Recognition of weeds with image processing and their use with fuzzy logic for precision farming

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[1]*Department of Agricultural and Biosystems Engineering and* [2]*Department of Food Science and Agricultural Chemistry, Macdonald Campus of McGill University, Ste-Anne-de-Bellevue, QC, Canada H9X 3V9.* *Received 18 May 2000; accepted 1 November 2000.*

Yang, C.-C., Prasher, S.O., Landry, J.-A., Perret, J. and Ramaswamy, H.S. 2000. **Recognition of weeds with image processing and their use with fuzzy logic for precision farming.** Can. Agric. Eng. **42**:195-200. Herbicide use can be reduced if the spatial distribution of weeds in the field is taken into account. This paper reports the initial stages of development of an image capture/processing system to detect weeds, as well as a fuzzy logic decision-making system to determine where and how much herbicide to apply in an agricultural field. The system used a commercially available digital camera and a personal computer. In the image processing stage, green objects in each image were identified using a greenness method that compared the red, green, and blue (RGB) intensities. The RGB matrix was reduced to a binary form by applying the following criterion: if the green intensity of a pixel was greater than the red and the blue intensities, then the pixel was assigned a value of one; otherwise the pixel was given a value of zero. The resulting binary matrix was used to compute greenness area for weed coverage, and greenness distribution of weeds (weed patch). The values of weed coverage and weed patch were inputs to the fuzzy logic decision-making system, which used the membership functions to control the herbicide application rate at each location. Simulations showed that a graduated fuzzy strategy could potentially reduce herbicide application by 5 to 24%, and that an on/off strategy resulted in an even greater reduction of 15 to 64%. **Keywords**: precision farming, image processing, fuzzy logic, site-specific herbicide application, weed coverage, weed distribution, weed map.

L'usage d'herbicides peut être réduit si l'on considère la distribution spaciale des mauvaises herbes à l'intérieur du champs. Cet article rend compte des premières étapes dans le développement d'un système d'acquisition/gestion d'images pour la détection des mauvaises herbes, ainsi qu'un système de *fuzzy logic* pour la prise de décisions pour établir l'emplacement et la quantité d'herbicide à appliquer sur un champs agricole. Le système a fait usage d'une caméra digitale et d'un ordinateur personnel. Dans la phase de la gestion d'images, les objets verdâtres dans chaque image ont été identifiés en comparant leurs intensité en rouge, en vert et en bleu. La matrice RBV a été réduite sous une forme binaire d'après les critères suivant: si l'intensité verte d'un pixel dominait sur les intensités rouge ou bleu, le pixel obtenait une valeur de un; sinon le pixel recevait une valeur de zéro. La matrice obtenue a été utilisée pour calculer la surperficie verdâtre attribuable aux mauvaises herbes et la distribution verdâtre des mauvaises herbes. Les valeurs pour la surperficie verdâtre et la distribution verdâtre des mauvaises herbes ont été entrées dans le système de fuzzy logic pour la prise de décisions. Celui-ci a utilisé des fonctions d'appartenance pour controller la quantité et l'emplacement de l'application de l'herbicide. Les simulations ont démontré une réduction de l'ordre de 5 à 24% dans l'application de l'herbicide et qu'une stratie *on/off* a permis une plus grande réduction (15 à 64%) comparativement à la stratégie de *fuzzy logic*.

INTRODUCTION

While herbicides have undoubtedly enabled farmers to increase crop yields by eliminating competition from weeds, these substances have potential to cause damage to the health of humans and other living organisms. Nevertheless, herbicides are still the primary method of weed control in mechanised agriculture (Cousens and Mortimer 1995). Herbicides are considered to be one of the main sources of non-point pollution from agriculture (Mannion 1995; Paice et al. 1996; Smith Jr. et al. 1995).

