height weeds and the taller avoid glyphosate reaches the smaller ones. Table 5 shows the required rate of glyphosate to achieve control of different herbaceous

Table 5. Rate of glyphosate isopropylamine (IPA salt) required to control various herbaceous weeds.

Rate (kg ai ha^{-1})		
0.72	**1.08**	**1.5-2.88**
Bromus spp. (15 cm)[1]	*Cerastium vulgatum* (15 cm)	*Sida spinosa* (7 cm)
Sisymbrium altissimum (15 cm)	*Senecio vulgaris* (15 cm)	*Geranium carolinianum* (30 cm)
Hordeum vulgare (30 cm)	*Conyza canadensis* (15 cm)	*Eleusine indica* (30 cm)
Cenchrus spp. (30 cm)	*Thlaspi arvense* (15 cm)	*Richardia scabra* (30 cm)
Sorghum bicolor (30 cm)	*Sisymbrium irio* (15 cm)	*Cassia obtusifolia* (30 cm)
Eragrostis cilianensis (30 cm)	*Lolium multiflorum* (15 cm)	*Erodium* spp. (30 cm)
Avena fatua (30 cm)	*Ranunculus* spp. (30 cm)	*Agrostis* spp. (30 cm)[2]
	Sonchus spp. (15 cm)	*Prunella* spp. (15 cm)[2]
	Xanthium pensylvanicum (30 cm)	*Achillea millefolium* (7 cm)[2]
	Digitaria spp. (30 cm)	*Dactylis glomerata* (15 cm)[2]
	Polygonum aviculare (15 cm)	*Brachiaria* spp. (15 cm)[2]
	Alopecurus carolinianus (30 cm)	*Festuca* spp. (7 cm)[2]
	Chenopodium album (30 cm)	*Hypochaeris* spp. (15 cm)[2]
	Bidens pilosa (15 cm)	*Brachiaria decumbens* (30 cm)[2]
	Amaranthus spp. (30 cm)	
	Panicum spp. (30 cm)	

[1]Maximum weeds height at which glyphosate should be applied.
[2]Perennials.

weeds, and their maximum height at which they should be sprayed.

As indicated before exist different susceptibility to glyphosate according to the brush weed or tree. However this product must be applied when plants are actively growing, after full leaves expansion. The higher recommended rate should be used for larger plants and for dense areas of growth. Due to its polar movement towards more active sinks in plants, normally best results are obtained when application is made in late summer or fall after fruit formation. When brush weeds have been moved or tilled or trees have been cut, do not apply glyphosate until regrowth have reached at least 1-m of height. If these plants are at high moisture content and are flowering best results are obtained. As mentioned, glyphosate can need a partner to effectively control some of this brush or woody trees. Also repeated treatments may be necessary to control plants regenerating from underground parts.

When dealing with deciduous trees (e.x. *Nothofagus* spp.) or brush (e.x. *Rubus* spp., *Rosa moschata*), our experience indicate that glyphosate application for their control in site preparation (reforestation) must be performed before senescence and leaf drops, which occurs during the winter, when low temperatures prevail. In general, reduced glyphosate efficacy may result if treatment is made following a frost.

Application technique, volume and water quality. In the control of woody species in site preparation (reforestation), roots represent the main target. Because glyphosate will translocate in both the phloem and xylem the quantity of the herbicide translocated in the phloem will depend on the application rate and the distance from the receptor area (the foliage where glyphosate was deposit), to the strongest sink (most of cases the roots). The longer of this distance, the more glyphosate will move and concentrate in the youngest aerial shoots, while the toxic effect to the roots will be minimum (Lund-Hoie, 1980). Effective control of brush species will therefore be dependent not only on its height, but also on the applications technique. Thus, when spraying with an aircraft like a helicopter, most of the spray will reach and depositate in the upper half of the crown, with only a small volume able to penetrate to the lower part of the crown. Ground-based application equipments results in the opposite effect, with most of the spray deposited on the lower part of the crown, therefore a shorter path to the roots and consequently, greater effectiveness. This could explain why when using aircraft, glyphosate rate should be increased, and according to Lund-Hoie (1980) about 50% higher rate of glyphosate is required to control brush and trees its aircraft or helicopter if used than when using ground equipments.

