Journal of Soil Science and Environmental Management Vol. 2(6), pp. 159-166, June 2011
Available online at http://www.academicjournals.org/JSSEM
ISSN 2141-2391 ©2011 Academic Journals

Full Length Research Paper

The integration of variable rate technologies for a soil-applied herbicide in leafy green production

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Accepted 13 June, 2011

While lettuce is an intensively managed specialty crop for which there is little tolerance for weeds, the herbicide benefin (Balan®) is commonly used in preplant and preemergence applications to control weeds during lettuce stand establishment. In fields with high clay and low organic matter contents, considerably more of the herbicide is required for adequate weed control than in soils with higher sand contents where excessive herbicide rates can injure young lettuce roots. A three year effort involving variable rate application (VRA) of Balan® was conducted on three, 10 ha grower-cooperator leaf lettuce fields in Yuma, AZ (USA) each consisting of three distinct soil textures and application rates; a clay (2.8 kgai/ha), a loam (2.2 kgai/ha) and either a sandy loam or loamy sand (1.7kgai/ha). The effectiveness of VRA was determined by comparing conventional applications at the standard rate of 2.2 kgai/ha and quantifying lettuce injury, yields at harvest, and overall weed control.Site-specific placement of Balan® resulted in over 30% reducedlettuce seedling injury in loamy sand textured soils with 35% lower application amounts than using conventional methods; weed control was similar among all treatments. As over 40% more marketable lettuce was demonstrated in sandy loam textures using VRA, the application shows promise for weed control in leafy greens where non uniform soil textures show a severe challenge to production.

Key words: Benefin, variable rate application, variable rate application, precision agriculture, soil texture, soil uniformity, lettuce, site specific, herbicide, weed control, crop injury.

INTRODUCTION

Since in the mid 1990's, advances in global positioning systems (GPS), microprocessors, actuators, controllers, plant/soil sensors and geographical information systems (GIS) have spawned the development of new, site-specific, variable-rate techniques for chemical applications. At the same time, agricultural production has embraced other new technologies that increase the productivity of mechanized operations such as tractor auto-guidance systems. The combination of automatic tractor steering and variable rate technology is well suited for site-specific application of pre-emergence herbicides. With tractor guidance control and variable rate controllers, growers can increase the efficiency of chemical application by eliminating swath overlap, while increasing the efficacy of herbicide action by applying optimum rates based on soil texture.

These technologies have primarily been adopted by growers of major crops such as corn, wheat and soybeans (Koch and Khosla, 2007). Recently however, vegetable producers have become increasingly interested in using these technologies for variable rate application of soil applied preemergence herbicides. In many fields where vegetables are grown in the United States, there is large spatial variation of soil properties, including soil texture. In fact, Bauer and Schefcik (1994) found that recommended application rates of preemergence, soil applied herbicides can vary as much as 50% in a given field due to varying soil textures.

Soil-applied preemergence herbicides are widely used in vegetable production for controlling weeds during stand establishment. These types of herbicides are used to control weeds after sowing, but prior to crop emergence. In vegetable production, they are typically broadcast applied to the soil surface and then incorporated into the top several inches of soil. After weed seed germination, the herbicide is absorbed by the

Table 1. Physical properties of common preemergence herbicides used in Arizona vegetable production.

Product name	Common name	Water solubility (ppm)[1]	Herbicide soil/solution distribution Index (K_d)	Herbicide soil/organic affinity index (K_{oc})[1]	Soil half-life (days)[1]	Mobility rating[1]
Balan® 2.5-G	Benefin	<1	16.7 – 48.6[2,3,4]	9,000	40	Extremely low
Kerb® 50-WSP	Pronamide	15	6.2 – 15.4[2]	200	60	High
Prefar® 4-E	Bensulide	6	5.4 – 13.5[2,5]	1,000	120	Moderate

[1]Weed Science of America, 2007, [2]Weber et al., 2000, [3]Jacques and Harvey, 1979, [4]Weber, 1990, [5]Carlson et al., 1975.

roots and/or shoot of the seedling. This kills the weed seedling, typically before it emerges from the soil. Contrary to conventional wisdom, preemergence herbicides do not kill plants by preventing seed germination (Ross and Childs, 1996).

