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Injector-size and the time of application affects uptake of tree trunk-injected solutions

M.A. Sánchez Zamora, R. Fernández Escobar*

Departamento de Agronomía, Universidad de Córdoba, Apartado 3048, 14080 Córdoba, Spain

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Abstract

Three different injectors, each 25 mm in length and with diameters of 6, 4, and 3 mm, respectively, were tested with low-pressure injections of 250 ml of water into 23 different species of fruit-trees, *woodland* and *ornamental trees* at different times of year. The 6 and 4 mm injectors performed well, yielding uptake of 75–100% of water volume 1 or 48 h after injection, depending on the species; however, the *ornamental* species *Melia azedarach* did not perform well with all three injectors. The 3 mm injector yielded highly irregular results. The 4 mm injector could substitute the more widely-used 6 mm injector in most cases, with the added advantage of reducing healing time. Injection uptake rates were greater on clear than on rainy days, this difference increasing with smaller-diameter injectors. *Prunus* species took up a high water volume when injected prior to budbreak, and this could avoid leaf burning caused by later injections of some chemicals. Uptake rates were lower during the winter rest period than during the peak growth season (spring). All these factors are to be taken into account in order to ensure the best and most efficient use of low-pressure injection of chemicals in agricultural, forestry or landscape practices.

Keywords: Chemical treatments; Fruit trees; Ornamental trees; Trunk injection; Trunk injector; Woodland trees

1. Introduction

Chemical products used in agriculture such as fertilisers, pesticides or growth regulators, are usually applied to leaves or directly to the soil.

* Corresponding author. Tel.: +34-957-218498; fax: +34-957-218569.
E-mail address: rfernandezescobar@uco.es (R.F. Escobar).

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Although, these traditional application techniques have great advantages they are sometimes inefficient, often unacceptable for use in urban areas due to the potential hazard they represent and to the increase in water and air pollution. Trunk-injection of these substances directly into the tree vascular system is an alternative, offering the following advantages: (1) more efficient product use; (2) elimination of environmental contamination; (3) a viable alternative to ineffective or costly leaf or ground treatments; (4) possibility of use in urban areas where other methods prove problematic; and (5) generally more precise results.

Numerous factors influence the uptake and distribution of substances injected in tree trunks. Technical application-related factors include: injection pressure of the treatment solution, which, depending on the system used, may vary between 0.7 and 1.4 MPa in high-pressure systems (Reil and Beutel, 1976; Sachs et al., 1977; Reil, 1979), and reduced values for low-pressure systems such as the Chemjet system (Whiley et al., 1991; Guest et al., 1994), the Mauget system (McCoy, 1979; Webb et al., 1988; McClure, 1992), and the system developed by Navarro et al. (1992); the type of substance injected (Reil, 1979; Guest et al., 1994); hole-diameter (Sachs et al., 1977); the number of injections and hole depth (Nyland and Moller, 1973; Sachs et al., 1977; Reil, 1979; Navarro et al., 1992); the speed and type of drill used (Sachs et al., 1977; Reil, 1979); and the injection site in the tree trunk or branch (Sachs et al., 1977; Kondo, 1979; Reil, 1979; Rice, 1979; Shriver et al., 1979). Other factors affecting uptake include the plant material and, more particularly, the species treated (Filer, 1973; Sachs et al., 1977; Sterrett and Creager, 1977), tree transpiration rate, which, in turn, varies according to the timing of treatment (Reil, 1979), stress conditions (Reil and Beutel, 1976; Reil, 1979), wind speed (Reil, 1979), soil water content (Reil, 1979), tree size (Filer, 1973; Helburg et al., 1973; Reil, 1979; Roberts et al., 1979; Tawil et al., 1991; Navarro et al., 1992), tree health (Sachs et al., 1977; Lewis, 1979; Reil, 1979; McClure, 1992), and the phenological state of the tree (Reil, 1979; Fernández-Escobar et al., 1993; Whiley et al., 1995).