Relatively low water volume (12 to 40 L ha^{-1}) are used when aerial application equipment are utilized to spray glyphosate in forest site preparation (reforestation). To avoid drift is a must under this application conditions. Therefore glyphosate should not be applied during air mass inversions and when winds are gusty. Also, buffer zones must be maintained to avoid damage to sensible crops and to contaminate any body of water. For this reason drift control additive may be used. If land is plane, other equipment as a mist blower can be used.

Spray volume is a key factor to obtain glyphosate potential efficacy. As the volume increased the proportion of the surfactant (that the formulated glyphosate carry) in the mixture water-glyphosate decreased. If application water contains suspended colloids or ions in solutions (hard water) glyphosate efficacy can be drastically decreased. In the first case glyphosate would bind or be adsorbed by organic colloids and in the second case glyphosate can react with ions in solution forming an insoluble complex by quelation. Thus, Riesk *et al*. (1974) showed a reduction of 80 to 90% of toxicity of glyphosate in corn plants (1.14 kg ia ha^{-1}) if the spray water contained 1% of montmorillonite or organic matter in the spray tank. Also, Pulver and Romero (1976) showed that adding 20 mg of soil to the solution (equivalent to 21% of clay), glyphosate effectively decreased by 15% on *Cyperus rotundus*. However, the rate of glyphosate used can overcome the effect of "dirty" spray water, as can be seen in Table 6 (Kogan and Correa, 2000).

Table 6. Effect of two rate of glyphosate with different concentration of soil in the spray solution (equivalent to 200 L ha^{-1}) on *Cyperus esculentus* (48 days after herbicide application) (adapted from Kogan and Correa, 2000).

Treatments		Foliar damage	Foliar fresh weight
Glyphosate	Soil		
kg ai ha^{-1}	mg kg^{-1}	%	g plant^{-1}
0	0	0e*	99.4a
1.08	0	50b	56.2cd
1.08	3 270	55b	54.0cd
1.08	6 540	60b	78.2ab
1.08	9 800	25cd	90.2ab
1.08	13 080	36c	82.0ab
2.16	0	72a	41.2d
2.16	3 270	86a	36.8d
2.16	6 540	81a	42.2d
2.16	9 800	85a	40.6d
2.16	13 080	77a	43.8d

*Means of a given column followed by the same letter are not significantly different (P ≤ 0.05) according to Tukey-Kramer multiple comparison test.

Glyphosate behaves as a "zwiterion" which means it presents positive and negative charges in the molecule or functional acid and base groups. According to Franz (1985) glyphosate can show different pKa values, depending on solution pH (pK$_1$ = 0.78; pK$_2$ = 2.27; pK$_3$ = 5.56 and pK$_4$ = 10.5). Because of glyphosate can react with ions in solution forming a complex glyphosate-ion (quelate).

To know the concentration and type of dissolved ions in the spraying water is fundamental to understand the potential effect of them on glyphosate phytotoxicity. Several factors can determine whether or not dissolved ions in the spray solution affect glyphosate efficacy. Thus, ion types, ion concentration, glyphosate rate and spray volume are very important. In general it is well accepted that trivalent ions (Al^{+3}, Fe^{+3}) are more antagonic than the bivalent (Ca^{+2}, Mg^{+2}) and these more than the monovalents (Na$^+$, K$^+$).

Some selected research reports will be used to briefly discuss the interactions between factors that can explain glyphosate antagonism with dissolved ions in the spray water. The work of Buhler and Burnside (1983) clearly shows that Ca^{+2} concentration in the spray solution can produce no effect, antagonic effect o no additional effect, even though Ca^{+2} concentration is drastically increases (Table 7).

Evidences for the interaction spray volume and Ca^{+2} concentrations are presented by Sandberg *et al.* (1978). They showed Ca^{+2} did not reduce glyphosate phytotoxicity to *Ipomoea* sp. when spray volume was equal or less than 190 L ha^{-1} and Ca^{+2} concentration was equal or less than 0.02 MCaCl$_2$ (800 mg kg^{-1} Ca^{+2}, which means 2000 mg CaCO$_3$ water hardness equivalent). There is a clear relationship between spray volume, Ca^{+2} concentration on antagonistic effect on glyphosate (Table 8).