After a herbicide has been applied to soil, it has one of three fates. It can either remain dissolved in the soil solution, be adsorbed by smaller soil colloidsor be absorbed by plant roots and shoots (Colquhoun, 2006). Herbicide that is adsorbed by soil is bound to soil and is not readily available for weed absorption. Soil properties that affect soil adsorption can include the presence of mineral oxides, soil organic matter and clay composition, the level of crop residues in the soil, soil pH and soil water content. However, typical of western soils with high clay and low organic matter contents, the amount of herbicide adsorbed by most western desert soils is highly dependent on the soil's clay content - the higher the clay content, the greater the amount of soil adsorption (Moomaw et al., 1992). Because of this, recommended rates for soil-applied herbicides are commonly based on soil texture. Herbicide adsorption to soil can be described using soil/organic matter (K_{oc}) and soil/soil solution indices (K_d) (Table 1). Both parameters are defined as the ratio between the level of herbicide adsorbed by a reference and the amount found in soil solution. Herbicides with high sorption indices are typically prone to soil adsorption when applied in soils high in clay or organic matter contents. This reduces herbicide available for root uptake in the soil solution, and higher herbicide application rates are needed to increase soil solution herbicide concentrations for effective weed control. When the same high herbicide rates are applied to soils with low clay content, less herbicide is adsorbed by soil and crop injury can result from excess herbicide in the soil solution. For herbicides with low sorption indices, herbicide effectiveness is much more consistent and less likely to cause crop injury problems since the herbicide is not readily adsorbed by soil.

The three most common soil incorporated preemergence herbicides used in Arizona vegetable production are listed in Table 1 along with the physical properties that are most important to their fate in soil. Of these, benefin (Balan®; active ingredient, N-butyl-N-ethyl-α,α,α-trifluoro-2,6-dinitro-*p*-toluidin) requires the most critical consideration of soil texture when determining the proper application rate to use. The herbicide has a very high soil sorption index making it strongly adsorbed by soil colloids and highly immobile (Table 1). In soils with high clay content, a greater amount of the herbicide is required for adequate weed control as compared to sandy soils. If rates necessary for good weed control in high clay content soils are used on sandy soils, excessive herbicide concentrations in soil solution can cause injury to lettuce seedling roots (Tickes and Kerns, 1996). This high concentration problem is not easily resolved since Balan®has an extremely low mobility rating and is relatively insoluble in water, and therefore not likely to leach below the depth where crop seedlings develop. The objectives of this study were: (i) to quantify and demonstrate the benefits of variable rate technologies for mediating the damage caused by the over application of the herbicide Balan® across non-uniform soil textures; and (ii) to evaluate crop yield in response to Balan® VRA.

MATERIALS AND METHODS

Study location

The feasibility of site-specific, variable rate application strategies for preemergence herbicides in vegetable production was investigated on three commercial lettuce fieldsnear Yuma, Arizona (USA). Typically, candidate fields for variable rate technologies are chosen based on past experience with herbicide injury and the variable nature of soil textures within a field. Prior aerial imagery of the field may also indicate distinct zones of non-uniformity. The 10 ha fields used in this study were selected because the fields had significant variability in soil type and the grower-cooperators had experienced some form of crop injury when applying uniform rates of soil incorporated herbicides in previous seasons.The ten hectares field locations included those within the Yuma Valley (latitude, 32.726442; longitude, -114.674720), Dome Valley (latitude, 32.724776; longitude, -114.310878) and Gila Valley (latitude, 32.727126; longitude, -114.793710) whose soil characteristics are described in Table 2.

VRA map generation

To generate site specific application maps, a onehectare grid sampling scheme was used to prepare a geo-referenced soil textural map based on soil saturation percentage (SP). Saturation

Table 2. Soil characteristics, leaf lettuce cultivars and dates of various field operations.