The quantities of herbicide applied may be reduced using a site-specific precision farming approach (Felton and McCloy 1992; Blackmore 1994; Vangessel et al. 1995; Zanin et al. 1998), rather than the conventional method of applying herbicide uniformly across the field. The proposed method recognises that certain portions of a field may not require herbicide at all or may require a lower application rate than that recommended by the retailer (Zanin et al. 1998). Thus, a priori knowledge of the weed status across the field is required to determine where and how much herbicide to spray. As long as there are areas where the recommended rate is not necessary, the site-specific approach guarantees that less herbicide will be applied to a given field, while continuing to provide the appropriate and needed weed control.

The challenge of the precision approach is to equip the farmer with adequate and affordable information and control technology (Felton and McCloy 1992; Schueller and Wang 1994; Tyler 1993). The basic elements required to operate a precision herbicide sprayer are: 1) a source of information on weed density pattern; and 2) a processing unit to translate the information into commands for the spraying unit. Reasonably inexpensive tractor-mounted cameras can provide real-time imagery at such a scale. The desire to quickly and precisely locate objects in real time has made image processing systems important and essential to precision farming. In precision farming, various kinds of near-infrared and infrared sensors are used to automatically detect weeds in fields (Felton and McCloy 1992; Reetz 1999). However, it is very difficult to process variable inputs to obtain suggested chemical distribution during the planting season, since crops and weeds grow and mingle together, and the colour variation of plants and soils is greater than that of plants and weeds (Blackmer and Schepers 1996). The wavelengths reflected from the surface of weeds and crops are quite similar and cannot be distinguished by sensors in real-time. The solution to this image processing problem could be machine vision (Blackmer and Schepers 1996; Meyer et al. 1998; Tian et al. 1997). Machine vision can be used to detect and distinguish crops and weeds to permit application of different chemicals at specific spots, instead of distributing them everywhere in the field (Blackmer and Schepers 1996). The distinction between crops and weeds can be made with the help of a digital camera. Digital images can be used to measure weed and crop leaf covers (Ngouajio et al. 1998).

The main objective of the research presented in this paper was the development of a methodology for processing digital images taken from cornfields in order to determine a weed map. Based on the weed map, a program was then developed to simulate the control of a herbicide sprayer. Given that information concerning economic thresholds of weed impact on crop productivity cannot easily be adapted to a given region or even to a given farm, it was decided that the fuzzy logic approach to convert image data into sprayer commands should be used. This would essentially allow the farmer to use experience to classify weed status at a given location in the field. Underlying these objectives was the motivation to use a commonly available digital camera and a personal computer. This project was limited to the development of the software and did not involve setting of equipment on a tractor or any other field-testing. Additionally, the existing fuzzy logic controller was limited to the control of one nozzle, but can easily be generalized to control several nozzles emitting different kinds of herbicides when necessary.

MATERIALS and METHODS

The digital images used in the system development were collected in three cornfields of the Macdonald Campus Experimental Farm of McGill University, Ste-Anne-de-Bellevue, southwestern Québec, Canada. Field areas were 3.0, 11.7, and 8.5 ha. The images were taken over the period of May 19 to 30, 1998. These were dates on which herbicide applications for corn production would normally be carried out. A total of 1386 images were taken at randomly chosen sites in the fields.

The most common weeds in the images were velvetleaf (*Abutilon theophrasti* Medic), quack grass (*Agropyron repens* (L.) Nevski), common ragweed (*Ambrosia artemisiifolia* L.), lamb's-quarters (*Chenopodium album* L.), yellow nutsedge (*Cyperus esculentus* L.), field horsetail (*Equisetum arvense* L.), broad-leaved plantain (*Plantago major* L.), and dandelion (*Taraxacum officinale* Weber). Other species included redroot pigweed (*Amaranthus retroflexus* L.), common milkweed (*Asclepias syriaca* L.), barnyard grass (*Echinochloa crusgalli* (L.) Beauv), common mallow (*Malva neglecta* Wallr), and wild buckwheat (*Polygonum convolvulus* L.). The species of corn was *Zea mays*, L.

