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Performance Study of Variable-rate Herbicide Applications based on Remote Sensing Imagery

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Weed control effectiveness and herbicide savings were determined for a variable-rate technology (VRT) herbicide application scenario involving three rates, including 100, 67 and 33% rates. Four herbicide treatments, including the VRT scenario and three blanket applications, were tested over a plot of soya beans with a severe weed problem. In the comparison of VRT and conventional methods, the former achieved the best performance in terms of weed control effectiveness and herbicide use efficiency. However, the particular rate scenario used for VRT applications was shown to have flaws. Specifically, the low rate did not provide adequate weed control even over areas of low weed cover. Also, the medium and high rates performed equally well over areas of high weed cover, indicating that the high rate exceeded the minimum dose required for adequate weed control. Adjustment of the rate scenario is necessary for optimum performance of VRT applications in future experiments. These adjustments may involve changes in the active ingredient application rates, the rate reduction percentages, the number of rates used, or the rate selection criteria. In addition, the results demonstrated the importance of using weed species information in the selection of herbicide dosages.

1. Introduction

Variable-rate technology (VRT) has become increasingly popular for fertiliser applications in recent years; however, several complicated issues continue to limit the success of VRT herbicide applications. For example, researchers have not yet developed an appropriate strategy for defining rate scenarios for VRT weed management. A rate scenario consists of several parameters, including the number of rates to be sprayed, the percent by which each rate is reduced from the full rate, the herbicide doses associated with each rate, and the criteria for rate selection. If defined properly, the ideal rate scenario will provide adequate weed control while maintaining efficient use of herbicide. The current difficulty in defining appropriate rate scenarios for VRT herbicide applications is due mainly to the great variability and complexity of weed infestations. Namely, weed infestations can vary in height, size, density, and composition, and these factors collectively affect the amount of herbicide necessary for controlling the infestation. Other criteria, which influence herbicide rate requirements to a lesser degree, include the age of the weeds, the level of plant activity at the time of spraying, the weed history, and the desired level of weed control. To approach this problem, Young *et al.* (2001) developed a model to select herbicide rates based on weed density, soil properties, previous weed management practices, and expected costs and returns. However, standardised procedures for selection of herbicide rates based on multiple factors are typically difficult to find.

The success of VRT herbicide applications has also suffered because current sensing technology is unable to address many of the variables that affect weed infestation controllability. Remote sensing has been widely explored for locating weeds in crops based on the strengthened vegetative spectral response over areas of excessive weed biomass (Thorp & Tian, 2004). In addition, machine vision technology has been implemented to detect weeds based on spatial and spectral properties of weed patches (Tian *et al.*, 1999). These sensing technologies are limited because only one variable, usually the reflectance of radiant energy, is used to measure the extent of weed infestation over an area. Assuming that a weed infested area has a stronger vegetative spectral response than a non-infested area, spectral reflectance is certainly related to the level of weed infestation; however, it may not fully describe the significance of the weed infestation condition in terms of the amount of herbicide necessary for adequate weed control. Since a variety of other factors, such as weed species and height, also influence the herbicide dosage required to control a specific weed infestation condition, the potential for failure in VRT herbicide applications exists in the instance that herbicide rates are improperly assigned based on the values generated in a weed sensing procedure. Therefore, further exploration is necessary to establish a link between weed infestations, sensing results, and required herbicide dosages, such that optimum rate scenarios can be developed for VRT applications.

Though improvements in VRT herbicide technology are necessary, the benefits of the practice have already been demonstrated. Many studies have shown that, using VRT technology, herbicide usage can be significantly reduced with no decline in weed control (Shearer & Jones, 1991; Thompson *et al.*, 1991; Stafford & Miller, 1993; Brown & Steckler, 1995; Gerhards *et al.*, 1997; Hanks & Beck, 1998; Tian *et al.*, 1999; Wartenberg & Dammer, 2001; Thorp, 2002). The net economic gains of the practice have also been shown in the research of Medlin and Shaw (2000). They predicted net gains of the order of $100 per hectare when using VRT herbicide applications instead of broadcast applications in soya beans (*Glycine max* (L.) Merr.), although the costs associated with data sampling and VRT equipment were not included in their calculations. Ecological benefits can be measured by the percent of field area that receives no herbicide treatment. In the research of Timmermann *et al.* (2001), large areas of fields managed by VRT practices often remained unsprayed for several years. Given the success of the practice so far, VRT weed control is certainly a potential solution for growers in the European countries, Denmark, Sweden, and the Netherlands, that have mandated restrictions in pesticide use per ha (Timmermann *et al.*, 2001).

2. Objective

Since no standard procedure currently exists to define rate scenarios for VRT herbicide applications, the objective of this experiment was to judge the performance of an arbitrary rate scenario and make recommendations for improvement of scenario development strategies. Variable-rate herbicide treatments were made in a soya bean plot using a weed map developed from remote sensing imagery. The representative herbicide, glyphosate, was used at 100, 67 and 33% of the recommended label rate, and the 100% rate was assigned an herbicide dose of 1·29 k of the acid equivalent of active ingredient per hectare (kg [ae] ha^{-1}). To achieve the rate reductions, a standard boom sprayer was equipped with pulse width modulated nozzle valves and a 30-channel control system. In this way, the volume of herbicide mix flowing from individual nozzles could be modulated while the concentration of herbicide in the system remained unchanged. Low, medium, and high levels of weed infestation were determined from an analysis of airborne remote sensing imagery. Ground-based digital images were collected and used as a reference for remote sensing image processing. These reference images were segmented to determine the percent weed cover at various locations, and weed cover percentages were used as the criteria to define three levels of weed infestation in the remote sensing image analysis. Three ranges of weed cover percentages, 0–35%, 35–59% and 59–100%, were chosen arbitrarily to represent low, medium, and high levels of weed infestation, respectively. Thus the rate scenario, selected arbitrarily for testing in this VRT herbicide experiment, can be summarised as shown in Table 1.