Experimental descriptor	Variable	Location: Yuma valley 2006	Yuma valley 2007	Dome valley 2007	Dome valley 2008	Gila valley 2007	Gila valley 2008
Soil description	Name	Indio / Ripley		Glenbar / Indio		Indio / Ripley	
	Texture	SC[1] / SCL[2] / LS[3]		C[4] / SCL / LS		C / SC / SL[5]	
Soil composition	SP[6] (%)	49 / 32 / 18		66 / 38 / 16		69 / 47 / 25	
	Sand (%)	46 / 65 / 80		23 / 51 / 88		17 / 47 / 58	
	Silt (%)	1 / 5 / 15		22 / 15 / 1		8 / 5 / 35	
	Clay (%)	53 / 30 / 5		55 / 34 / 11		65 / 48 / 7	
	OM[7] (%)	0.4 / 0.4/ 0.5		0.4 / 0.3 / 0.4		0.5 / 0.5 / 0.4	
	pH	7.8 / 7.7 / 7.8		7.8 / 7.8 / 7.7		7.6 / 7.7 / 7.7	
Lettuce cultivar	Green leaf /Red leaf	Two star / Vulcan	Two star / Red fire	Green star / Blackhawk	Green star / Firecracker	Green star / Red sails	Tropicana / Vulcan
Balan® application	Date	25 Sept	28 Sept	4 Oct	28 Sept	1 Oct	30 Sept
Lettuce planting	Date	28 Sept	1 Oct	8 Oct	1 Oct	5 Oct	5 Oct

[1]SC: Sandy Clay, [2]SCL: Sandy Clay Loam, [3]LS: Loamy Sand, [4]C: Clay, [5]SL: Sandy Loam, [6]SP: Saturation Percentage, [7]OM: Percent Organic Matter.

percentage, expressed as grams of water required to saturate 100 g of soil, is a variable correlated with soil texture (Peacock, 1998) where the higher the SP, the greater the soil clay content. Each experimental field was composed of three distinct soil textures found within three distinct area locations as summarized in Table 2. A herbicide application rate map was created (Farm Works Site Software, Trimble Navigation, Limited, Sunnyvale, CA, USA) based on soil texture with zones having the highest clay contents receiving greater rates of herbicide (2.8 kgai/ha) than in sandy areas (1.7 kgai/ha), an example of which is shown in Figure 1. The regions within fields containing transitional clay contents were assigned to receive an intermediate level of the herbicide (2.2 kgai/ha). The intermediate rate was also applied within each soil textural zone and served as the standard treatment.

VRA techniques

Balan® was applied either at a standard rate or variably and in response to soil conditions (2.8 – 1.7 kgai/ha) in lengthwise strips (200 × 20 m) across the field. Each strip (six for each variable-rate and standard rate treatments) represented one replication in the experiment's randomized complete block design. Variable rate, site-specific herbicide applications were made using a 2004, model 4640 SpraCoupe® (AGCO Corp., Atlanta, GA, USA) integrated with Trimble® GPS guidance technology and a Raven Viper® flow control module. Two key components in this variable rate technology spraying system are the vehicle ground speed sensor and the CAN-bus (Controller-Area Network) hardware that includes: (a) a boom control node that regulates the operation of the sprayer in sections (booms) through the interface with the operator and a switch box; and (b) a CAN control node which receives information from pressure and flow meter sensors and then sends a signal to the flow control valve.

Application rates were adjusted by a variable rate controller, which incorporated an embedded computer that read sensor inputs, the GIS prescription map, user commands, and ground speed to calculate the correct application rate through an appropriate algorithm. The correct rate was then translated into actual product output through actuators, through opening/closing of solenoid valves and changes in rotational speed of hydraulic motors driving the pumps. Numerous variable rate controllers are available commercially which can interface with different devices through standard connectors. An important consideration when selecting a variable rate control system is the response times of its various components, because a rapidly responding system is needed to make the quick rate changes while moving from different application zones. The system used in this study incorporated an automatic look a head feature capable of providing the predictive speed compensation required to correctly synchronize product rates with the correct zones after subtracting inherent system lag times.