Table 7. Effect of Ca^{+2} concentration on glyphosate phytotoxicity to *Avena sativa* (rate = 0.4 kg ha^{-1}; spray volume = 190 L ha^{-1}) (adapted from Buhler and Burnside, 1983).

mM CaCl$_2$	Effect on glyphosate
0	No effect
1	No effect
2	No effect
4	Antagonism
6	Antagonism
8	Antagonism
16	No additional antagonism
32	No additional antagonism
64	No additional antagonism
128	No additional antagonism

Another interesting interaction is the relation between antagonistic effect of ion concentrations and glyphosate rate. In an unpublished work (Figure 1) (Martínez and Kogan) in which is possible to see that Al^{+3} was antagonic to glyphosate when its rate was only 180 g ai ha^{-1}. At that rate the antagonic effect was directly proportional to Al^{+3} concentrations. However as glyphosate rate increased to 270 g ai ha^{-1}, Al^{+3} antagonism was only detectable with the highest ion concentration (120 mg kg^{-1}). No antagonism was produced by Al^{+3} when glyphosate rate was 450 g ai ha^{-1}, independent of ion concentration.

The examples given are just a small portion of the numerous references that can be found in the literature revealing interactions between glyphosate rates, ion concentrations and spray water volume. Also the test plant used can also affect the obtained result. Even thought it should be considered that in real circumstances, at field level, hard water may content the most diverse proportions of different ions in solution. For that reason it is not enough to express water hardness as mg kg^{-1} CaCO$_3$ equivalent, because in that way we do not know the exact proportion of the main ions present. Even though, mainly Ca^{+2} and Mg^{+2} are the most considered ions to calculate waters hardness. Two different water samples could have the same hardness expressed as mg kg^{-1} CaCO$_3$, but they can markedly differ in type and proportions if ions. Besides the criteria used to define and establish different level of water hardness was not developed thinking in agricultural pesticide applications. Thus, hard water not always will be antagonistic to glyphosate. For all these reasons if one suspect that water hardness could affect glyphosate, a water chemical analysis should be made looking the different ions present, and their concentrations, under these circumstances, it should not be forgotten that using lower spray volume (no > 150 L ha^{-1}) most of factors that can affect glyphosate efficacy diminish their real impact.

Glyphosate rainfastness. During the period between spraying and foliar absorption of a lethal dose by the plant, glyphosate is vulnerable to removal by rain. In wet period, the "wash off" of glyphosate from the leaves will reduce the performance of the mixture, because of their relatively slow uptake. Woody species are more vulnerable in this respect than grasses or other herbaceous species. Even though rate of foliar uptake will depends on specific species morphology mainly on leaf characteristics, physical and chemical. The type of spraying equipment used will also influence glyphosate rainfastness. Mix blower, which deposit compound in both sides of the leaves, can require a shorter period with no rain after application.

Several workers have reported that a 6-8 h rain-free period is required for penetration of sufficient active ingredient to produce acceptable performance of

Table 8. Effect of the interaction Ca^{+2} and spraying water volume to *Ipomoea* spp. growth under greenhouse conditions, 30 d after glyphosate 1.68 kg ha^{-1} application (adapted from Sandberg *et al.*, 1978).

Volume	CaCl$_2$					
	0	0.0025	0.005	0.01	0.02	0.04
L ha^{-1}	cm					
130	3.0a	7.3a	10.0ab	6.3a	16.3ac	30.3ce
190	7.9a	8.1a	8.0a	18.6ad	8.6e	41.6de
375	11.0ab	33.3ce	39.5ce	46.3e	43.7e	44.4e
750	3.0ce	51.3e	44.1a	31.8e	48.9e	44.7e

Different letters indicate significant differences.
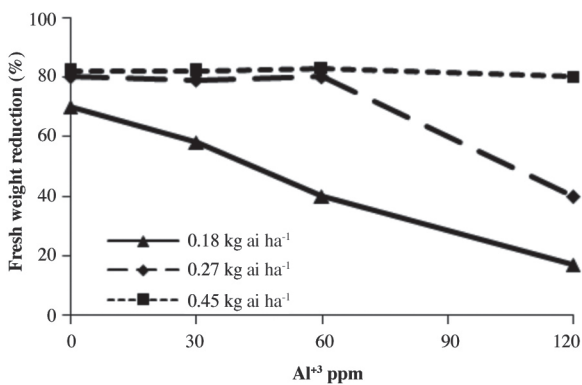
Figure 1. Antagonistic effect of Al^{+3} concentration on different glyphosate rates, measured as reduction of *Avena sativa* fresh weight (Martínez and Kogan, unpublished data).

glyphosate (Behrens and Elakkad, 1976; Coupland and Caseley, 1981).