Images were obtained with a Kodak DC50 zoom camera (Eastman Kodak, Rochester, NY). This camera had a maximum resolution of 756x504 pixels with 24-bit, millions-of-colours, built-in high-quality mode. The built-in internal storage memory was 1 MB, sufficient to store up to 27 to 28 field images compressed in Kodak digital camera format (KDC) in the high-quality mode. The camera was equipped with a 3x zoom lens and a built-in flash with a range of 4.3 m. The auto-focus range was from 0.737 m to infinity and the minimum distance to the object was 0.483 m. The lens' focal length could be adjusted from 0.037 to 0.111 m, the aperture ranged from f/2.5 to f/24, and the shutter speed ranged from 1/16 to 1/500 second. The camera was held perpendicular to the ground at a height of 600 mm. To obtain clear images, it was necessary to zoom in or zoom out depending on the sizes of plants at a given location. Thus, the object field was not constant throughout. Nevertheless, the area of the field covered by an image was kept at approximately 300 mm x 200 mm.

The image processing and weed mapping development was carried out on a PC computer with a Pentium II microprocessor, 4 GB of hard disk space, 128 MB of RAM and the Windows 98 operating system. The image files were 134 to 137 KB in KDC format. The files were 373 KB in size after conversion to bitmap format (BMP). Although the BMP format required more memory, it was supported by many more commercial graphic-processing programs than other formats were. The BMP files were pre-processed with the Image Processing Toolbox v2.1 of MATLAB v5.2.1 for Windows 98, developed by MathWorks, Inc. (MathWorks 1998b, 1998c) and converted to images using the red-green-blue (RGB) colour system. Each pixel of the pre-processed images consisted of three values ranging from zero to one, each value representing the intensities of red, green, and blue. These three intensity coordinates defined the colour of each pixel. Therefore, each image of MxN pixels was represented by a 3-D matrix of size MxNx3.

Since the images were taken in agricultural fields, it was reasonable to assume that "green" pixels, defined as those having a green intensity greater than blue or red intensities, would be parts of plants. Furthermore, since the images were taken so as to exclude corn plants (i.e. before emergence, or between rows after emergence), the green pixels were specifically associated with weeds. This definition of greenness provided the basis for extracting green objects from the digital images. This involved recoding the pixels as "one" for green or "zero" for any other colour, using the MATLAB matrix language programming capability. The weed coverage of each image at location (x,y) was defined as the percentage greenness area of this image.

It was assumed that the weed coverage in a given area between rows would adequately represent the probability that weeds would occur along the rows of that area. It is a fair assumption that weed populations between the corn rows are highly correlated to the occurrence of weeds within the corn rows. Thus, it is possible to estimate the weed populations in the field, both in between the corn rows and also within the corn rows, by collecting images between the rows. Otherwise, methods would have to be developed to differentiate corn plants from weeds in order to calculate the weed coverage. The latter approach would be more tedious and would require longer computational time. Sample images with greenness ratios and the extracted plant objects are shown in Fig. 1.

The decision to spray or not to spray a given area should depend on whether or not weeds are clustered at that location (Zanin et al. 1998). If the area covered by a given image is very small, it is necessary to combine images to determine whether or not there is clustering. This implies that it is necessary to take several images simultaneously to determine the extent of the weed patch at any one location. The weed patch for the image