VRA assessment

Following disc incorporation of Balan® to a depth of 10 to 15 cm, rows were prepared on 100 cm centers and shaped to a height of 25 cm. Green and ruby red leaf lettuce (*Lactuca sativa* var. *crispa*) was planted within one week following herbicideapplicationat two seed-lines per bed and germinated using sprinkler irrigation. Flood irrigation (~30 cm) was used to irrigate the crop to harvest. Four weeks after germination, seedling injury assessment was determined by counting plants within each soil textural class which showed stunting and a leathery leaf appearance, similar to those described by Tickes and Kerns (1996). All injured lettuce seedlings and weeds which survived herbicide effects within an area measuring 25 m × 5 min each plot were counted. Herbicide efficacy was determined by counting the number of weeds in each plot at 14 and 28 days after germination, and weed control was similar among all treatments (Table 3). Weed species controlled during the study included pigweed (*Amaranthus* sp.), common purslane (*Portulaca oleracea*), lambsquarters *(Chenopodium album*) and ground cherry (*Physalis wrightii*). Treatment effects were also determined at lettuce maturity by counting unharvested lettuce heads within each experimental plot. All original observations were square root transformed prior to statistical analyses using SAS (Statistical Analysis System Institute, Inc.). Fisher's LSD means separation

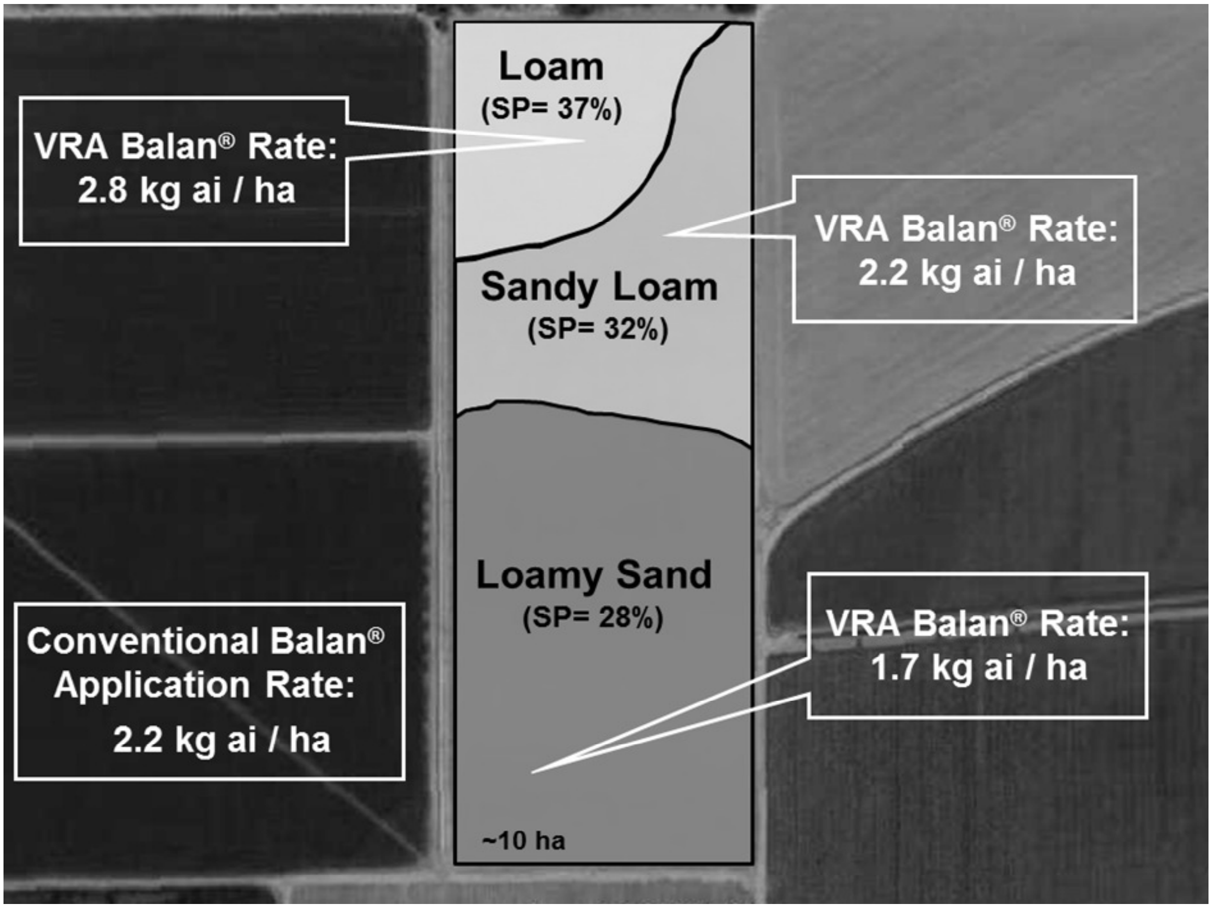

Figure 1. An example of site-specific Balan® application using standard and variable rates made on a 10 hectare commercial lettuce field near Yuma, Arizona. Applications were based on a geo-referenced soil textural map. A standard rate of 2.2 kg ai/ha was used as the control application rate.

tests (P=0.05) were used to determine if weed control efficacy, lettuce injury and crop yield loss was significantly affected by herbicide treatment within each soil textural class.

RESULTS AND DISCUSSION