Table 1
The rate scenario selected for testing in this experiment

Rate scenario		*Percent of full rate, %*	*Herbicide dose, kg [ae] ha^{-1}*	*Selection criteria, % weed cover*
1	Low (L)	33	0·43	0 – 35
2	Medium (M)	67	0·86	35 – 59
3	High (H)	100	1·29	59 – 100

3. Theoretical considerations

Theoretically, for a three-rate VRT application scenario to most efficiently and effectively control weeds, various relationships between spray rates and weed infestation conditions must be satisfied, as summarised in Table 2. To explain, over areas of low weed infestation, all three spray rates should each provide adequate weed control. If this is true, herbicide use efficiency will decrease when the medium and high rates are used, because adequate weed control can be achieved with the low rate. On the other hand, over areas of high-weed infestation, adequate weed control should only be obtained when using the high rate, and a decline in weed control should be seen when using the low or medium rates over these areas. In this way, it is shown that the high rate is the minimum requirement over areas of high-weed infestation. Over areas of medium weed infestation, the low rate should not provide adequate weed control while the high rate should prove to be inefficient. If these criteria are shown to be true, the VRT scenario is subsequently shown to provide adequate weed control more efficiently than applying any of the three rates as a blanket application. On the other hand, if these criteria are not met, several options for VRT scenario optimisation can be explored. Clearly, the herbicide dosage assigned to each rate is an important component of the VRT scenario. Knowledge of the minimum dose required to control the most severe weed infestation in the field is therefore helpful for properly setting the herbicide dose for the 100% rate. A current procedure for obtaining this information involves a sighting application in the area of the greatest weed infestation. However, such a procedure is highly impractical for VRT scenario development, because the weed threat in the field will change while the results of the sighting application are being generated. After setting the dosage for the full rate, assignment of the dosages for lower rates depends on the variability of weed infestation conditions within the field. If a large variability exists, the use of several rates that cover a wide range of herbicide doses is warranted. On the other hand, if the variability is small, an on-off scenario or a two-rate scenario is perhaps the best choice. Ultimately, accurate measurement of weed infestation variability depends on the ability of a sensing system to delineate weed infestations according to the level of herbicide required for adequate control. Because of the limitations in current sensing technology, such measurements are difficult to make with accuracy, and this has hampered the development of theoretically sound rate scenarios for VRT applications.

Table 2
Given the proper scenario for a variable-rate technology (VRT) application of three rates, the following relationships, in terms of herbicide use efficiency and weed control effectiveness, theoretically exist between spray rates and weed infestation

Spray rate	*Weed infestation*	*Weed control*	*Herbicide use efficiency*
Low	Low	Adequate	Adequate
	Medium	Reduced	Adequate
	High	Reduced	Adequate
Medium	Low	Adequate	Reduced
	Medium	Adequate	Adequate
	High	Reduced	Adequate
High	Low	Adequate	Reduced
	Medium	Adequate	Reduced
	High	Adequate	Adequate

4. Materials and methods

The experiment took place in a 2·8 ha plot on the University of Illinois Agricultural Engineering Farm south of Urbana, Illinois, USA, shown in *Fig. 1*. Geographic coordinates for the centre of the plot are 88·214455212°W and 40·070524948°N. On June 9, 2002, glyphosate-tolerant soyabeans were planted at a 76 cm spacing in cultivated soil. No pre-emergence herbicide was used at the time of planting, and weeds were allowed to grow freely for one month. The plot layout for the experiment involved a randomised complete block design with four treatments per block. The blocks were replicated four times across the length of the field

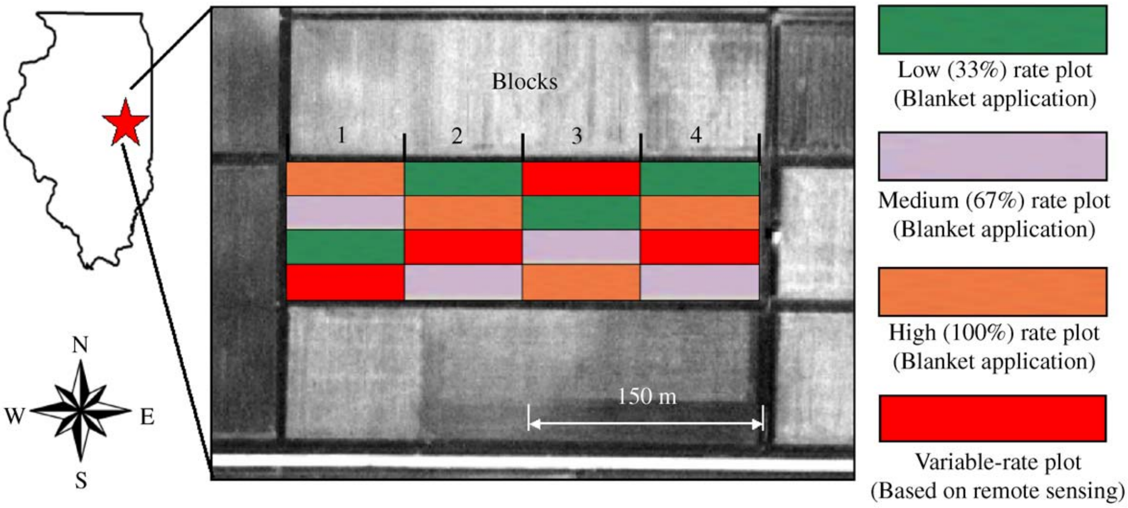

Fig. 1. Study site and experimental design

as shown in *Fig. 1*. Within each experimental block, four herbicide treatments were tested. The first treatment involved a remote sensing-based VRT application using the rate scenario summarised in Table 1. The remaining three treatments utilised the three rates from the VRT scenario to make blanket applications over separate plots. In this way, the effectiveness of each rate could be determined independent of the weed infestation condition. Ground reference data was collected on July 8, 2002 and July 10, 2002 at 95 locations across the plot area. At each of these ground reference locations, weeds within an area of 1 m^2 were counted according to species. In addition, a digital photograph of each location was collected such that the weed cover percentage at each location could be generated through image processing. On July 11, 2002, a 120-band hyperspectral image at a spatial resolution of 1 m was collected over the plot using the hyperspectral scanner developed by Mao (2000). The scanner collected spectral information from 472 to 826 nm with a 3 nm bandwidth. With a procedure involving principle component analysis, vegetation indices, and supervised classification methods, this imagery was used in the development of a weed map for VRT applications. A map-based, VRT herbicide application system (Thorp, 2002) was then used to complete an application of glyphosate (Roundup Ultra Max) on July 13, 2002. To measure the effectiveness of the herbicide treatments, weed counts were recollected at each of the 95 ground reference locations on July 23, 2002, approximately one and a half weeks after applying the herbicide.