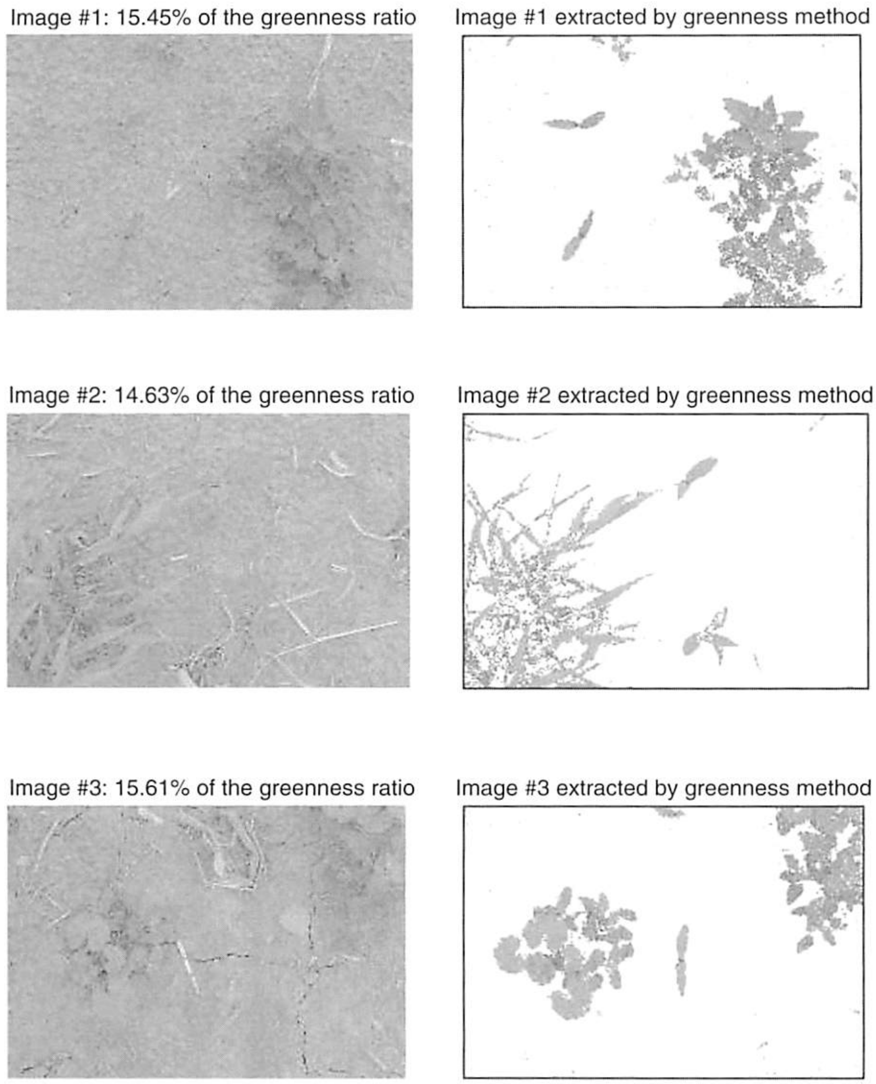

Fig. 1. Some sample images and their greenness ratios determined by the greenness method.

at a location (x,y) was therefore represented by the average greenness of the image at that location and its 8 nearest neighbours. For the real-time application, it is reasonably assumed that the camera will be mounted some distance ahead of the nozzle, so that the image at location (x,y) and those of its 8 neighbours have been collected and the weed patch for the location (x,y) determined before the nozzle passes over the location. When dealing with locations on the field borders, it was necessary to assume that the nearest neighbours outside the border would have high weed coverage because no herbicide would have been previously applied. Although this artificially increased the average greenness of the images taken along the border, these areas would be very likely to be invaded by weeds and should therefore be sprayed.

Table I. Fuzzy rules for site-specific herbicide application model.

		Weed coverage (w_c)		
	Application (a_h)	High	Normal	Low
Weed patch (w_p)	thick	large	large	medium
	average	large	medium	small
	thin	medium	small	small

The Fuzzy Logic Toolbox v2.0 of MATLAB was used to develop the fuzzy logic model for the herbicide application (MathWorks 1998a, 1998c). In this project, a fuzzy logic system was developed to simulate human decision-making in determining herbicide application based on greenness and patch size. There are three components in a fuzzy logic system: fuzzy values for inputs and outputs, a set of fuzzy rules, and fuzzy inference mechanism (Kasabov 1996). In fuzzy inference, several fuzzy membership functions are developed to generate a degree of truth (Heske and Heske 1996; Kasabov 1996; MathWorks 1998a).

It is not easy to develop the membership functions because the weed coverage and weed patch thresholds are very difficult to determine for a given site without experimentation (Hartzler 1997). Indeed, judging from various studies of competition between crops and specific weeds, the economic threshold can very well be dependent on external factors such as weather, management practices, etc. (Lindquist et al. 1999; Scholes et al. 1995; Stoller et al. 1979). Even when some thresholds are known, they can be applied to only certain weed species (Lindquist et al. 1999; Scholes et al. 1995). Moreover, these thresholds are based on the number of weed plants per unit area and thus they are not directly applicable to our method since we deal with the area covered by the plant canopy. In consequence, the threshold in this study was varied arbitrarily from 1 to 5%.