Site-specific placement of Balan® in a field with non-uniform soil textures resulted in no significant differences in weed control efficacy as compared to the conventional application method (Table 3). Use of variable rate application technology however, significantly reduced levels of seedling injury from 30 to 35% in regions of our experimental fields where soil textures were classified as light or sandy while application amounts were 35% lower than in conventional application approaches (Table 4). Crop injury effects were visually striking in loamy sand conditions four weeks after planting (Figure 2), emphasizing the consequence of enhanced herbicide availability to plant roots in light textured soils. Reduced lettuce leaf injury also resulted in more uniform crop growth and consequently, increased yields of marketable lettuce up to 40% at harvest. In loamy sand and sandy clay loam textured soils, the quantity of unmarketable lettuce was reduced by approximately 3,000 and 5,000 heads per hectare, respectively, when VRA is utilized (Table 4).

The interaction between herbicide chemistry and soil properties greatly affects herbicide weed control efficacy and the potential for crop injury. Because of this, fields with significant variability in soil properties are good candidates for variable-rate application of soil-applied herbicides. A study conducted on ten hectare commercial field in this study showed that, use of variable rate technology with the herbicide Balan® resulted in significantly less crop injury and significantly more marketable yield as compared to uniform application. In the portions of the lettuce field with loamy sand textured soils, 35% less herbicide was applied and up to 40% more heads were harvested, which saved the grower approximately $32.50 (US)/ha and increasing gross revenues by over $3,750 (US)/ha. Furthermore, there were no significant differences in weed control efficacy found between the two application methods examined. In

Table 3. Weed control 4 weeks following variably and conventionally applied preemergence Balan® at three field locations during 2006-2008.[1]