It is likely any plant or environmental factor that slows entry of glyphosate into the plant would prolong the rainfastness. Manipulation of formulations may reduce the risk of glyphosate wash off from the foliage. Also higher concentration of glyphosate as a consequence of low volume application could also diminish the effect of rain after application, may due to enhancement of glyphosate foliar rate uptake.

Intrinsic plant tolerance to glyphosate can also determine its rainfastness requirement. Thus, a 4 h rainfastness was required to control johnsongrass (*Sorghum halepense*) from seeds, with glyphosate isopropylamine salt at rate of 680 g ai ha^{-1}, but lowering rate to 340 g ai ha^{-1} the adverse effect of rain was much more drastic. Maybe because 4 h were not enough to allow the entry of a lethal rate of glyphosate (Bryson, 1988). In a more tolerant herbaceous weed like purple nutsedge (*Cyperus rotundus*), it was required 12 h of rain free-period for glyphosate isopropylamine salt at 2.16 kg ai ha^{-1}, to effectively decrease tuber sprouting capacity, and 24 h at a rate of 1.44 kg ai ha^{-1} (Kogan, 2000). Even

though Bariuan *et al.* (1999) indicate that a rain free period of 72 h prevented loss of glyphosate activity on *C. rotundus*.

Glyphosate formulations can be differently affected by rain after their application. Jakelaitis *et al.* (2001) showed it was required a rainfastness of 4 and 6 h to control *Digitaria horizontalis* when were treated with glyphosate isopropylamine (IPA salt; Roundup Transorb), glyphosate potassium (K-salt) or glyphosate trimethylsulfonium salts (TMS salt). However the conventional glyphosate formulation and the ammonium salt (AM salt), were the most affected because of the rain (Jakelaitis *et al.*, 2001). In a different grass, *Brachiaria decumbens*, it was required a rainfastness of 8 ,11 and 12 h when glyphosate was applied as K-salt, IPA salt, and AM salt, respectively (Verlag *et al.*, 2003). Increasing the rate from 1004 to 2160 g ai·ha^{-1} they were able to shorten the rainfastness. On the other hand, Jakelaitis *et al.* (2003) spraying a lower rate, 720 g ai ha^{-1}, found a rainfastness of 2, 4 and 6 h for IPA salt, K-salt and AM salt, respectively.

It looks like not the salt type, but the formulated product (type and concentration of coadjuvants) can account for the different rainfastness requirements for the several commercial glyphosates.

When dealing with woody species glyphosate rainfastness could be prolonged. Thus, Lund-Hoie (1980) found an absorption period of almost 2 wk of glyphosate for *Fraxinus excelsior*, and for *Picea abies*, about one half of this (Lund-Hoie, 1976). Comparing rainfastness of glyphosate with triclopyr and clopyralid (Table 9), it is possible to see that 15 min of rain free period was enough for Pyridine herbicides to achieve 92 and 100% of *Prosopis gladulosa* control, but glyphosate efficacy was very variable and required no rain after application to get similar level of control.

Dew effect on glyphosate efficacy. Most field applications of glyphosate in forestry conditions in Chile, start early in the morning to avoid windy conditions that develop later during the day. Under these conditions, the presence of dew on weeds during herbicide application has caused

Table 9. *Prosopis gladulosa* control (%) with glyphosate, triclopyr and clopyralid at 0.8 kg ai ha^{-1} under 2.5 cm of simulated rain with different rainfastness periods (adapted from Bovey *et al.*, 1990).

Herbicide	Rainfastness	Control
	min	**%**
Glyphosate	0[1]	37
	15	54
	30	39
	60	11
	240	57
	Without rain	95
Triclopyr	0	46
	15	92
	30	84
	60	97
	240	96
	Without rain	100
Clopyralid	0	62
	15	100
	30	100
	60	100
	240	100
	Without rain	100

[1]Rain right after application.

some concern among herbicide applicators. Dew defined as the presence of free water on plant foliage (Slatyer, 1968) could affect foliar uptake and therefore efficacy of foliar-applied herbicides, mainly those of height water solubility, like glyphosate.

Dew before spraying has tended to be regarded as undesirable by many forest managers and contractors, but the limited experimentation on this topic does not fully support this view (Caseley and Coupland, 1985).