Many of the trunk-injection methods developed over the last 100 years are affected differently by these factors. The method developed by Navarro et al. (1992) has given the best results in the treatment of pathological (Fernández-Escobar et al., 1994; Fernández de Córdova and Orpez, 1996; Fernández de Córdova and Gallego, 1997; Fernández-Escobar et al., 1999) and nutritional problems (Fernández-Escobar et al., 1993), since it is inexpensive, easy to use and does not require special equipment. However, in order to establish the correct application technique, certain aspects require further study. These include the influence of injector type and size, species and environmental conditions on the uptake of injected solutions. This was the aim of the present study.

Fig. 1. Injection capsule placed in tree trunk (right) and 6 mm diameter injector inserted in the drilled hole (left).

2. Materials and methods

The low-pressure injection system described by Navarro et al. (1992) was used in all experiments. This method consists of two elements: a plastic injector for insertion in the tree trunk once a hole has been drilled; and a latex tube containing the solution to be injected closed at both ends by clips or tape (Fig. 1). Working pressure was between 60 and 80 kPa, and a 9 mm-diameter latex tube was employed. The application process was as follows: (a) a 6 mm-diameter hole was drilled in the tree trunk or branch, (b) the injector was hammered into the hole, and (c) the sealing clip or tape was removed from one end of the tube and the open end fitted to the injector.

2.1. Influence of injector type and tree species on uptake

Tests were performed on the species listed in Table 1. Individuals selected from each species presented similar trunk diameter and leaf mass. Three different injectors were used with a common length of 25 mm and diameters of 6, 4, and 3 mm, respectively. The 6 mm-diameter injector is currently the most widely used. In each tree, three 50 mm-deep holes were made with diameters of 6, 4, and 3 mm, respectively, at intervals around the trunk, and at heights ranging from 20 to 40 cm above the soil surface. Five to ten trees (replications) per species were selected for the experiments, with the exception of apricot and European plum in which only three trees were available. The three injectors were then hammered

Table 1
Tree species injected in the experiment and trunk diameter

Common name	Species	Average trunk diameter (cm)
Fruit trees		
Almond	*Prunus dulcis* (Mill.) D.A. Webb	19.4
Apricot	*Prunus armeniaca* L.	22.3
Common apple	*Malus domestica* Borkh	12.7
English walnut	*Juglans regia* L.	21.6
European plum	*Prunus domestica* L.	16.8
Grapefruit	*Citrus paradisi* Macfady	19.5
Japanese plum	*Prunus salicina* Lindl.	22.3
Mandarin orange	*Citrus reticulata* Blanco	17.1
Olive	*Olea europaea* L.	19.2
Peach	*Prunus persica* (L.) Batsch	15.2
Pear	*Pyrus communis* L.	15.9
Sweet orange	*Citrus sinensis* (L.) Osbeck	17.3
Ornamental trees		
Chinaberry	*Melia azedarach* L.	18.7
Common oleander	*Nerium oleander* L.	8.7
Eastern sycamore	*Platanus occidentalis* L.	39.8
Elm	*Ulmus minor* Miller	31.3
Flame bottle tree	*Brachychiton acerifolius* (A. Cunn.) F. J. Muell.	37.7
Globe elm	*Ulmus carpinifolia cv.* Umbraculifera	11.7
Glossy privet	*Ligustrum lucidum* Ait.	18.7
Horsetail tree	*Casuarina equisetifolia* Forst.	33.1
White poplar	*Populus alba* L.	35.9
Woodland trees		
Holm oak	*Quercus ilex* L.	35.6
Murray red gum	*Eucalyptus camaldulensis* Dehnh	17.6

into the wood to a depth of 15 mm. Pressurised capsules containing 250 ml of water were then inserted as shown in Fig. 1. The volume of liquid taken up at 1, 3, 24, and 48 h after injection was measured. Each capsule was divided into four nominal sections, each representing 25% of the total amount of liquid, and the following scale was used to indicate the amount of liquid absorbed: 0 for 0%; 1 for 0–25%; 2 for 25–50%; 3 for 50–75%; 4 for 75–100%; and 5 for 100%.