4.1. *Collection and processing of ground reference data*

Ground reference data describing the extent of weed infestation across the field area was collected for two purposes: to serve as training and accuracy assessment datasets for the development of a weed map from remote sensing imagery and to measure the success of the herbicide applications in terms of weed control effectiveness. Locations for ground referencing were selected at 95 points across the 2·8 ha field area using both a random point generator and an image-based approach. First, within each of the 16 treatment plots, five locations were chosen at random using a random point generator script within a geographic information system (GIS). Therefore, each treatment plot was guaranteed to contain at least five ground reference measurements for a total of 80 random locations. The remaining 15 ground reference locations were selected based on a hyperspectral image acquired on June 30, 2002. The imagery collected on this date was beginning to show the areas of the field that were developing higher and lower levels of weed cover. After preprocessing steps were completed on this imagery, five locations, believed to represent each of the three weed cover classes, were selected from the imagery as points for additional ground reference data collection. By including this image-based selection approach in the data collection procedure, the ground reference dataset was sure to span the full extent of weed infestation in the field.

On July 8, 2002, weeds were counted according to species within an area of 1 m^2 at each ground reference point. Results of the weed counts indicated that velvetleaf (*Abutilon theophrasti* Medik.), common lambsquarters (*Chenopodium album* L.), common cocklebur (*Xanthium strumarium* L.), ivy-leaf morning glory (*Ipomoea hederacea* Jacq.), carpetweed (*Mollugo verticillata* L.), giant foxtail (*Setaria faberi* Herrm.), common purslane (*Portulaca oleracea* L.), jimsonweed (*Datura stramonium* L.), common ragweed (*Ambrosia artemisiifolia* L.), and a variety of pigweed (*Amaranthus* L.) species were present to a varying degree across the field area. After the herbicide applications were made, weeds were counted again on July 23, 2002, to determine the weed control effectiveness of each herbicide treatment. For this experiment, weed control effectiveness was defined as the percentage of weeds killed by a given treatment. Unfortunately, this is an overly simplistic measure, because glyphosate can control some species of weeds more easily than others. According to label recommendations for the herbicide, ivy-leaf morning glory and common purslane are relatively difficult weeds for glyphosate to control while common cocklebur and giant foxtail are more easily controlled. Therefore, in addition to the rate of herbicide sprayed over an area, the percent of weeds killed by an herbicide treatment also depends on the species of weeds in that area. As a result, comparisons of the treatment effectiveness can be misleading if the weed species in one plot are more difficult to control than the weed species in another plot. This issue was difficult to address in this experiment, because the sensing equipment was unable to separate weeds according to their species.

Prior to spraying, digital images of the field condition were taken at each of the ground reference locations on July 10, 2002. Examples of the ground-based images collected over areas of high and low weed cover can be found in *Figs 2*(*a*) and *2*(*b*), respectively. Also, *Fig. 2*(*c*) shows a general view of the weed infestation condition in the field at the time of spraying. After collecting the ground-based images, each was processed, using a commercial image processing software package, to determine the vegetation cover and the weed cover percentages at each ground reference location. Images showing the vegetation cover and weed cover processing

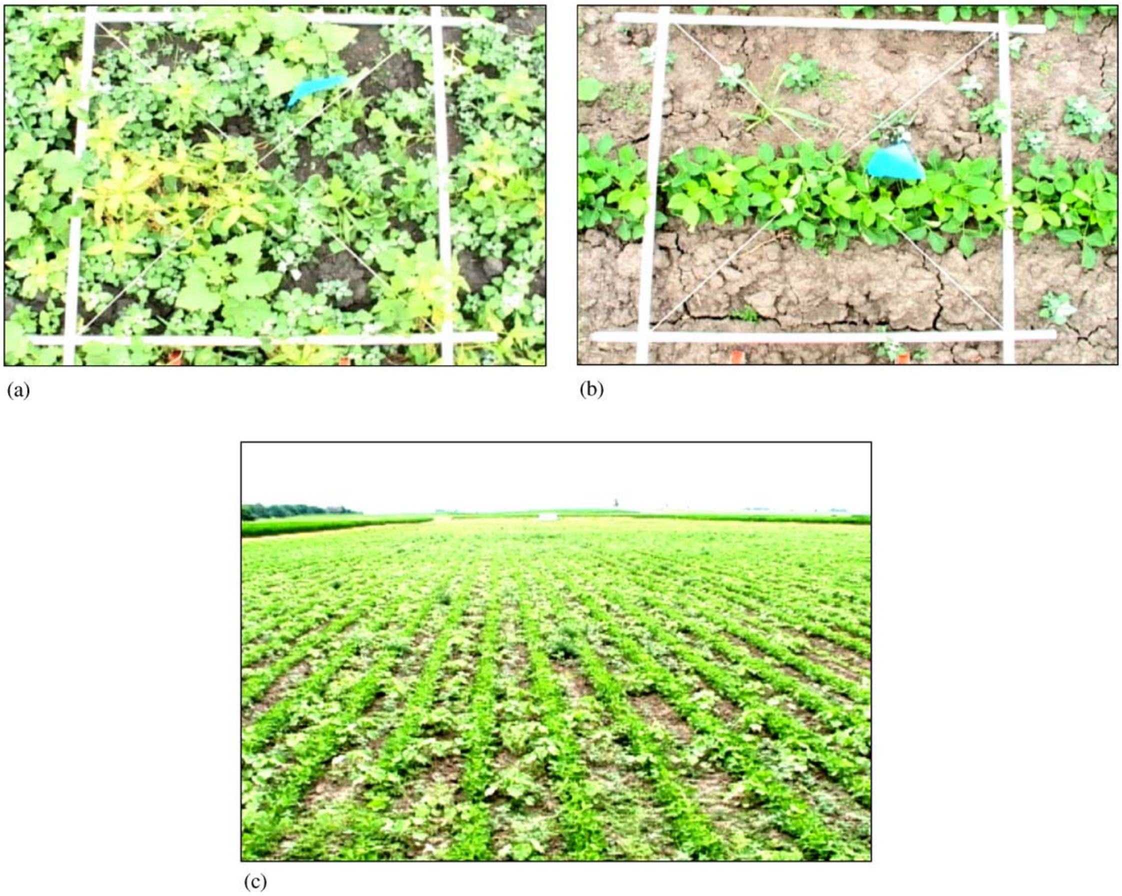

Fig. 2. Field conditions at the time of the experiment; weed cover (July 10, 2002) across the field varied from (a) very high to (b) very low, but (c) weeds were present to some degree across nearly all of the field area