Sometimes, glyphosate application is not performed when dew is present, delaying application until the foliage dries (Kudsk *et al.*, 1988). The presence of dew at application is believed to increase or decrease foliar herbicide efficacy (Caseley, 1989). Herbicide runoff and herbicide dilution could explain the negative effect of dew (Muro, 1991). By contrast, dew can increase the total area of herbicide interception and reduce the impact of large drops on foliage surfaces, avoiding their loss from the leaves (Johnstone, 1973). At the same time, the presence of dew results in hydration of the cuticle and may play an important role favoring foliar uptake (Caseley, 1989).

The effect of dew on herbicide activity is not thoroughly understood due to limited research, where

dew has not been quantified. Thus, measurement taken on a given day showed that some plants were able to retain an average of 195 mL water g[-1] fresh weight of foliage, which could represent from 36 to 90% of their fresh weight, and others retained an average of 76 mL water g[-1] fresh weight of foliage, which varied from 12 to 35% of their fresh weight. The natural variability we observed makes results on effect of dew on herbicide performance difficult to explain. Because of the general lack of empirical knowledge about the effect of dew, an experiment was conducted to study the effect of known dew levels on glyphosate efficacy applied with different spray volumes (Kogan and Zúñiga, 2001). Results showed that glyphosate phytotoxicity decreased with increasing carrier volume for plants without or with dew (Table 10; Figure 2). Several reports indicate that glyphosate efficacy is greater when applied in low rather than in high volumes (Sandberg *et al.*, 1978; Rambakudzibga 1989; Liu-Shuhua *et al.*, 1996). Nevertheless, other reports have shown no effect of carrier volume on glyphosate phytotoxicity (Messersmith *et al.*, 1992; Willard *et al.*, 1998).
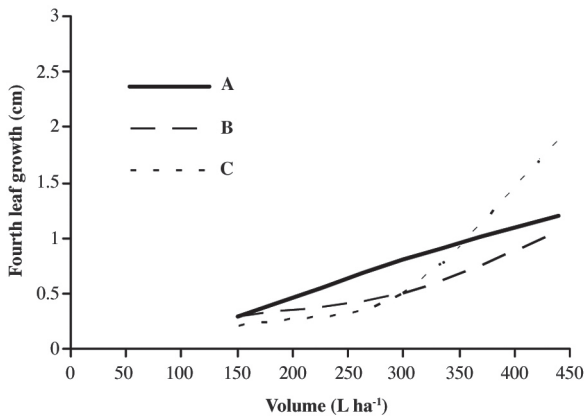
The effect of dew level on glyphosate efficacy can depend on spray volume. Thus, glyphosate activity at low and medium volumes (150 and 300 L ha^{-1}) was not affected by dew level. Decrease of plant fresh weight of treated plants with glyphosate at 150 and 300 L ha^{-1} was statistically equal, regardless of dew level. Decrease in glyphosate efficacy was seen only when applied in high spray volume (450 L ha^{-1}). This effect is more obvious from analyzing the growth of the fourth leaf of the treated plants (Table 10 and Figure 2).

The presence of dew on plant foliage is conducive to a fully hydrated cuticle, and it aids water-soluble compounds as glyphosate to remain in solution (Caseley and Coupland, 1985). Thus, glyphosate will remain in solution for a longer period of time before drying, when leaves are covered with dew and a low spray volume is used, which will not cause runoff. These conditions could

Table 10. Effect of volume and dew levels on glyphosate (0.54 kg ai ha^{-1}) efficacy on oat plant fresh weight per pot, 15 d after treatments (adapted from Kogan and Zúñiga, 2001).

Spray volume	Dew levels (%)		
	0[*]	50	100
L·ha^{-1}		g	
150	0.52cd	0.46d	0.48d
300	0.74c	0.50cd	0.52cd
450	1.48a	1.49a	1.72a

[*]Untreated oat check plant average fresh weight was 4.2 g.
Different letters indicate statistical differences, Duncan (P < 0.05).

Figure 2. Effect of dew level and spray volume on glyphosate (0.54 kg ai ha^{-1}) efficacy, measured 15 d after application as increase in oat fourth leaf growth. A) Plants with no dew, B) plants with 50% dew (239.7 μL water g^{-1} fresh weight of foliage), and C) plants with 100% dew (479.5 μL water g^{-1} fresh weight of foliage) (adapted from Kogan and Zuñiga, 2001).

enhance foliar uptake. However, Merrit (1982) reported an enhancement of glyphosate foliar absorption by moisture and concentrated deposit. Consequently, a fully hydrated cuticle should support foliar uptake of mainly water-soluble herbicides, which are believed to enter a hydrophilic pathway. Accordingly, the enhanced uptake of glyphosate applied with a low spray volume in leaves with heavy dew can compensate for the dilution of the herbicide deposit.