Location	Soil texture	Treatment (kg ai/ha, am)[2]	Weed control (%)											
			Common purslane			Lambs quarters			Pigweed			Total weeds		
			Year			Year			Year			Year		
			2006	2007	2008	2006	2007	2008	2006	2007	2008	2006	2007	2008
YV[3]	Non-treated control		0	0	--	0	0	--	0	0	--	0	0	--
	SC	2.2, Conv.[4]	96[a,6]	95[a]	--	92[a]	88[a]	--	90[a]	94[a]	--	96[a]	95[a]	--
	SC	2.8, VRA[5]	94[a]	94[a]	--	93[a]	94[a]	--	91[a]	85[a]	--	96[a]	96[a]	--
	SCL	2.2, Conv.	89[a]	95[a]	--	94[a]	85[a]	--	95[a]	96[a]	--	94[a]	94[a]	--
	SCL	2.2, VRA	95[a]	92[a]	--	98[a]	96[a]	--	94[a]	89[a]	--	95[a]	95[a]	--
	LS	2.2, Conv.	88[a]	88[a]	--	96[a]	89[a]	--	95[a]	94[a]	--	95[a]	95[a]	--
	LS	1.7, VRA	87[a]	96[a]	--	94[a]	94[a]	--	92[a]	90[a]	--	89[a]	88[a]	--
DV[7]	Non-treated control		--	0	0	--	0	0	--	0	0	--	0	0
	C	2.2, Conv.	--	97[a]	96[a]	--	86[a]	91[a]	--	96[a]	95[a]	--	94[a]	94[a]
	C	2.8, VRA	--	96[a]	95[a]	--	95[a]	94[a]	--	96[a]	96[a]	--	86[a]	86[a]
	SCL	2.2, Conv.	--	96[a]	85[a]	--	95[a]	85[a]	--	91[a]	94[a]	--	94[a]	94[a]
	SCL	2.2, VRA	--	95[a]	94[a]	--	84[a]	96[a]	--	91[a]	95[a]	--	94[a]	94[a]
	LS	2.2, Conv.	--	93[a]	87[a]	--	93[a]	89[a]	--	95[a]	95[a]	--	96[a]	93[a]
	LS	1.7, VRA	--	95[a]	96[a]	--	91[a]	94[a]	--	91[a]	90[a]	--	88[a]	91[a]
GV[8]	Non-treated control		--	0	0	--	0	0	--	0	0	--	0	0
	C	2.2, Conv.	--	95[a]	92[a]	--	95[a]	95[a]	--	96[a]	92[a]	--	94[a]	92[a]
	C	2.8, VRA	--	96[a]	91[a]	--	96[a]	96[a]	--	96[a]	93[a]	--	86[a]	96[a]
	SC	2.2, Conv.	--	94[a]	95[a]	--	94[a]	94[a]	--	91[a]	94[a]	--	94[a]	94[a]
	SC	2.2, VRA	--	95[a]	94[a]	--	95[a]	95[a]	--	91[a]	98[a]	--	94[a]	95[a]
	SL	2.2, Conv.	--	95[a]	96[a]	--	95[a]	95[a]	--	95[a]	96[a]	--	96[a]	95[a]
	SL	1.7, VRA	--	84[a]	89[a]	--	90[a]	91[a]	--	91[a]	94[a]	--	88[a]	90[a]

[1]Non-treated control not included in statistical analysis; data were square root transformed before analysis, [2]Kilograms of active ingredient per hectare(kg ai/ha), application method (am), [3]YV: Yuma valley, Arizona, 2006 and 2007, [4]Conv.: Conventional application method, [5]VRA: Variable rate application method, [6]Means followed by the same letter in each column are not significantly different at P=0.05 according to analysis of variance and the Fisher's LSD means separation test,[7]DV: Dome valley, Arizona, 2007 and 2008, [8]GV: Gila valley, Arizona, 2007 and 2008.

summary, this project shows the potential for using variable rate technologies in vegetable production to apply preemergence herbicides. Although these technologies have been used commercially to apply fertilizers for over a decade, they are just now being explored for use with preemergence herbicides in vegetables. While precision application approaches have the potential to lower production costs and improve farm profitability, the actual level of savings realized will vary from field to field depending on the degree of spatial variability, costs associated with sampling, and the capital investment for technology and equipment (Roberts et al., 2001). Future studies should address the specific costs of implementing this technology, as well as including more variable inputs. Also, a thorough risk analysis would be beneficial in future

Table 4. Damaged lettuce seedlings[4] and unmarketable lettuce at harvest following conventionally and variably applied preemergence Balan® at three Arizona field locations during 2006-2008.[1]