2.2. *Influence of phenological and environmental conditions on uptake*

Adult mandarin, orange and grapefruit trees were selected in order to compare the uptake rate of injections in two seasons (vegetative rest and spring) for different injectors. In a second experiment, olive and azedarach species were used to study the effect on uptake of moisture conditions on the day of application. A third experiment was performed to study the uptake rate in peach trees under different phenological stages. Injection procedures, techniques, materials, and measurements in these tests were as described for Experiment 1. Since the variable studied here was discrete, statistical data analysis was based on mean values and interval of variation among the trees of each experiment.

3. Results

Uptake rates varied according to species and injector type, but usually increased with time. In fruit-tree species (Table 2), uptake of water 1 h after injection decreased as the injector diameter decreased, with the exception of olive trees in which all the injections were taken up when they were inserted in injectors of 4 and 6 mm in diameter. After 24 or 48 h, the 4 and 6 mm injectors gave the same results in all fruit-tree species, with the exception of peach. Complete uptake was observed after 3 h in apricot, European plum, pear and olive trees with both 4 and 6 mm injectors, and with the 6 mm injector in sweet orange. Test were performed prior to budbreak in peach, almond, apricot, Japanese plum and European plum; following leaf growth in common apple, pear and English walnut; and at the peak of the growing season in citrus species.

A similar pattern was observed when *ornamental* and *woodland trees* were injected (Table 3). Uptake rates were lower with the 3 mm injector, but both the 4 mm and the 6 mm injectors showed the same good results. After 24 or 48 h most of the injection capsules placed on these injectors were taken up in all the species, with the exception of chinaberry.

Phenological and environmental conditions may affect the rate of uptake of injections. In citrus, the overall uptake rate in June, at the peak of the growing season, was the same or slightly higher than in February, during the rest (Table 4). In olive trees there was a clear decrease in uptake rates with all three injectors on rainy days compared to clear days (Table 5). This effect was not observed in chinaberry trees, probably because of the low and variable uptake rates showed by this species. In peach trees, uptake of injections were similar in March, when the calyx was visible on leafless trees, and in May, when fruit had recently set, but was lower in April, during full bloom (Table 6).

4. Discussion

Injector-size, and therefore hole-diameter, had a direct influence on injection uptake rate; with these injectors of 6, 4 and 3 mm in diameter, the volume of injection uptake during the early stages of sampling (1 and 3 h after injection)

Table 2
Uptake rate of trunk injectios in 12 different fruit-tree species during the first 48 h following injections in relation to the injector-size

Species	Trees (no.)	Time	Injector-size(mm)	Uptake[a]							
				1 h		3 h		24 h		48 h	
				Mean	Interval	Mean	Interval	Mean	Interval	Mean	Interval
Deciduous species											
Peach	10	March	6	–	–	3.8	1–5	4.8	3–5	5.0	5–5
			4	–	–	2.2	0–5	3.5	0–5	4.3	0–5
			3	–	–	1.6	0–5	2.4	0–5	3.2	0–5
Alamond	7	March	6	–	–	–	–	4.1	1–5	4.6	3–5
			4	–	–	–	–	4.6	2–5	4.8	4–5
			3	–	–	–	–	2.1	0–5	2.8	0–5
Apricot	3	March	6	–	–	5.0	5–5	5.0	5–5	–	–
			4	–	–	5.0	5–5	5.0	5–5	–	–
			3	–	–	3.7	1–5	5.0	5–5	–	–
Japanese plum	7	March	6			4.1	1–5	4.4	1–5	4.4	1–5
			4	–	–	4.6	2–5	5.0	5–5	5.0	5–5
			3	–	–	1.4	0–5	3.0	0–5	3.0	0–5
European plum	3	April	6	4.0	3–5	5.0	5–5	5.0	5–5	–	–
			4	2.0	2–2	5.0	5–5	5.0	5–5	–	–
			3	1.0	1–1	3.0	2–4	5.0	5–5	–	–
Common apple	6	May	6	3.7	0–5	4.3	1–5	4.5	2–5	–	–
			4	3.2	0–5	4.0	1–5	5.0	5–5	–	–
			3	1.7	0–5	2.8	0–5	3.0	0–5	–	–

Table 2 (*Continued*)