The majority of plants have leaf surfaces with a high contact angle hysteresis, and reflection of spray drops is likely. The major exception is when drops hit a surface that is already covered with a film of water (Scotland, 1960), which could occur for sprays soon after a rain or with heavy dew. High spray volumes used during heavy dew conditions could exceed the water-holding capacity, and runoff could occur. Thus, heavy dew before a high volume glyphosate application would lead to decreased performance.

Caseley *et al.* (1975) reported that a heavy dew (554 to 864 μL g^{-1} fresh wt of foliage) delayed drying of the glyphosate spray deposit by 3 to 3.5 h on quackgrass (*Elytrigia repens*) foliage, and herbicide performance was not diminished following application to wet compared to dry leaves. In contrast, they showed that the highest water load significantly increased the reduction of foliage fresh weight, believing that glyphosate uptake was enhanced. It must be mentioned that these authors used a normal (low) spray volume of 230 L ha^{-1}.

By contrast, Behrens (1977) indicated a heavy dew deposit at the time of herbicide application resulted

in some runoff and diminished the performance of glyphosate. In this case, it should be noted that plants were nearly saturated with dew, approaching runoff when herbicide was applied. These conditions were very much like the heavy dew level applied to the oat plants in the experiment reported by Kogan and Zuñiga (2001). Kudsk *et al.* (1988) showed that the effect of glyphosate on barley (*Hordeum vulgare* L. cv. Jenny) was considerably greater on plants with natural dew, independent of the herbicide applied in a volume 130 or 278 L ha^{-1}, but in experiments with simulated dew, light or heavy dew did not influence glyphosate applied in a volume of 307 or 149 L ha^{-1}. No rational explanation was offered by the authors for those contradictory results. In contrast to the results with barley, heavy dew on white mustard (*Sinapsis alba* L.) foliage reduced glyphosate efficacy applied at a high volume (307 L ha^{-1}).

According to Behrens (1977), dew could increase or decrease herbicidal activity to different degrees depending on the specific herbicide, herbicide rate, and plant species involved. It can be said that glyphosate efficacy can be reduced when applied in high volume (450 L ha^{-1}) with heavy dew, probably attributable to spray runoff. As a summary, it could be said that the limited knowledge on this topic, as well as all factors involved in glyphosate foliar uptake, does not permit oneself to make universal recommendations, but it can concluded that heavy dew level and high spray volume appear to reduce glyphosate efficacy. Considering that, low volume spray of glyphosate will directly increase herbicide performance and will reduce the potential for reduced efficacy from dew. In normal field conditions, dew would be mostly moderate with little effect on glyphosate applied relatively low volume ($\leq$ 200 L ha^{-1}).

Use of extra coadjuvants with formulated glyphosate. Materials which for some reason are not included in the manufacturer's formulation and are added to the spray just before using are considered additives or adjuvants. Some are similar or identical the formulation ingredients which are used by the chemical companies, for example surfactant, whereas others, such as ammonium salts, are rarely found in commercial formulations. Others herbicides may be used as an additive, to widen spectrum of weed control. In Chile authors have had excellent results with mixtures of glyphosate (0.72-1.08 kg ia ha^{-1}) with oxyfluorfen (54 g ha^{-1}) or with flumioxazin (25 g ha^{-1}). Both at very low rate (54 and 25 g ha^{-1}, respectively) offered a quick burn down of many weeds that are relatively tolerant to glyphosate (e.x. *Malva* spp., *Modiola caroliniana*, *Urtica* spp., *Pitrea cuneo-ovata*, *Trifolium* spp., *Euphorbia* spp.).