procedures can be found in *Fig. 3*. First, since the apparent size of the quadrat in each image, shown in *Fig. 3(a)*, could vary depending on the camera orientation, a region of interest was drawn for each of the 95 images by creating a polygon that spanned the area inside the measurement tool. In this fashion, the results of the remaining processing steps could be normalised to the known 1 m^2 area. Next, the colour image segmentation function of the software was implemented to separate vegetation from soil within the region of interest for each image. By adjusting the hue, saturation, and intensity (HSI) colour ranges specific for each image, a reasonable estimate of vegetation cover was generated by dividing the number of pixels marked as vegetation by the total number of pixels within the area of interest, as shown in *Fig. 3(b)*. To generate an estimate for weed cover, crop rows within the images were coloured out with a neutral colour prior to image segmentation as shown in *Fig. 3(c)*. This step insured that crop vegetation would not be counted in the calculation of weed cover estimates, shown in *Fig. 3(d)*. The weed and vegetation cover information extracted from the ground-based images was then used for training and accuracy assessment of the remote sensing data classifier.

4.2. *Weed map development from hyperspectral remote sensing imagery*

Aerial hyperspectral imagery collected on July 11, 2002 was used to develop a weed map. Initial preprocessing steps included distortion removal, georectification, noise removal, and calibration. Spatial distortion in raw hyperspectral images of this type can be produced by roll, pitch, and yaw of the aircraft during the scanner-based image collection process. Some of this distortion was removed using the hyperspectral image straightening program developed by Yao *et al.* (2001). Georectification of the imagery was performed using the field boundary coordinates as a reference. Given the small field size and the lack of significant spatial distortion in the raw imagery, georectification was accomplished with

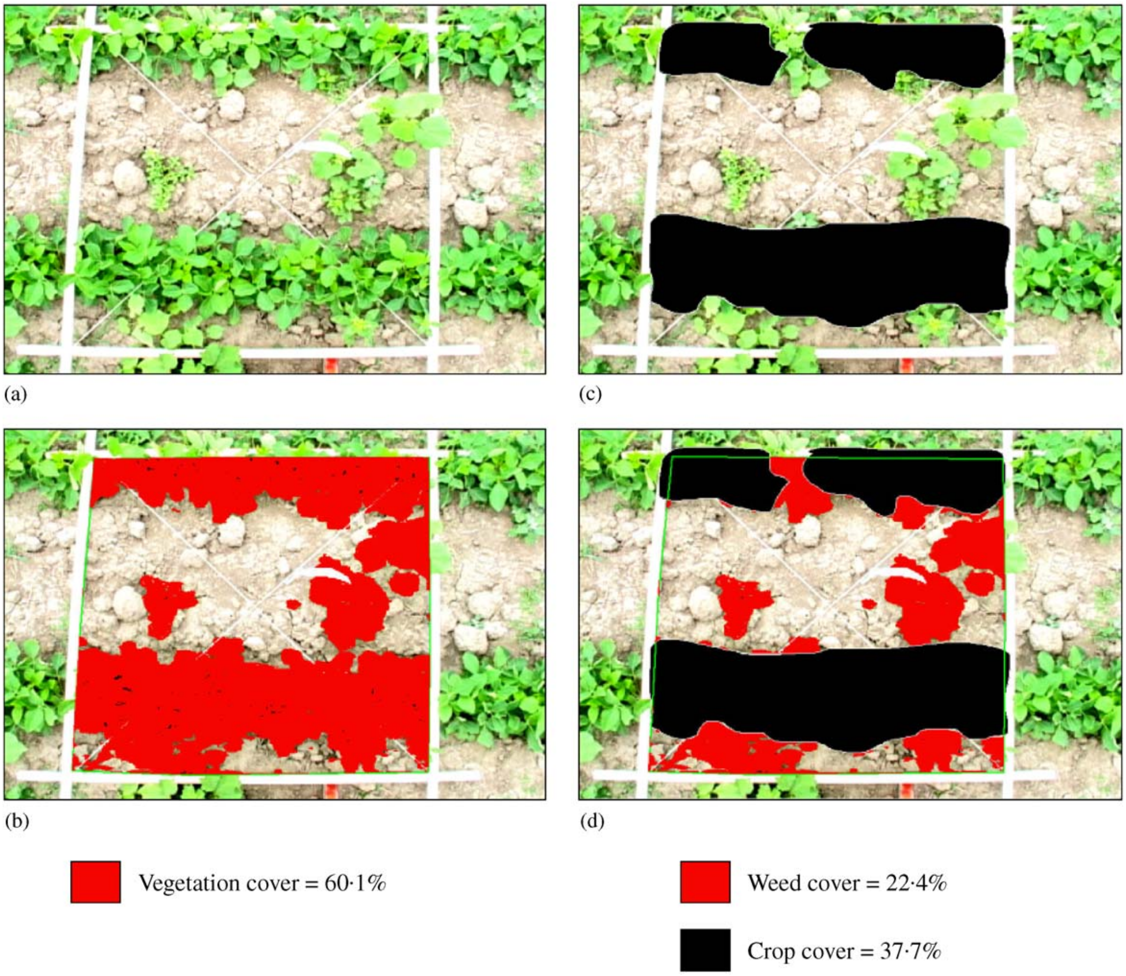
(a) (c) (b) (d)

Fig. 3. Ground-based image processing; (a) ground-based images (July 10, 2002) were processed to generate estimates for (b) percent vegetation cover, (c) percent crop cover, and (d) percent weed cover at each ground reference location; since the separation of weeds from crop is difficult at this time, crop was removed from the images by manually colouring them with a neutral colour

relatively low root mean square errors. Next, a minimum noise fraction (MNF) transformation (Green *et al*., 1988) was implemented to remove sensor noise from the raw spectral information. A dark current image was used to generate the noise statistics for this calculation. Finally, the imagery was calibrated using an empirical line calibration routine (Smith & Milton, 1999). In the hours prior to image collection, three standard reflectance panels were placed near the field of interest, and the reflectance of each was measured with a handheld spectrometer. Outdoor lighting conditions on this day were stable, and any variation in lighting between the time of ground-based spectral measurements and aerial remote sensing data collection was assumed to be negligible. Using the measured spectral response of the reflectance panels, the raw spectral information in the hyperspectral imagery was then calibrated to percent reflectance.

