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Yield mapping system for vegetables picked up with a tractor-pulled platform

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Abstract

The aim of this work was to develop a yield mapping system for vegetables. A harvest assistance equipment was modified and instrumented to obtain yield maps. Instrumentation consisted in the implementation of a mass accumulation rate measurement system, which was used to determine weight of harvested broccoli (*Brassica oleracea* var. *italica* Plenck), a sensor of distance travelled to determine harvested area and a Global Positioning System (GPS) to determine position of harvested area within the field. Results found in evaluation purpose tests of the yield mapping system showed an error of less than 2.69% in the weight data and 1.49% in the area data, whereas in yield mapping tests, the system worked properly without interfering with the harvesting methodology employed for field workers. Also, the comparison of yield maps obtained with the two GPSs of different precision, confirmed that the less precise and lower cost GPS can be used to map yield. In the future, the yield mapping system can be used to assess the causes of yield variability and field workers performance.

Additional key words: geo-referenced data, harvest, low cost GPS, precision farming.

Resumen

Sistema de mapeo de rendimiento de cosecha de hortalizas recolectadas con un remolque tirado por tractor

El principal objetivo de este trabajo fue desarrollar un sistema de mapeo de rendimiento para hortalizas. Un equipo de asistencia a la recolección de bróculi ha sido modificado e instrumentado para obtener mapas de rendimiento. Se han instalado y verificado la siguiente instrumentación: sensores de carga para determinación del peso de bróculi cosechado; sensor de distancia recorrida para determinar el área cosechada y sistema de posicionamiento global (GPS) para georreferenciar el área cosechada en campo. Los resultados de las pruebas realizadas para evaluar los montajes y procedimientos de medida mostraron errores inferiores al 2,69% en las mediciones de peso y menores al 1,49% en las mediciones del área. Los resultados obtenidos en las pruebas de verificación de mapeo del rendimiento —localización de sus valores— fueron asimismo satisfactorios. Por último, se valida el uso de un GPS de bajo costo, para mapear la variabilidad del rendimiento de cosecha en campos de hortalizas. En el futuro, el sistema de mapeo de rendimiento puede ser empleado para identificar las causas de variación del rendimiento y el desempeño de los trabajadores en el campo.

Palabras clave adicionales: agricultura de precisión, cosecha, datos georreferenciados, GPS de bajo costo.

Introduction

Precision farming comprises a set of technologies and techniques that allow farm enterprises to improve management by considering spatial variability (Blackmore, 1996). One of these technologies is the yield mapping system. Yield maps have been regarded as the starting point for precision farming (Moore, 1998). It is well known that in order to perform a yield variability study of other sources of variation, broad data registers are required. Yield mapping systems for grains (*Triticum aestivum* L., *Hordeum vulgare* L. and *Zea mays* L.) have been commercially available for over a decade (Pelletier and Upadhyaya, 1999). Also, several systems and methodologies have been developed for non

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combinable crops, including: a non-grain crops yield sensing system developed using the measurement of mass accumulation rate (Godwin and Wheeler, 1997); a sugar beet (*Beta vulgaris* L. var. *saccharifera* Alef*)* yield sensing system based on flow rate, developed in the US (Hofman *et al.,* 1995); a continuous mass flow yield monitor for tomato developed in the US (Pelletier and Upadhyaya, 1999). However, there are many other crops, which have not yet been involved in the concept of 'precision farming'. For the last twenty years the importance of vegetables has increased significantly in Mexico, especially cauliflower (*Brassica oleracea* L. var. *botrytis* L.) and lettuce (*Lactuca sativa* L.). According to SAGARPA (2005), from 2000 to 2002 the annual production has exceeded 500,000 tons worth over 190 million dollars. Particularly, these crops are important in Guanajuato, where the cultivated area with these crops represents more than 50% of the cultivated area with these crops in Mexico, and a high percentage of this production is being exported. This work outlines the general aspects of the design, construction and evaluation of a yield mapping system for vegetables together with an evaluation of the results. Finally the yield mapping system was used to obtain yield maps for broccoli (*Brassica oleracea* var. *italica* Plenck) fields.

The aim of this work was to develop a harvest assistance system, a tractor-pulled platform, employed for picking up vegetables and able to record yield and position data in order to make yield maps for vegetable fields.