Pear	5	April	6	4.6	4–5	5.0	5–5	5.0	5–5	–	–
			4	3.2	2–5	5.0	5–5	5.0	5–5	–	–
			3	2.6	1–5	4.4	2–5	5.0	5–5	–	–
English walnut	7	May	6	–	–	4.6	2–5	5.0	5–5	5.0	5–5
			4	–	–	3.6	1–5	4.6	3–5	5.0	5–5
			3	–	–	0.6	0–2	1.6	0–3	2.6	0–5
Evergreen species											
Sweet orange	10	June	6	5.0	5–5	5.0	5–5	5.0	5–5	–	–
			4	3.9	0–5	4.3	1–5	4.7	2–5	–	–
			3	0.7	0–1	1.1	0–4	2.1	0–5	–	–
Grapefruit	5	June	6	4.0	0–5	4.0	0–5	4.2	1–5	–	–
			4	3.2	0–5	3.6	0–5	4.0	0–5	–	–
			3	0.4	0–1	1.4	0–3	3.0	0–5		
Mandarin orange	5	June	6	2.6	0–5	3.0	0–5	3.4	0–5	–	–
			4	3.0	0–5	3.6	0–5	4.0	0–5	–	–
			3	0.2	0–1	0.4	0–1	0.6	0–1	–	–
Olive	7	May	6	5.0	5–5	5.0	5–5	5.0	5–5	–	–
			4	5.0	5–5	5.0	5–5	5.0	5–5	–	–
			3	3.0	0–5	4.4	2–5	5.0	5–5	–	–

[a] Water volume uptake was measured on a scale 0 (0% water uptake) to 5 (100% water uptake). The table indicates mean, the minimum and maximum values within each species for each sample time.

Table 3
Uptake rate of trunk injectios in eleven different *ornamental* and *woodland* tree species during the first 48 h following injections in relation to the injector-size

Species	Trees (no.)	Time	Injector-size (mm)	Uptake[a]							
				1 h		3 h		24 h		48 h	
				Mean	Interval	Mean	Interval	Mean	Interval	Mean	Interval
Ornamental tress											
Deciduous species											
Eastern sycamore	5	May	6	5.0	5–5	5.0	5–5	5.0	5–5		
			4	4.2	1–5	4.2	1–5	4.8	4–5		
			3	0.8	0–1	1.4	1–2	3.8	1–5		
Globe elm	5	May	6			5.0	5–5	5.0	5–5	5.0	5–5
			4			4.4	2–5	5.0	5–5	5.0	5–5
			3			0.8	0–1	1.6	0–3	2.2	0–4
Elm	7	May	6	5.0	5–5	5.0	5–5	5.0	5–5		
			4	4.4	1–5	4.5	2–5	5.0	5–5		
			3	3.4	0–5	3.6	0–5	3.9	0–5		
White poplar	5	May	6	5.0	5–5	5.0	5–5	5.0	5–5		
			4	4.4	2–5	4.8	4–5	5.0	5–5		
			3	1.4	0–3	3.2	1–5	5.0	5–5		
Chinaberry	8	May	6	0.9	0–5	1.1	0–5	2.2	0–5	2.4	0–5
			4	0.9	0–5	1.5	0–5	2.0	0–5	2.2	0–5
			3	0.1	0–1	0.2	0–2	0.6	0–5	0.6	0–5

Table 3 (*Continued*)

Evergreen species											
Common oleander	7	May	6	4.7	4–5	5.0	5–5	5.0	5–5		
			4	3.0	1–5	4.4	1–5	5.0	5–5		
			3	1.0	0–2	1.7	0–4	3.7	0–5		
Flame bottle tree	5	June	6	4.6	3–5	5.0	5–5	5.0	5–5		
			4	5.0	5–5	5.0	5–5	5.0	0–5		
			3	0.6	0–1	1.4	0–3	3.0	0–5		
Horsetail tree	5	June	6	5.0	5–5	5.0	5–5	5.0	5–5		
			4	3.0	1–5	4.6	4–5	5.0	0–5		
			3	0.6	0–1	1.0	0–2	3.0	0–5		
Glossy privet	6	May	6	5.0	5–5	5.0	5–5				
			4	5.0	5–5	5.0	5–5				
			3	4.3	2–5	5.0	5–5				
Woodland trees											
Holm oak	10	April	6	5.0	5–5	5.0	5–5	5.0	5–5		
			4	4.5	2–5	5.0	5–5	5.0	5–5		
			3	1.4	2–5	2.5	0–5	3.8	0–5		
Murray red gum	10	April	6					5.0	5–5	5.0	5–5
			4					4.0	0–5	4.0	0–5
			3					1.2	0–5	1.7	0–5

[a] Water volume uptake was measured on a scale 0 (0% water uptake) to 5 (100% water uptake). The table indicates mean and the minimum and maximum values within each species for each sample time.