After the initial pre-processing steps were complete, a procedure similar to the one described in Thorp (2002) was used to develop a weed map from the hyperspectral imagery. First, a principle component (PC) analysis was performed to reduce the dimensionality of the hyperspectral data. The PC-transformed spectral data was then extracted from the imagery and correlated to the measurements of percent vegetation coverage at each ground reference location. Results of this correlation indicated that PC band 2 was most highly correlated to vegetation cover with a coefficient of 0·80. Correlation coefficients for all other PC bands were less than 0·15, indicating that PC band 2 most accurately represented vegetation cover in the scene. Vegetation indices were used to generate additional bands having a high sensitivity to vegetation cover. A variety of narrow-band vegetation indices, developed by Thorp (2002), were applied to the calibrated hyperspectral remote

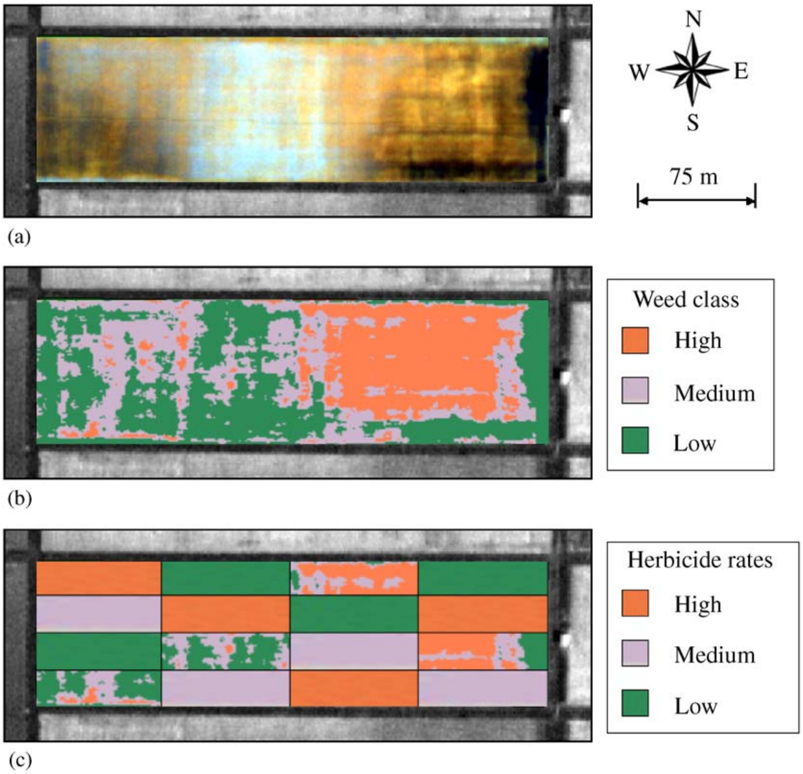

Fig. 4. Weed map development. With a procedure involving a principle component analysis, vegetation indices, hyperspectral derivative methods, and a Mahalanobis distance supervised classification, an (a) 120-band, calibrated, 1·0 m hyperspectral image (July 11, 2002) was (b) classified according to three levels of weed infestation. The classification result was (c) further modified such that the herbicide application would support the experimental design shown in Fig. 1

sensing image, shown in *Fig. 4(a)*. To test their performance, the index values at each of the ground reference locations were extracted from the imagery and correlated to the measurements of vegetation cover at those locations. Results indicated that a narrow-band index based on the normalised difference vegetation index (NDVI) performed the best with a coefficient of 0·78. Derivative methods were used in the generation of a third vegetation-sensitive band for weed map development. Thorp (2002) determined the wavelengths near the red edge whose derivatives were most highly correlated to vegetation cover, and equations developed by Philpot (1991) were used to calculate first and second derivatives at those wavelengths. Derivative values were then correlated to vegetation cover at the ground reference points. Results indicated that the first and second derivative calculations had correlation coefficients of 0·78 and 0·76, respectively. Therefore, the first derivative image band along with the PC band 2 and the narrow-band NDVI were used as vegetation-sensitive bands for weed map development.

After combining the PC band 2, the narrow-band NDVI, and the first derivative image band together as a three-band image, supervised classification procedures were used to break the data into three weed classes. First, the percent weed cover reference dataset was divided in half, such that a training dataset and an accuracy assessment dataset were available for the supervised classification. The training dataset was then broken into three weed classes, such that the percent cover values ranged from 0 to 35% for the low weed class, 35–59% for the medium weed class, and 59–100% for the high weed class. These ranges were chosen by judging, through a visual inspection of ground images, which of the three herbicide rates would most probably be required for adequate weed control at each of the ground reference locations. The three-band image was then classified using the Mahalanobis distance supervised classification algorithm within a commercial image processing software package. Class values were extracted from the classification result at the location of the accuracy assessment data points, and an analysis of the classification accuracy was performed. The overall classification accuracy was 66%. The image classification generated for use as a weed map is shown in *Fig. 4(b)*. However, this weed map was used to apply herbicide only over the plots marked for the remote sensing-based, VRT treatment, as shown in the experimental design in *Fig. 1*. The rest of the treatment plots received blanket applications, and these blanket applications were made using the three herbicide rates used in the VRT application treatment. For this reason, the final weed map was modified to account for the plots that would receive the blanket applications. These modifications are shown in *Fig. 4*(*c*).

4.3. *Application of herbicide*

When all the preparations for the herbicide application experiment were complete, the weed threat within the field had become severe, especially in the areas where the map had called for the high application rate. Since the weed infestation condition was quite heavy, the full rate of glyphosate was selected, according to label recommendations, to be 1·29 kg [ae] ha^{-1}. This meant that the 67% rate was applied at 0·86 kg [ae] ha^{-1} and the 33% rate was 0·43 kg [ae] ha^{-1}. Herbicide was prepared in a tank mix with water such that the application rate for the full rate was 187·1 $l\,ha^{-1}$. This corresponded to a 125·2 $l\,ha^{-1}$ application rate for the 67% rate and a 61·7 $l\,ha^{-1}$ application rate for the 33% rate. Herbicide was applied based on the modified VRT application map on the evening of July 13, 2002 using the map-based, VRT herbicide application system developed by Thorp (2002).