Material and Methods

There are three types of harvest assistance machines for vegetables used in Mexico: a tractor-pulled platform operated manually; a harvesting aid self-propelled machine consisting basically of an 18 m conveyor; and a self-propelled machine with a 9 m conveyor and trays for harvesting packaged vegetables. In the harvest assistance system, the vegetables picked up by workers are placed on the platform. In this work, the aid harvesting system was modified by adding four sub-systems and some structures required for the installation of instruments. The four sub-systems were: a weighing system, an area measurement system, a positioning system and a data acquisition system.

Weighing system

To implement a weighing system in the tractor-pulled platform the platform had to be altered. This modification consisted of building a false frame, similar to that suggested by Godwin and Wheeler (1997), mounted on four «S» type load cells (453.6 kg ± 0.05%). Load cells were previously placed on each corner of the main frame of the tow (Fig. 1). Thus, harvested product weight was determined by mass accumulation rate.

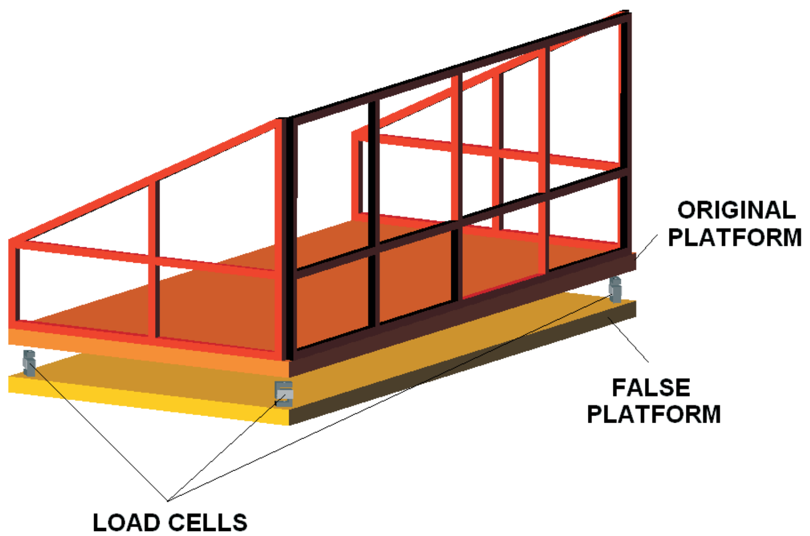

Figure 1. Diagram of the weighing system used under the platform.

Area measurement system

The area was calculated by multiplying the distance travelled and the width of the harvester. The distance travelled was determined by an electronic distance meter installed under the harvesting aid system. The travelled distance meter was built by mounting a drilled disc (36 holes) on a tyre as shown in Fig. 2a. A phototransistor was placed on one side of the drilled disc and a small lamp on the other side (Fig. 2b). When the disc is rolling and holes pass in front of the phototransistor, the photocell is exposed to the light of the lamp, and consequently a pulse is generated. The number of pulses and distance travelled were correlated and distance was measured with an error of 0.57%.

Positioning system

Two GPSs receivers were used to obtain position data. A GPS1000 (AgLeader Technology, Inc., Ames, IA, USA) is accurate to within 4 m (2DRMS) without a differential correction capabilities and GPS4100 (AgLeader Technology, Inc., Ames, IA, USA) is accurate to within 0.5 m with differential correction capabilities by means of a geo-stationary satellite signal. Geo-referenced data from both GPSs were recorded and used to generate yield maps. Yield maps made from GPS1000 data were compared with yield maps made from GPS4100 data. Comparison was made by calculating the size of yield areas and their positions in the field.

Data acquisition system

The data acquisition system was built up from a CIO-DAS16/F board (Measurement Computing Corp., Middleboro, MA, USA) installed in a 200 Mhz processor computer. A two serial port card was added to connect two GPSs. Labtech Notebook 10.1 (Measurement Computing Corp., Middleboro, MA, USA) and a MicrosoftVisual Basic 5.0 (Microsoft Corp.) edited program were used for data processing and recording. Also, Golden Surfer 7.0 was used to produce yield maps.

Data calculated and recorded by the acquisition system

Mass accumulation rate allowed harvested product weight to be calculated for a period of time. Area was calculated and recorded for the same period of time and position data were determined by GPS. Weight and area were used to compute yield data. Data recorded by the yield mapping system were: time, geo-referenced position, GPS quality indicator, satellite number, HDOP (Horizontal Dilution of Precision), weight harvested from 14 m^2, total accumulated weight, distance travelled, area and yield data.