Location	Soil texture	Treatment (kg ai/ha, am)[2]	Damaged seedlings (seedlings/ha)			Unmarketable lettuce (heads/ha)		
			Year			Year		
			2006	2007	2008	2006	2007	2008
YV[3]	Non-treated control		0	0	--	0	0	--
	SC	2.2, Conv.[4]	3,355[a6]	3,995[a]	--	1,280[a]	2,130[a]	--
	SC	2.8, VRA[5]	3,668[a]	4,152[a]	--	1,223[a]	2,735[a]	--
	SCL	2.2, Conv.	7,089[a]	6,045[a]	--	3,775[a]	6,715[a]	--
	SCL	2.2, VRA	6,495[a]	5,181[a]	--	3,108[b]	5,490[b]	--
	LS	2.2, Conv.	13,970[b]	12,410[b]	--	11,400[a]	8,220[a]	--
	LS	1.7, VRA	9,087[a]	8,505[a]	--	6,825[b]	4,770[b]	--
DV[7]	Non-treated control		--	0	0	--	0	0
	C	2.2, Conv.	--	5,197[a]	3,547[a]	--	4,256[a]	5,745[a]
	C	2.8, VRA	--	4,884[a]	3,054[a]	--	3,995[a]	6,010[a]
	SCL	2.2, Conv.	--	6,854[a]	4,253[a]	--	6,215[a]	4,236[a]
	SCL	2.2, VRA	--	4,987[a]	2,941[a]	--	4,964[b]	3,096[b]
	LS	2.2, Conv.	--	15,295[a]	14,965[a]	--	11,236[a]	14,863[a]
	LS	1.7, VRA	--	10,524[b]	10,025[b]	--	7,241[b]	9,244b
GV[8]	Non-treated control		--	0	0	--	0	0
	C	2.2, Conv.	--	1,395[a]	2,415[a]	--	6,521[a]	7,523[a]
	C	2.8, VRA	--	1,901[a]	2,248[a]	--	6,354[a]	7,214[a]
	SC	2.2, Conv.	--	2,104[a]	3,687[a]	--	8,698[a]	6,409[a]
	SC	2.2, VRA	--	1,769[a]	2,689[a]	--	6,981[a]	5,687[a]
	SL	2.2, Conv.	--	13,521[a]	11,984[a]	--	9,547[a]	10,950[a]
	SL	1.7, VRA	--	9,523[a]	7,952[a]	--	6,465[a]	7,790[a]

[1]Non-treated control not included in statistical analysis, [2]Kilograms of active ingredient per hectare(kg ai/ha), application method (am), [3]YV: Yuma valley, Arizona, [4]Conv.: Conventional application method, [5]VRA: Variable rate application method, [6]Means followed by the same letter in each column are not significantly different at P=0.05 according to analysis of variance and the Fisher's LSD means separation test, [7]DV: Dome valley, Arizona, [8]GV: Gila valley, Arizona.

explorations. However, as researchers, manufacturers and growers learn more about precision management approaches, the productivity and cost savings gains of these technologies can be expected to only improve.

Precision herbicide management is an effective tool for spatial application of soil-incorporated herbicides which have a tendency for soil adherence. Although field