The vehicle used for herbicide applications was a Tyler Patriot XL-772 agricultural sprayer. A Trimble AgGPS 132 receiver was incorporated for global positioning, and two optical encoders were used for measurement of vehicle speed. For pressure control, the Synchro® Pressure Control Module was retrofitted to the sprayer for the ability to maintain a constant system pressure, 276 kPa, in response to flow changes during VRT applications. The pressure system used a feedback signal to operate a butterfly flow valve in the main line based on the measurements from a downstream pressure transducer. To vary the application rate, 29 solenoid nozzle valves were attached to nozzle bodies at a 76 cm spacing along the sprayer boom. Two Tern TinyDrive 16-bit C/C++ controllers, each with 15 channels, were used to independently control the flow output from each of the 29 nozzles by operating the solenoid valves with pulse width modulation. Solenoids were operated on a 10 Hz duty cycle. Since the nozzles were controlled individually on this system, TeeJet DG9503EVS nozzles tips, a banding nozzle offering drift guard and an even flat-fan spray pattern, were selected for spray administration. A decision algorithm with incorporated user interface was developed in Microsoft Visual C++ 6·0 to operate the system, and processing was accomplished using a desktop computer with a 233 MHz Pentium® II processor and 384 MB of random access memory.

Since the nozzles were controlled individually, the spatial resolution capability of the sprayer across the width of the boom was equal to the width of one nozzle fan, or 0·76 m. Also, the processing loop was operated at 5 Hz, so at a forward travel speed of approximately 4·83 km h^{-1}, the spatial resolution capability of the sprayer in the direction of travel was approximately 0·26 m. Thus, the system was designed such that VRT applications could be made using prescription maps of 1 m spatial resolution. By using pulse width modulation to operate solenoid nozzle valves, the dose capability for the spray system ranged from 10 to 100% of the full application rate with a dose resolution of 2% of the full rate. Below the 10% duty cycle, the system could not produce an adequate spray pattern. System testing showed that the algorithm for map-based applications functioned correctly, but the herbicide delivery accuracy was affected in the spatial realm by GPS positioning errors and in the dose realm by inaccurate measurements of vehicle speed. The latter was attributed to the inability of wheel encoders to account for wheel slip. Although errors in herbicide delivery volume were noticed, a VRT field test prior to the one presented here showed that these errors were not greater than 9% (Thorp, 2002).

5. Results

Weed counts collected before and after the herbicide application were used in the generation of experimental results. However, some difficulty arose in the collection of the post-application weed counts, which subjected the accuracy of the dataset to some uncertainty. During the post-application weed counting procedure, difficulty arose in judging whether or not a weed was adequately controlled. To explain, most weeds present at the time of post-application ground referencing were controlled to some variable degree, but many of them were not completely dead. Therefore, error in human judgment was certainly introduced in determining whether a weed was 'dead enough'. Further exploration is necessary to determine the precise point at which a controlled weed no longer proposes a threat to the crop.

5.1. *Contrast of variable-rate technology and conventional methods*

To compare the performance of the VRT application to that of the three blanket applications, weed counts collected before and after the applications were used to analyse the ability of each treatment to remove weed threat. In addition, the volume of herbicide used for each treatment was measured against that used in the full-rate blanket application to establish a value for herbicide savings. To calculate the herbicide savings for the VRT treatments, the percent of field area covered by each of the three rates was calculated from the application map. A summary of the weed counts, weed kill effectiveness, and herbicide savings calculations are presented in Table 3. Weed kill effectiveness was defined as the percentage of weeds killed by each herbicide treatment, although this measure can be misleading because glyphosate controls some species of weeds easier than other species. To address this problem, weed kill effectiveness was also calculated according to weed species for each of the four treatments. The results of these calculations, shown in Table 4, indicate that the performance of herbicide applications did indeed depend on weed species. For instance, common cocklebur and giant foxtail were successfully controlled by all herbicide treatments while every treatment had difficulty controlling ivy-leaf morning glory and common purslane. Label recommendations confirm that the former weeds are quite easy for glyphosate to control, while the latter weeds are more difficult to control with glyphosate. In addition, because of the creeping nature of morning glory and purslane, lack of effective control was also caused by the inability of the applicator to introduce herbicide beneath upper layer of the canopy. For this reason, a second calculation of weed kill percentage was made for each herbicide treatment without using the weed counts for morning glory and purslane, and these results are included with the original weed kill calculations in Table 3. Since all the treatments were unable to adequately control these weed species, removing their counts from the kill effectiveness

Table 3
Summary of the herbicide treatments, herbicide savings, weed counts, and kill effectiveness for each experimental unit: H, high rate; M, medium rate; L, low rate; VRT, variable-rate technology

Block treatment rate	*1*				*2*				*3*				*4*			
	1	*2*	*3*	*4*	*1*	*2*	*3*	*4*	*1*	*2*	*3*	*4*	*1*	*2*	*3*	*4*
	H	*M*	*L*	*VRT*	*L*	*H*	*VRT*	*M*	*VRT*	*L*	*M*	*H*	*L*	*H*	*VRT*	*M*
% Area low rate	0	0	100	56	100	0	57	0	3	100	0	0	100	0	19	0
% Area med. rate	0	100	0	37	0	0	41	100	28	0	100	0	0	0	28	100
% Area high rate	100	0	0	7	0	100	2	0	69	0	0	100	0	100	53	0
Weed count pre-spray	139	203	159	126	285	320	177	160	680	700	561	349	334	254	418	303
Weed count post-spray	20	26	17	16	124	12	72	40	99	584	50	26	178	13	25	36
% Herbicide savings	0	33	67	50	67	0	52	33	11	67	33	0	67	0	22	33
% Weed kill	86	87	89	87	56	96	59	75	85	17	91	93	47	95	94	88
% Kill—less m. glory, purslane	96	89	91	88	62	98	88	95	86	17	93	99	47	97	95	89

Table 4
Herbicide treatment effectiveness in terms of weed kill percentage for each weed species; pre- and post-application weed counts were separated according to the treatment type and the kill percentages were calculated; VRT, variable-rate technology