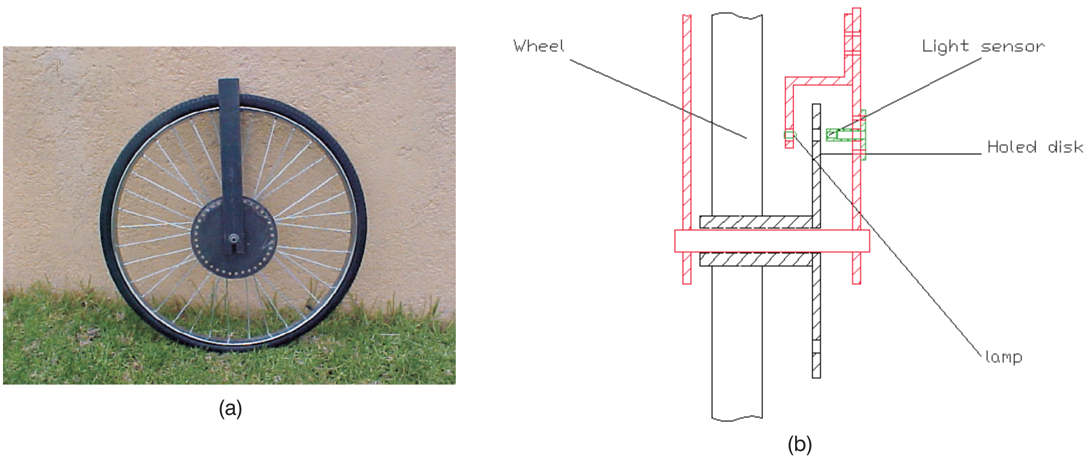

Figure 2. Area measurement system. (a) Distance sensor photo; (b) Distance sensor diagram.

Yield mapping system evaluation

The evaluation was carried out in a field of 42 x 163 m, which was divided into three sections of 14 x 163 m. To test whether the system was working properly it was decided to: 1) compare weights of broccoli harvested obtained by the yield mapping system and weights obtained on an electronic scale; and 2) compare the yield map obtained by using the yield mapping system data and yield map made by using the electronic scale yield data.

Procedure established for validation

The yield sensing system started the harvest followed by seven workers who cut ripened broccoli. Then, the harvested broccoli was placed on the platform of the system. On the tow there were two workers and 60 containers. The harvesting aid system travelled 15 m into the field (while workers harvested seven rows) and then stopped. Harvested broccoli was placed in the containers. The workers on the tow put the broccoli in the containers and also numbered the containers. The number corresponded to an area in the field. Once the containers with broccoli were numbered and placed on the tow, the harvesting aid system travelled another 15 m and the procedure was repeated. Then, the tractor went to the side of the field, where there was an electronic scale. The containers with broccoli were weighed on the electronic scale and then emptied. The emptied containers were weighed. Container and broccoli weight, the weight of emptied containers and the area number were recorded by hand. The emptied containers were then replaced on the platform. The data were registered by hand and later recorded on a calculus spread sheet for processing and analysis.

Map shown in Fig. 3 was made by drawing rectangles that represent areas as they were harvested. The color of each area is a visual classification according to yield (Mg ha^{-1}). Classification was done on a calculus spread sheet and the map was drawn in Surfer 7.0. The map shown in Fig. 4 was made by geo-statistical interpolation of the data by using Surfer 7.0 and general details of the method are described in the Figure.

Yield mapping tests

As can be seen from the evaluation methodology, the harvesting methodology was modified to make it