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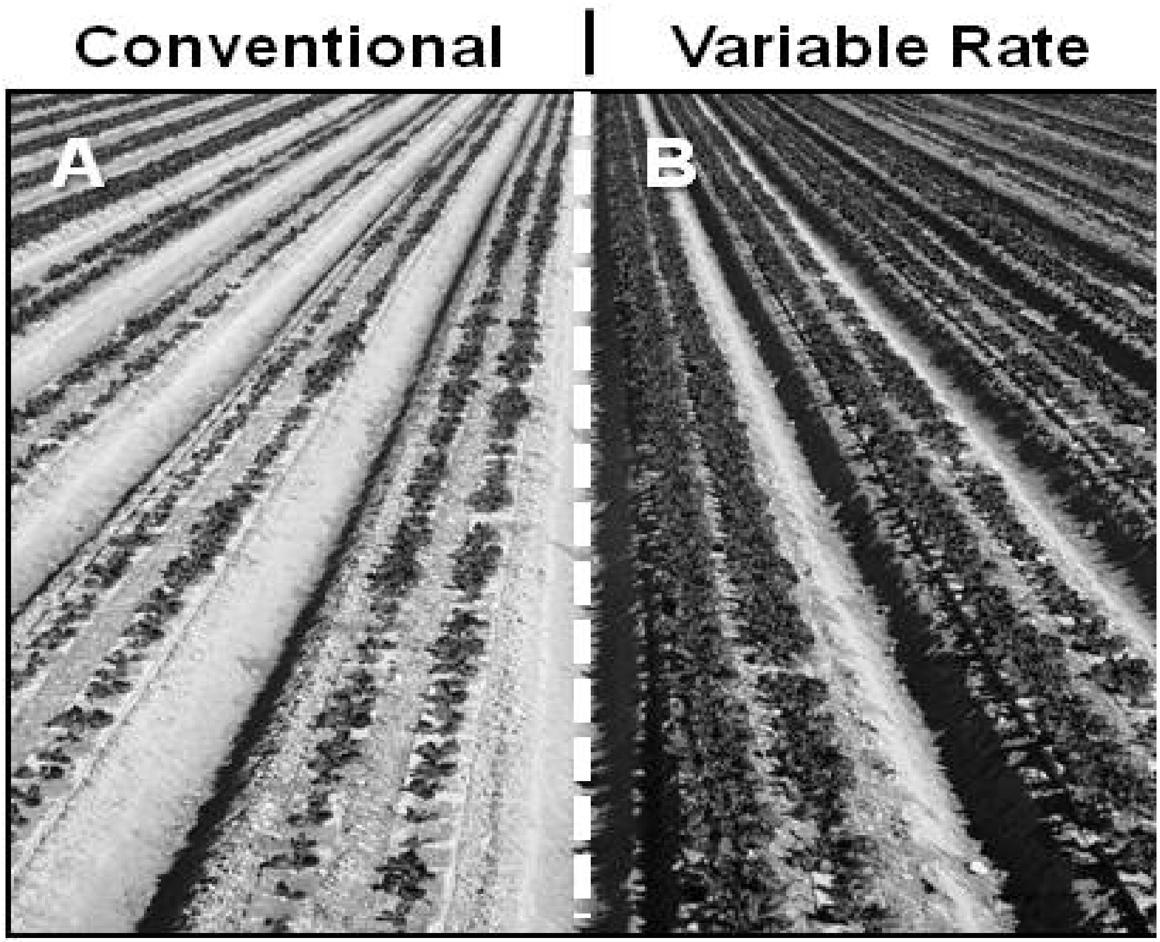

Figure 2. Ruby red leaf lettuce seedling injury (stunting) 4 weeks after planting as a result of applications of Balan® preemergence herbicide using standard (A) and variable rate (B) application schemes in loamy sand textured soil.

preemergence herbicides in vegetables. While precision application approaches have the potential to lower production costs and improve farm profitability, the actual level of savings realized will vary from field to field depending on the degree of spatial variability, costs associated with sampling, and the capital investment for technology and equipment (Roberts et al., 2001). Future studies should address the specific costs of implementing this technology, as well as including more variable inputs. Also, a thorough risk analysis would be beneficial in future explorations. However, as researchers, manufacturers and growers learn more about precision management approaches, the productivity and cost savings gains of these technologies can be expected to only improve.

Precision herbicide management is an effective tool for spatial application of soil-incorporated herbicides which have a tendency for soil adherence. Although field implementation depends on previous knowledge of soil textural variability (soil test and texture evaluations), site-specific technologies show promise for Arizona vegetable fields with non-uniform soils. Regardless of the method used for textural characterization, growers should keep in mind that textural differences do not change in the short/medium term, so the costs associated with defining texture-based management zones can be spread over many years.

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