Weed	*Low rate*			*Medium rate*			*High rate*			*VRT*		
	Weed count		*Kill, %*	*Weed count*		*Kill, %*	*Weed count*		*Kill, %*	*Weed count*		*Kill, %*
	Pre	*Post*		*Pre*	*Post*		*Pre*	*Post*		*Pre*	*Post*	
Velvetleaf	20	20	0	71	4	94	40	0	100	21	1	95
Common lambs-quarter	1116	744	33	889	83	91	640	17	97	1056	116	89
Common cocklebur	24	0	100	4	0	100	18	0	100	55	0	100
Pigweed species	96	10	90	98	3	97	186	3	98	66	7	89
Ivyleaf morning glory	14	14	0	9	8	11	17	14	18	7	7	0
Carpetweed	60	52	13	43	8	81	73	2	97	96	43	55
Giant foxtail	76	0	100	49	3	94	36	0	100	38	4	89
Common purslane	71	62	13	63	43	32	48	35	27	62	34	45
Jimsonweed	0	0	—	0	0	—	3	0	100	0	0	—
Common ragweed	1	1	0	1	0	100	1	0	100	0	0	—
Total	1478	903	39	1227	152	88	1062	71	93	1401	212	85

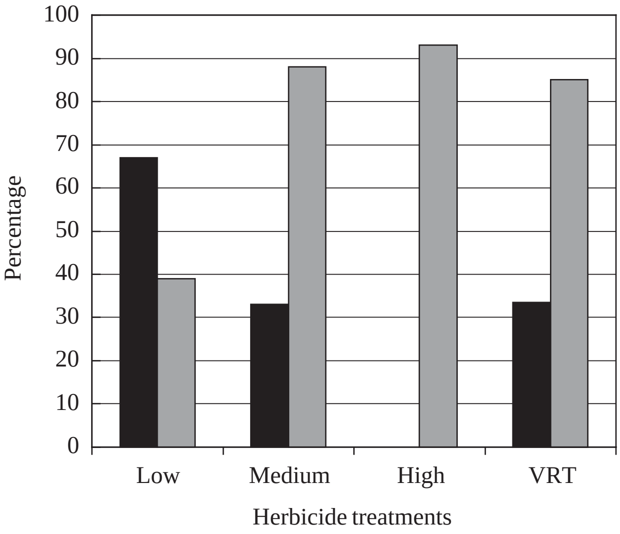

Fig. 5. Overall weed kill effectiveness and herbicide savings; the blanket low rate was ineffective at controlling weeds while the blanket high rate used herbicide inefficiently; the blanket medium rate and variable-rate technology VRT treatments performed nearly identically; ■, *% savings (theoretical);* ▨, *% weed kill*

calculation partially removed the dependence of herbicide treatment performance on weed species. In this way, the results more clearly show the effectiveness of the herbicide treatments in terms of the weed species that glyphosate can effectively control.

For each of the four treatments, the overall percent herbicide savings is plotted along with the overall total weed kill percentage in *Fig. 5*. As expected, a great lack of weed control effectiveness was seen in the plots that received the low rate of glyphosate, 0·43 kg [ae] ha^{-1}, although this treatment reduced herbicide use by 67% of the full rate. Overall, the low treatment was successful in controlling 39% of the weeds present while the other three treatments all achieved a weed control percentage of 85% or better. The plots that received the high rate of glyphosate, 1·29 kg [ae] ha^{-1}, showed the greatest level of weed control with a 93% weed kill effectiveness; however, no herbicide was saved in this treatment. Following closely behind the high rate treatment with an 88% effectiveness overall was the 0·86 kg [ae] ha^{-1} medium rate. Therefore, the 33% increase in applied active ingredient between the medium and high rates only contributed to a 5% increase in weed kill effectiveness, indicating a low herbicide use efficiency for the high rate. This demonstrates the importance of knowing the minimum herbicide dose required to control the most severe weed infestation in the field, such that the full dose in the VRT scenario can be selected without exceeding the minimum required dose. With an overall effectiveness of 85%, the performance of the VRT treatment followed closely behind the medium rate treatment. Results showed that the VRT treatment achieved a 33% savings in herbicide, although this value was dependent mainly on the relative size of the areas assigned to each of the three rates. In a field with a less severe weed threat and a greater area assign to reduced rates, savings from a VRT treatment would be greater.

All calculations of herbicide savings represent the theoretical savings that could be realised with an error-free herbicide applicator. The actual herbicide savings then differs from the theoretical amount depending on the errors associated herbicide applicator functionality. The actual herbicide volume applied over each plot in this experiment was measured by tracking the change in herbicide volume in the spray tank after making each treatment. However, since the treatment areas were relatively small, the changes in the herbicide volume were not great enough to be accurately measured using the graduations on the spray tank measuring tool, and this data is therefore unworthy of presentation. Previous testing of the application equipment over a larger area showed that the error between actual and theoretical herbicide volumes was not greater than 9% (Thorp, 2002). In future experiments, an in-line flow meter will be incorporated in the application system to obtain more accurate measurements of the actual herbicide use.

The results in *Fig. 5* suggest that a blanket application of the low rate does not provide adequate weed control while a blanket application of the high rate represents highly inefficient herbicide use. Since the performance of a blanket application of the medium rate was roughly identical to that of the VRT application, it follows that these two treatments performed relatively well in terms of both weed control effectiveness and herbicide use efficiency. Theoretically then, the VRT application method emerges as the top performing application method since it attempts to maximise herbicide use efficiency in the spatial realm. The remaining analysis therefore focuses specifically on the performance of the rate scenario used for the VRT application in this experiment.

5.2. *Analysis of the variable-rate technology application scenario*

To further explore the VRT scenario used in this experiment, the weed counts collected before and after the herbicide application were divided into nine categories. Since the VRT herbicide map was modified to account for the experimental design, a significant area of the field received an herbicide rate that did not correspond to the rate called for in the original weed map. This is shown in the comparison of *Figs 4(b)* and

4(*c*). Therefore, the performance of each of the three herbicide rates could be analysed for its effectiveness over each of the three weed classes. Since there were three possible herbicide rates (33, 67 and 100%) and three original weed cover classes (0–35%, 35–59% and 59–100%), there existed nine possibilities for the combination of herbicide rates and weed classes within the field. After dividing the 95 ground reference data points according to the nine herbicide-rate/weed-class combinations, the effectiveness of each combination was calculated in terms of the weed kill percentage. The results of these calculations are plotted in *Fig. 6*. As expected, the high rate performed adequately, with a weed kill effectiveness greater than 90%, over all three weed classes. The medium rate also performed well over all three weed classes with weed kill percentages that ranged from 80 to 90%. In particular, the medium rate performed just as well as the high rate over high weed class areas, indicating that the high rate was altogether inefficient and that knowledge of the minimum rate necessary to control the most severe weed infestation would have been helpful in setting the full herbicide dosage for this VRT scenario. Compared to the medium and high rates, the low application rate showed a marginal decline in weed kill effectiveness over all weed classes. Even when the low rate was sprayed over areas of low weed infestation, the weed kill percentage was only 65%, and the effectiveness for the medium and high rates were much greater. This indicated that the low rate was altogether ineffective at controlling weeds. Although the VRT application was shown to be efficient and effective compared to blanket applications, further analysis indicated that the particular variable rate scenario needed optimisation, because the low rate was shown to be ineffective over areas of low weed cover and the high rate was shown to be inefficient over areas of high weed cover.