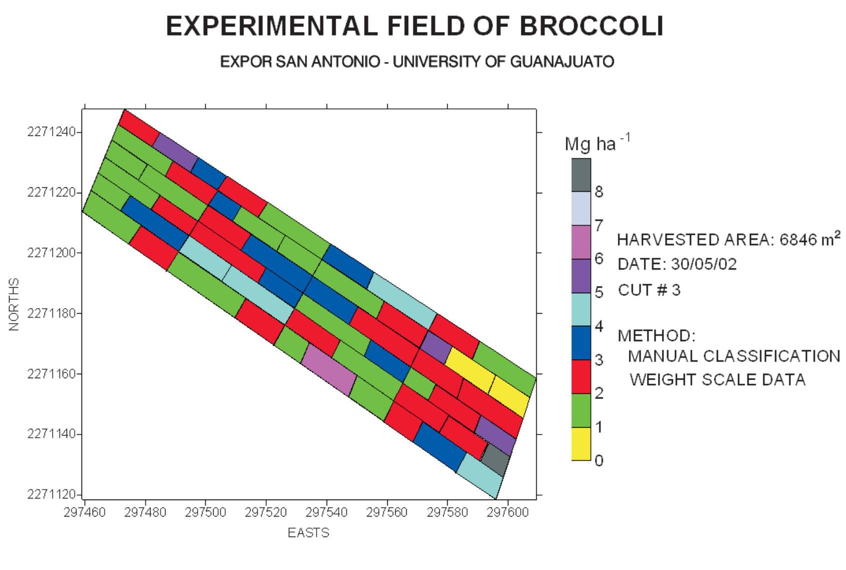

Figure 3. Yield map developed from data collected by manually measuring harvested product weight with an electronic scale.

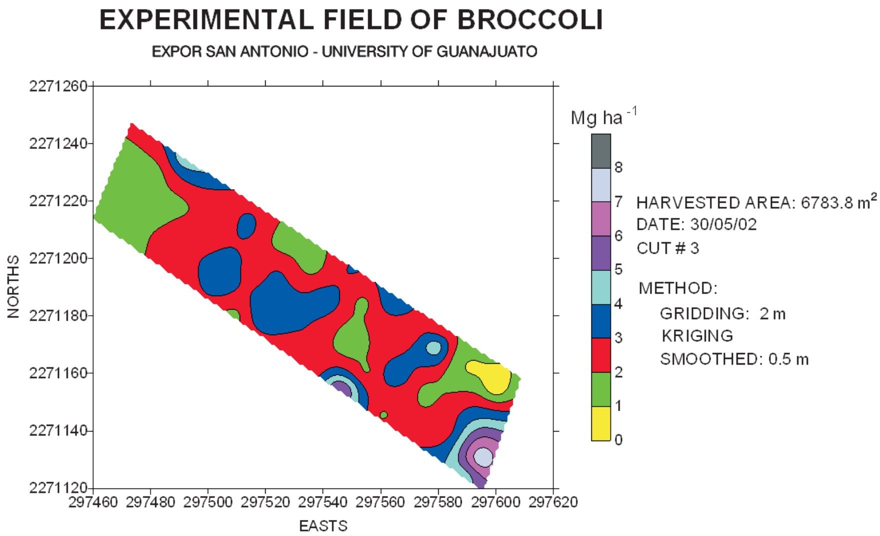

Figure 4. Yield map developed from weight, area and position recorded by the yield mapping system.

possible to evaluate the accuracy of the yield mapping system. So, the yield mapping tests were done to obtain yield maps of broccoli field without changing the harvesting methodology used at the farm.

Total harvested broccoli weight for the day was reported by the enterprise and compared with total harvested broccoli obtained by the yield mapping system. Distance travelled measured by the yield mapping system was compared with the distance measured by using a measuring tape. These tests were done in a 5 ha field but the area mapped was restricted to the maximum area that could be harvested in a journal day for one harvesting aid equipment.

Results

Yield mapping system validation

Tests were done to verify the precision of the yield mapping system. Table 1 shows errors comparing electronic scale data and weights obtained by the yield mapping system. The accuracy of the electronic scale was 0.01 kg. The greatest difference found between electronic scale data and yield mapping system data expressed as percentage of error was 3.76%.

Table 1. Electronic scale weights and yield mapping system weights comparison obtained from data recorded when section three of the experimental field was harvested. The percentage of error was calculated on the basis of electronic scale weights.

Area indicator	Yield mapping data (kg)	Electronic scale data (kg)	Error (%)
1	16.62	16.81	1.10
2	53.87	54.87	1.82
3	45.16	44.25	–2.05
4	74.83	75.24	0.54
5	29.86	30.31	1.50
6	34.07	34.07	0.00
7	23.59	23.82	0.96
8	24.11	23.52	–2.50
9	64.23	65.14	1.40
10	48.31	49.25	1.91
11	33.78	34.24	1.33
12	13.93	14.12	1.31
13	19.53	19.99	2.29
14	69.74	72.46	3.76
15	14.10	14.28	1.28
16	26.64	27.1	1.68
17	28.88	28.43	–1.59
18	22.66	22.71	0.21
19	31.47	31.92	1.42
Total	**675.38**	**682.53**	**1.05**

Table 2. The total weight of broccoli harvested recorded by the yield mapping system and the total weight of broccoli harvested determined by an electronic scale. The error was calculated on the basis of total weight determined by the electronic scale