A trial-and-error approach is often used to develop the membership functions for fuzzy logic models. Triangular and trapezoidal functions are the most commonly used, since they reduce development and execution time (Heske and Heske 1996). To simplify things initially, the input membership function was either a triangle or a trapezoid, and the output membership function was a triangle. The fuzzy rules were constructed as shown in Table I. The minimum method was used to combine the degrees from each rule (Kasabov 1996). This method seeks the output that is at a certain level of agreement with all the applicable rules.

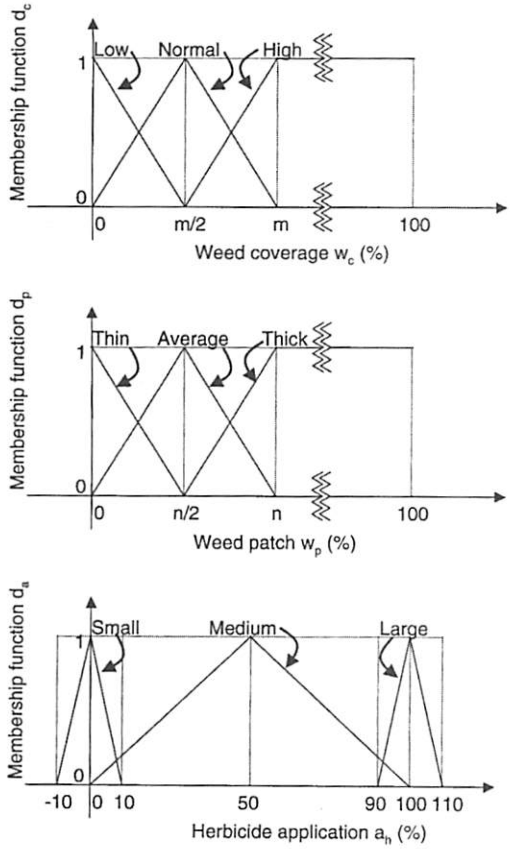

Fig. 2. Fuzzy logic herbicide application model.

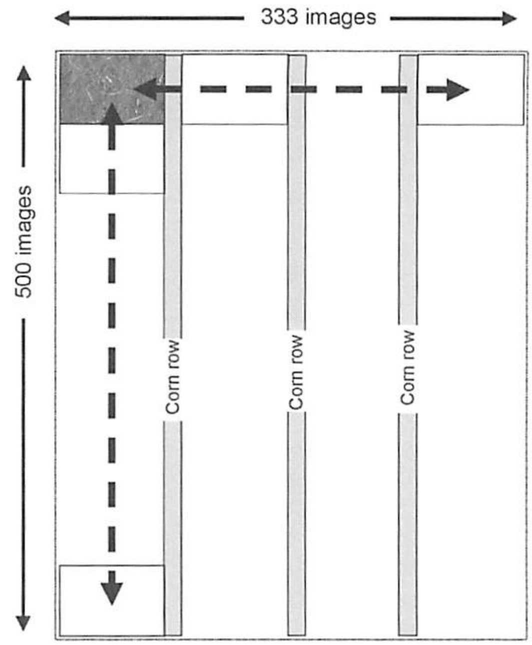

Fig. 3. General design for the hypothetical field based on the field images taken in 1998.

The threshold for weed coverage was selected as m%. The threshold of the weed patch was selected as n%. The degree of the membership function (d_c) for low, normal, and high coverage, as well as the degree of the membership function (d_p) for thin, average, and thick patch were defined in Fig. 2. Three triangular membership functions were built for small, medium, and large applied quantities of herbicide, as shown in Fig. 2. The actual application ranges from 0 to 100%. The negative value for the left bottom of the small application function (−10%) and the greater than 100% value for the right bottom of the large application (110%) were considered only in the calculation to ensure that the lowest application was 0% and the highest was 100%. The centroid (also known as the centre of mass or the centre of moments) method was used for defuzzification. Figure 2 illustrates the membership functions for the fuzzy variable weed coverage, weed patch, and herbicide application rate.