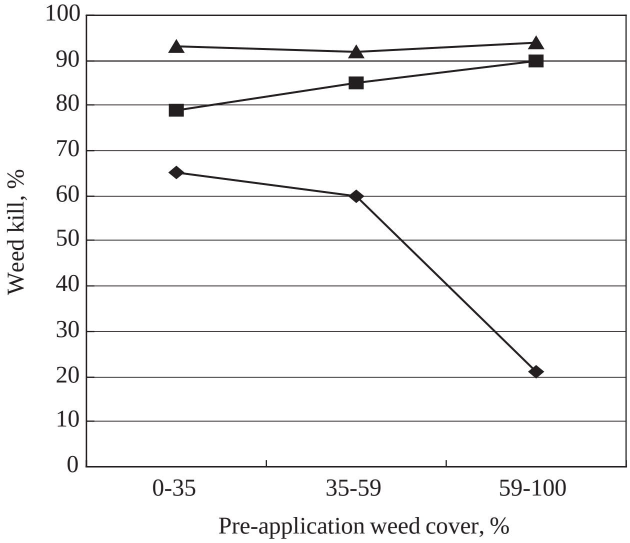

Fig. 6. Weed kill effectiveness of the herbicide rates as applied over each weed cover class; –◆–, sprayed low rate; –■–, sprayed medium rate; –▲–, sprayed high rate

6. Discussion

To improve the VRT scenario, a variety of options exist for adjustment of the parameters that define the scenario. However, since weed composition, height, density, and other important factors vary in time and space, extra care must be exercised when using the results of one VRT herbicide application to define the rate scenario for another application in a different field or a different year. Given a weed infestation condition similar to the one seen in this experiment, the first adjustment to the rate scenario involves the dose of active ingredient used for each rate. Since the high rate proved to use herbicide inefficiently, the herbicide dose for this rate can be lowered in future experiments. Similarly, since the low rate did not control weeds adequately, the low dose can be raised. Another factor affecting the performance of VRT application scenarios is the rate selection criteria. If remote sensing image classifications are used to develop weed maps, there must be ground reference weed information on which the classification is based. As described in this experiment, segmentations of ground-based digital images can generate values for percent weed cover, which can then be used to classify remote sensing images. Percent weed cover measurements are loosely related to the amount of herbicide necessary for controlling weed infestations, but other factors such as weed species, height, and size are more important for determining herbicide rates. Therefore, for rate selection criteria and remote sensing image classification in future experiments, use of weed species, height, and size information in addition to percent weed cover is an important modification to the rate scenario. Other scenario adjustment options involve the selection of rate reduction percentages and the number of rates used. In this research, the lowest and highest of the three rates displayed performance flaws, indicating that the range of rate reduction, from 33 to 100%, was too wide. These results also indicate that the operating range of glyphosate is fairly narrow. To circumvent this problem, a narrowing of the range of rate reduction percentages for the three-rate glyphosate scenario is necessary. As another option, the rate scenario can be simplified to include only two rates. A reduction in the number of rates also facilitates the development of weed maps from remote sensing images by reducing the number of weed classes required. Given the weed infestation condition in this experiment, a VRT scenario that implements more than three application rates most certainly is overdone. Four factors define a VRT application scenario, including the number of rates, the reduction percentages for each rate, the active ingredient dosages, and rate selection criteria. All of these factors are related, and adjustment of one factor can affect decisions on the others. Defining the relationship between these factors will aid in the selection of proper rate scenarios for VRT herbicide applications.

Although weed species and a variety of other factors affect the herbicide rate necessary for adequate control, the methods used in the development of a VRT weed map in this experiment account only for the canopy spectral response and the percent weed cover at select locations. In the development of a rate scenario for this experiment, weed species and size information is incorporated only in the decision for the herbicide dose of the full rate, based on the label recommendation. Other factors, such as weed density, soil types, or economic thresholds, are not considered at all. Most certainly, a variety of unrelated factors affect the rate of herbicide required for adequate control of a particular weed infestation. Development of methods for incorporation of the most important factors into a quantitative measure of 'weed infestation condition' can provide a more precise method for herbicide rate selection, aid in the development of proper VRT application scenarios, and speed the success of VRT herbicide applications.

7. Conclusions

A variable-rate technology (VRT) herbicide application scenario is selected arbitrarily and the performance of the VRT treatments are tested against blanket applications of each rate used in the VRT scenario. A major limitation of this work is that the sensing equipment is unable to detect weed species or weed height information for use in the selection of herbicide rates for variable weed control. Results indicate that blanket applications of the medium and high rates and the VRT application perform similarly in terms of weed kill percentage; however, blanket applications of the low rate do not provide adequate weed control. Also, blanket applications of the high rate are shown to use herbicide inefficiently, because a 33% increase in herbicide use between the medium and high rates only contribute to a 5% increase in weed control. Of the four herbicide treatments, the VRT application performs the best when considering both weed kill effectiveness and herbicide use efficiency. Using weed kill effectiveness in a further analysis of the VRT scenario, the performance of the low rate is shown to be ineffective even over the areas of low weed cover. In addition, the medium rate is shown to perform just as well as the high rate over the areas of high weed cover, indicating a lack of herbicide use efficiency for the high rate. Therefore, even though the VRT herbicide treatment performed well in contrast to blanket applications, further optimisations in the particular rate scenario used in this experiment are necessary to maximise weed control effectiveness and herbicide use efficiency in future VRT applications.

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