Harvest day number	Harvested weight registered by the mapping system (kg)	Harvested weight registered by an electronic scale (kg)	Weight error (%)
1	1728.7	1715	0.80
2	1322.5	1935	–31.65
3	3212.0	3175	1.17
4	3696.8	3600	2.69
5	4873.9	4870	0.08
6	4390.0	4600	–4.57
7	3762.4	3800	–0.99

Yield mapping tests

Seven trips through the field to harvest broccoli were required in a three weeks period. Thus, seven yield maps were obtained, one for each trip. Maximum area harvested during tests was 3.49 ha and the minimum area was 1.98 ha. Results of weight data obtained by the yield mapping system and weight data obtained by the electronic scale at the processing plant are presented in Table 2.

Table 3 shows the precision of the distance travelled measured using the sensor installed under the tow. Errors found for the distance sensor were below 1.49% compared with the distance measured using a measuring tape.

The yield mapping system recorded time and position continuously, which made it possible to calculate and summarize information about time dedicated to different activities while harvesting the crop. This information is presented in Table 4.

GPS comparison

Results for GPS comparison are shown in Fig. 5. Yield data and position data for both GPSs, were interpolated to obtain yield values for the same grids that was helpful when comparing the sizes and positions of areas. Then, yield maps were drawn up with interpolated yield data. From yield maps elaborated for both GPSs, areas yielding in a range were estimated and expressed as a percentage of total harvested area and compared as shown in Table 5.

As mentioned earlier, seven yield maps were obtained, each one for a trip through the field, so a total yield map was elaborated for the minimum common harvested area of the seven trips (1.98 ha). To make the total yield map, yield data were calculated on the same grid for each one of the seven yield maps, so that total yield in a grid of the total yield map was the sum of the seven sets of yield data (Figs. 6 and 7).

Table 3. Precision of travelled distance sensor was estimated by measuring distance travelled with a measuring tape

Sensed distance (m)	Repetition number (m)									
	1	Error (%)	2	Error (%)	3	Error (%)	4	Error (%)	5	Error (%)
2.21	2.22	0.45	2.19	–1.00	2.20	0.59	2.19	1.13	2.21	–0.09
4.42	4.48	1.27	4.48	1.29	4.36	–1.33	4.39	–0.80	4.39	–0.70
6.63	6.68	0.77	6.59	–0.57	6.60	–0.50	6.57	–1.10	6.73	1.40
8.84	8.82	–0.19	8.71	–1.49	8.91	0.70	8.78	–0.80	8.90	0.70
11.05	10.98	–0.63	11.11	0.52	11.19	1.10	11.14	0.70	10.96	–0.90

Table 4. The yield mapping system records time, weight and position during the harvest of a field. These data which are used to produce yield maps can also be used to estimate and analyze the performance of field workers

Cut	Havest start (h)	Harvest end (h)	Worked time (h)	Inactive time[1] (h)	Area (ha)	TFC[2] (ha h^{-1})	EFC[3] (ha h^{-1})	Weight (kg)	Yield (Mg ha^{-1})	Speed (m s^{-1})
1	07:37:30	13:18:33	05:41:03	02:14:18	3.49	1.013	0.653	1729	0.495	0.31
2	07:33:01	12:26:57	04:53:57	02:02:08	1.98	0.691	0.460	1323	0.668	0.21
3	07:46:22	13:53:16	06:06:54	02:18:49	3.02	0.794	0.553	3212	1.064	0.25
4	13:21:43	12:55:02	05:33:19	02:16:36	1.98	0.604	0.406	3697	1.867	0.19
5	07:21:25	14:38:18	07:16:53	02:56:53	1.98	0.457	0.310	4874	2.462	0.14
6	07:27:06	14:38:12	07:11:06	02:32:00	1.98	0.426	0.313	4390	2.217	0.13
7	07:28:57	14:18:21	06:49:24	02:14:02	1.98	0.431	0.330	3762	1.900	0.13
	Totals		43:32:36	16:34:46				22986	10.673	
	Mean				2.34	0.631	0.432			0.19

[1] This includes lunch-time, returns, product discharge time for tow, and lost time. [2] TFC = Theorical field capacity. [3] EFC = Effective field capacity.