The fuzzy logic herbicide application model was tested on a hypothetical field to determine the potential herbicide savings. The hypothetical field was 1 ha and was constructed from the 1386 images taken in actual fields in 1998. Since each image covered only 0.06 m^2, the images were randomly assigned repeatedly to fill 166,500 cells representing the 1 ha. The general design of the hypothetical field and the arrangement of random images are shown in Fig. 3. The weed coverage and weed patch for each location were used as inputs to the fuzzy controller in order to obtain the herbicide application for every row in each location. The output ranged from zero (representing no application) to one (representing the full application). It was assumed that when weed coverage and weed patch were higher than their respective thresholds, the application output would be at the maximum; otherwise, the application would be less than the full application. After the simulation, the difference between the site-specific application and the full application was calculated to determine the simulated saving of the herbicides.

The simulation was repeated for various thresholds of weed coverage and weed patch (ranges were 1 to 5%) to determine the impact of the farmer's perception of the weed threat to the crop. The simulated quantity of herbicide applied by the fuzzy logic controller was also compared to an on/off simulation. In the on/off application, the herbicide was fully applied only when the weed coverage in the image was higher than the threshold (m); otherwise, none was applied. Thus, when the weed coverage was higher than the threshold (m), the applied amount was the same whether the control was by fuzzy rules or by an on/off setting.

RESULTS and DISCUSSIONS

The weed coverage distributions for the original images and for the hypothetical field are given in Table II. This indicates that the randomization resulted in a hypothetical field with similar weed distribution as that in the original images. The green area accounted for slightly over 5% of the hypothetical field, which implied that it would not be necessary to apply herbicides uniformly throughout the farm. For example, if the weed coverage threshold was assumed to be 5% at a given location, then herbicide would have been applied in excess on 63.72% (100% - 36.28%) of the hypothetical field area, if the standard uniform spray had been applied.

The reductions in herbicide use compared to a uniform application for different combinations of weed coverage and weed patch thresholds are listed in Table III. Although the

Table II. Statistics for weed mapping of original images and the simulated field.

Range of greenness ratio w (%)	Original images		Hypothetical field	
	Images	Percentage (%)	Images	Percentage (%)
w > 5%	543	39.18	60 403	36.28
5% ≥ w > 4%	152	10.97	16 902	10.15
4% ≥ w > 3%	193	13.92	23 113	13.88
3% ≥ w > 2%	201	14.50	24 506	14.72
2% ≥ w > 1%	133	9.60	17 326	10.41
1% ≥ w	164	11.83	24 250	14.56
Total	1386	100.00	166 500	100.00
Total greenness area (%)	5.44		5.38	

Table III. Results for reduction in herbicide use (%) by variable-rate application using different threshold values compared to blanket application.

Weed patch threshold	Weed coverage threshold				
	1%	2%	3%	4%	5%
1%	4.86	6.44	8.28	10.33	12.76
2%	5.41	7.32	9.34	11.52	13.91
3%	6.39	8.74	11.38	14.19	16.71
4%	7.80	10.60	13.93	17.43	20.32
5%	9.78	12.82	16.66	20.72	24.03
On/Off application	14.56	24.97	39.69	53.57	63.72