Table 4
Uptake rate of trunk injections in three citrus species injected in winter rest (February) and in spring (June) in relation to the injector-size

Species	Trees (no.)	Injector-size (mm)	Update after 24 h[a]			
			February		June	
			Mean	Interval	Mean	Interval
Sweet orange	10	6	3.2	0–5	5.0	5–5
		4	4.0	1–5	4.7	2–5
		3	2.5	1–5	2.1	0–5
Grapefruit	5	6	4.0	0–5	4.2	1–5
		4	3.1	1–5	4.0	0–5
		3	2.0	0–5	3.0	0–5
Mandarin orange	5	6	3.6	1–5	3.4	0–5
		4	2.0	0–5	4.0	0–5
		3	0.8	0–2	0.6	0–1

[a] Water volume uptake was measured on a scale 0 (0% water uptake) to 5 (100% water uptake). The table indicates mean and the minimum and maximum values within each species for each sample time.

was slightly greater, or the same, with the 6 mm injector as with the 4 mm injector, and noticeably lower with the 3 mm injector. Most striking were the uptake rates obtained for the 6 and 4 mm injectors after 24 or 48 h, since no differences were recorded between the two injectors. However, when injector diameter was reduced from 4 to 3 mm, clear differences were observed in both uptake rate and the final quantity taken up. The widely-used 6 mm injector could therefore be replaced by the 4 mm injector in those cases where application conditions made this a viable alternative. This would reduce healing time (Sachs et al., 1977; Shigo, 1979). In these experiments, some isolated injections were not successful, possibly due to injector blockage by shavings in the drilled holes; this was confirmed when injectors were removed from trunks at the end of the experiment and was inversely proportional to the diameter of the injector ($6\ \text{mm} \leq 4\ \text{mm} < 3\ \text{mm}$). This may limit the use of the 3 mm injector as an alternative to the more popular 6 mm injector. When this was not the cause, failure to uptake injections may have been due to defects in internal tree structure at injection sites, or low growth activity at those sites, as has been reported previously (Sachs et al., 1977), and therefore not to the type of injector employed.

The species also had an important influence on rate and percentage of uptake, coinciding with findings reported elsewhere (Filer, 1973; Reil and Beutel, 1976; Sachs et al., 1977; Sterrett and Creager, 1977; Reil, 1979). The performance of deciduous and perennial fruit-trees in this experiment was generally good, with uptake rates above 75% and, in many cases, 100% (excluding the highly irregular

Table 5

Uptake rate of trunk injections in olive and chinaberry trees in relation to the environmental conditions (rainy vs. clear days) and injector-size

Species	Trees (no.)	Time	Environmental conditions	Injector-size (mm)	Uptake[a]							
					1 h		3 h		24 h		48 h	
					Mean	Interval	Mean	Interval	Mean	Interval	Mean	Interval
Olive	10	March	Clear day	6	5.0	5–5	5.0	5–5	5.0	5–5		
				4	5.0	5–5	5.0	5–5	5.0	5–5		
				3	3.0	0–5	4.4	2–5	5.0	5–5		
	10	March	Rainy day	6	4.2	0–5	4.6	1–5	4.7	2–5	4.8	3–5
				4	1.6	0–5	3.6	1–5	4.3	1–5	5.0	5–5
				3	0.3	0–1	1.9	0–5	3.8	1–5	4.5	3–5
Chinaberry	8	May	Clear day	6	0.9	0–5	1.1	0–5	2.2	0–5	2.4	0–5
				4	0.9	0–3	1.5	0–5	2.0	0–5	2.2	0–5
				3	0.1	0–1	0.2	0–2	0.6	0–5	0.6	0–5
	8	May	Rainy day	6	0.6	0–2	0.9	0–5	1.4	0–5	2.0	0–5
				4	2.0	0–5	3.0	0–5	3.6	0–5	4.0	0–5
				3	0.1	0–5	0.7	0–5	1.5	0–5	1.9	0–5

[a] Water volume uptake was measured on a scale 0 (0% water uptake) to 5 (100% water uptake). The table indicates mean and the minimum and maximum values within each species for each sample time.