Addition of extra surfactant to formulated

glyphosate is been a much explored research area. Many papers have been produced with the most variable responses (Nalewaja and Matysiak, 1993; Miller *et al.*, 1998; Feng *et al.*, 1999; Sharma and Singh, 1999; 2000; Sharma *et al.*, 2001; Belcher *et al.*, 2004; Singh and Singh, 2008; Martins *et al.*, 2009) from increasing, decreasing and no effect of adding extra surfactant. Most of these reports of adding surfactant or other adjuvant (e.g. ammonium sulfate) to formulated glyphosate have been performed in annual and or perennial monocots and dicot herbaceous weeds. Because weed species can differ in terms of leaf lipophilicity and this can affect wetability and foliar absorption, the addition of surfactant to formulated glyphosate could enhance herbicide efficacy in one weed but not in others (Table 11). No much research is being conducted on the effect of adding surfactant to formulated glyphosate applied to brush and trees. Because a higher glyphosate rate is used normally to control these weeds, the extra surfactant effect can be unlikely, mainly if relatively low spray volume are utilized (e.g. aircraft or helicopter application). Nevertheless addition of extra surfactant often improves the effect of commercial glyphosate, particularly when low rates (≤ 0.48 kg ai ha^{-1}), relatively high spray volume (> 300 L ha^{-1}) are applied to relatively tolerant weed species. Glyphosate (commercial) is used for many and varied purposes and dose may vary from 0.36 to 3 kg ai ha^{-1}, or more, and spray volume from 15 to 500 L ha^{-1}. The ratio of surfactant to herbicide in the traditional commercial glyphosate (Roundup®) is fixed so that the use of single formulation for such diverse treatments must involve compromise. It seems likely, the surfactant level in Roundup is being intended for application of about 1.5 kg ai ha^{-1} of herbicide in 200-250 L ha^{-1} and it will be inadequate when less amount of acid equivalent is applied in the same spray volume. Conversely, when higher doses are applied in very low volume, the surfactant concentration may be too high.

It is well known that some surfactant especially organosiliconates can reduce glyphosate rainfastness because initial foliar absorption rate may be increased. For this reason their use is recommended as an "insurance" when glyphosate is applied mainly in reforestation site preparation when rainfall can suddenly occur after application. Different commercial formulation can present rainfastness from 2 to more than 12 h in the case of some herbaceous weeds.

Glyphosate is a weak acid, sold as the isopropylamine salt, ammonium, potassium or trimethylsulfonium salt. Several commercial products containing these salts, from different companies, are in the market. Besides of differing in their equivalent acid content they can also differ in surfactant type and amount in their formulations. Therefore there is a clear necessity for more research in this field to find out if they really can shorten glyphosate rainfastness, and/or enhance its efficacy when they are applied to control different brush and tree weeds.

RESUMEN

Uso de glifosato en plantaciones forestales. Bajo las condiciones chilenas la falta de control de malezas al establecimiento de los árboles resulta en un promedio de al menos 60% menos acumulación de biomasa durante el primer año de crecimiento de pino radiata o eucalipto, y glifosato ofrece una serie de ventajas en el manejo de malezas forestales debido a su actividad en ambos grupos de malezas herbáceas, monocotiledóneas y dicotiledóneas, así como anuales, bianuales y perennes. Además, su eficacia en la vegetación leñosa indeseable hace al glifosato un herbicida muy importante que puede ser aplicado para controlar malezas herbáceas y leñosas en pre-plantación y durante el segundo o tercer año de crecimiento de los árboles como aplicaciones en franja. El objetivo de esta revisión es discutir los principales usos de glifosato en reforestación a lo largo del mundo, durante los primeros 2 años después del establecimiento de los árboles, como aplicación al voleo por sobre los árboles en el bosque y los factores más importantes que pudieron afectar la eficacia de glifosato como un herbicida forestal, como estado del crecimiento de maleza, técnica de aplicación, volumen y calidad del agua, resistencia al lavado por lluvia, efecto rocío y el uso de adyuvantes extra con glifosato formulado.

Palabras clave: pino, eucalipto, resistencia al lavado por lluvia, plantas leñosas.

Table 11. Effect of organosiliconate surfactant Silwet L-77 on the required glyphosate trimesium rate (g ha^{-1}) to achieve 90% of control on different herbaceous weed species (adapted from Baylis and Hant, 1993).

Species	Silwet L-77 concentration (% v/v)		
	0	0.125	0.5
		g ha^{-1}	
Chenopodium album	712	625	722
Conyza canadensis[1]	709	298*	169*
Polygonum aviculare	711	802	2080*
Eleusine indica	725	923	1338*
Digitaria sanguinalis	361	375	406
Lolium perenne	692	577	494*
Cyperus rotundus	1037	791	748*

*Indicates significant difference respect Silwet L-77 dose.
[1]Only 60% control in this case.

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