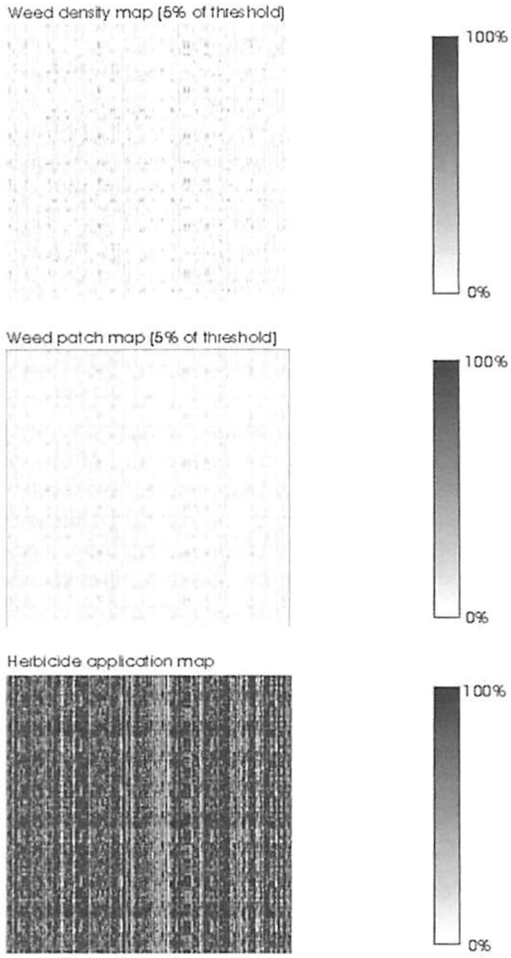

Fig. 4. Simulated herbicide application map on the hypothetical field.

reductions resulting from fuzzy rules (4.86 to 24.03% in the main body of Table III) are far less than those resulting from an on/off strategy (bottom row in Table III), there is less risk of near-future propagation of weeds to beyond the economic threshold. For example, if the weed coverage threshold is 5%, the on/off setting will not treat a location with weed coverage slightly below this value, leaving a high risk of significant competition a few days later. Furthermore, the on-off strategy requires much more accurate models of thresholds, as well as a high degree of precision in image processing and mapping. Given the multitude of factors involved in crop growth in a competitive environment, and that the fuzzy approach provides added insurance, it is unreasonable to depend too stringently on the on/off threshold models.

Once the operation has ended, the data can be kept as a combined file or weed map (Fig. 4), to which the farmer can refer for planning. Farmers can easily create their own maps and find out the locations of high and low weed coverage, draw more concerns on the high weed coverage area, and save more costs on the low weed coverage area. It can help to increase the efficiency of the farming. Approximately 50 minutes were required to determine the greenness ratios of the 1386 original images (2.16 s/image). Only seven minutes were needed to determine the herbicide applications for the 166 500 locations of the one-ha hypothetical farm (40 µs/image).

CONCLUSIONS and RECOMMENDATIONS

The results of this study have shown the feasibility of image capture/processing and fuzzy logic control in the development of a precision farming herbicide application system. Weeds can be located by the greenness method and a fuzzy logic controller automatically manages herbicide applications to obtain effective weed control, reduce costs, and minimize soil and water pollution. The fuzzy logic membership functions are very easy to modify and control instructions can be obtained quickly. These manageable properties are essential to precision farming systems.

In future works, a camera and a computer may be located on the tractor to receive and process the images to control the sprayer in real-time. For a real-time application, assuming tractor or 4-wheel drive vehicle speeds of 2.8 to 5.6 m/s, and an image projection 0.3 m in the forward direction, processing speed would have to be of the order of 0.1 to 0.05 s/image, or at least 20 to 40 times faster than obtained in the Windows 98/MATLAB environment. This could be achieved by running executable files without the Windows environment. The disadvantage of the real-time approach is that the computer must have high-speed image processing capabilities to ensure that the control information is generated synchronously with displacement of the spraying equipment. Thus, aerial photography, satellite imagery, and remote sensing may also be considered. However, the resolution for aerial photography, satellite imagery, and remote sensing should be high enough to satisfy the demand of precision farming. Therefore, the advantage of the real-time approach can be that the global positioning component is not necessary. Furthermore, the plant species in the image should be recognized since different weed species can generate different greenness ratio per plant. Artificial neural networks could be a good choice for image recognition.

The future developments for the fuzzy logic application system should be based on fieldwork. Many fuzzy logic parameters, including function shape, threshold, input and output levels, and function rules, should be tested with many possible alternatives. The ideal situation should be that where the herbicide is saved, the pollution is reduced, and survived weeds do not cause more losses to crop yields afterwards. Also, care should be taken to prevent the development of herbicide resistance of weeds. The crop yields under the fuzzy and full herbicide applications should be investigated and compared in further experiments and evaluations of the fuzzy logic application system.

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