Table 6
Uptake rate of trunk injections in peach trees in relation to their phenological stage and injector-size

Species	Trees (no.)	Time	Phenological stage	Injector-size (mm)	Uptake[a]					
					3 h		24 h		48 h	
					Mean	Interval	Mean	Interval	Mean	Interval
Peach	10	March	Visible calyx	6	3.8	1–5	4.8	3–5	4.8	3–5
				4	2.2	0–5	3.5	0–5	3.5	0–5
				3	1.6	0–5	2.4	0–5	2.4	0–5
	10	April	Full bloom	6	2.8	0–5	3.7	0–5	3.9	0–5
				4	0.3	0–3	1.9	0–5	3.3	1–5
				3	0.0	0–0	0.4	0–1	0.8	0–2
	10	May	Initial fruit set	6	4.4	1–5	4.5	1–5	4.5	1–5
				4	2.9	0–5	3.2	0–5	3.5	0–5
				3	1.9	0–5	2.6	0–5	3.1	0–5

[a] Water volume uptake was measured on a scale 0 (0% water uptake) to 5 (100% water uptake). The table indicates mean and the minimum and maximum values for each sample time.

results obtained with the 3 mm injector). Noteworthy results were obtained with species of apricot, European plum, and pear; olive showed particularly high uptake rates. Tests with *Prunus* spp. were carried out prior to leafing, with the exception of some European plum trees which had grown leaves but had not yet fully expanded. This suggests the interesting possibility of injecting chemical formulations into trees before the initial period of leaf development, when some chemical products might cause leaf burning by trunk-injection (Fernández-Escobar et al., 1993).

The performance of the leafy *woodland* and *ornamental* species was generally good, achieving uptake rates of over 75%, and, in many cases, 100% (excluding highly irregular results obtained with the 3 mm injector). The exception was chinaberry, which performed less well, with uptake rates below 50% in most cases for all three injectors and under all the environmental conditions studied. This low uptake rate may have been due to factors other than tree health, since the trees appeared to be healthy and well developed. This behaviour was common to the eight chinaberry trees studied here.

Uptake rates varied according to injection timing. In perennial species, such as the sweet orange, grapefruit and mandarin, uptake rates during the vegetative rest period (February) were generally lower than at the height of the growing period (June), due to the reduced physiological activity of the trees. In peach trees, the presence or absence of leaves between the phenological **C**(visible calyx) and **I**(recently-set fruit) stages only influenced the uptake rate shortly after injection, no significant differences being observed in terms of the final volumes taken up. This aspect is of agronomic interest, since uptake speed is of less importance than the uptake of the volume of liquid applied within an acceptable time (48 or 72 h). Similar results were also recorded in other *Prunus* species as indicated above.

Environmental characteristics (rainy vs. clear days) clearly influenced the uptake rate; on clear days, olive trees taken up the injections more quickly (higher uptake rate) than on rainy days and this difference increased with smaller-diameter injectors. This variation in the injection rate was due to the fact that rain increased relative air humidity, leading to greater water accumulation in the soil and thus reducing tree transpiration.

The results obtained here also suggest that in adult trees with thick trunks, it may not be necessary to drill holes right into the pith, requiring the use of a specially long bit as suggested by Navarro et al. (1992), since 4.5/5 cm-deep holes made in the trunk would reach the active xylem, the part of the wood where active water flow occurs. Furthermore, the internal part of the wood of some adult trees has normally lost its conductive capacity. Injectors would thus have to be inserted to a maximum depth of 1.5 cm in the hole, thus leaving an internal air chamber some 3–3.5 cm in length which is essential for ensuring injection uptake. Lastly, the number of injections at regular intervals around the trunk must be made according to trunk size.

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