Discussion

From Figs. 3 and 4 a visual comparison can be made of the maps. A similar pattern was found in areas of the same color. For example, yellow, green, red and purple areas appear in both maps in the same locations. However, in the map made using the yield mapping system there are mild changes in yield variation (Fig. 4) in contrast to abrupt changes of yield that can seen in Fig. 3. This is due to geo-statistics which considers that variability occurs in a gradient type behaviour so changes are averaged and replaced by a slope.

Yield mapping system accuracy was estimated from the precision of given load cells and from the travelled distance sensor to be around 0.51%. When comparing harvested weight data obtained by the yield mapping system and data obtained by a large electronic scale at the processing plant (precision of 0.0167%), it can be

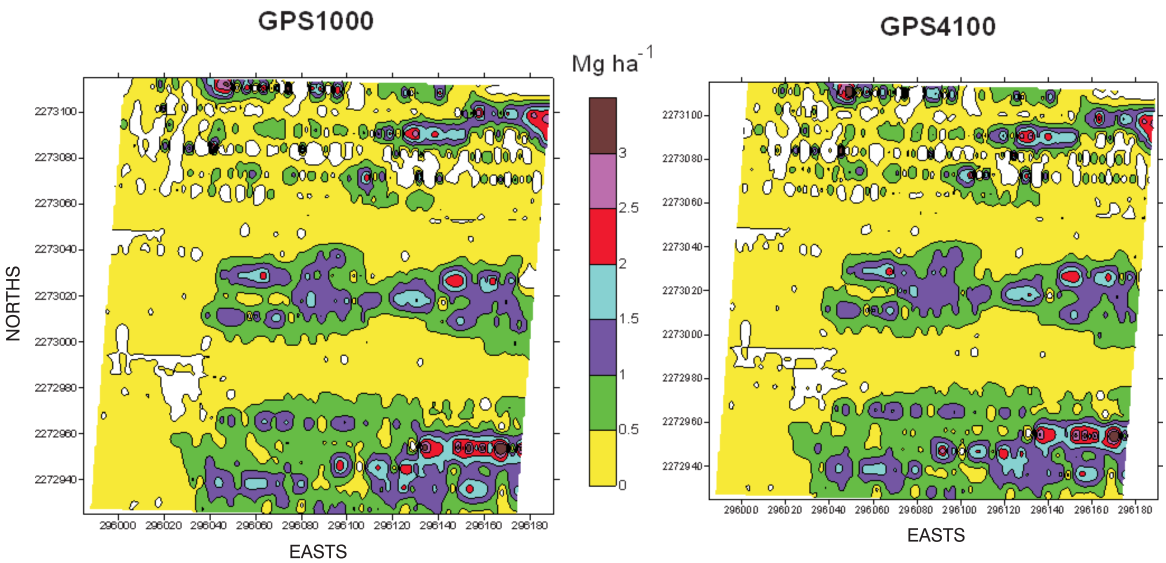

Figure 5. Yield maps for one trip through the field, elaborated using the same weight and area data and different position data obtained for each GPS1000 and GPS4100.

Table 5. Values and comparisons of areas and percentage of total area in a range. Data were estimated from both yield maps elaborated using positions obtained from GPS1000 and GPS4100

Yield (Mg ha^{-1})	Area			
	GPS1000		GPS4100	
	m^2	%	m^2	%
0-0.5	21667	55.6	21590	55.4
0.5-1	7884	20.2	8015	20.6
1-1.5	3709	9.5	4121	10.6
1.5-2	1179	3.0	772	2.0
2-2.5	384	1.0	331	0.8
2.5-3	101	0.3	95	0.2
> 3	4026	10.3	4025	10.3

seen that two data were significantly different (Table 2). The first significant difference was found for the second cut and corresponds to 612.5 kg, showing that the weight obtained on the large electronic scale is 31.6% larger. This significant difference could be explained because when the tow that transports broccoli to the enterprise is not completely filled, it may go to another field to collect broccoli. Therefore, the operator was unaware of this situation and made the usual calculations without making allowances for this situation. The second significant error (4.57%) can be seen in the sixth cut and was due to damage suffered by the yield mapping system. The test was stopped so the weight sensing system stopped recording harvested broccoli weight and the harvest continued for half an hour. Therefore, a greater amount of harvested broccoli was recorded to arrive at the enterprise than that recorded by the mapping system. Therefore, the greatest error that can be attributed to the yield mapping system was 2.69%. Godwin and Wheeler (1997) carried out an experiment with a trailer-based yield mapping system for non-combinable crops (8 Mg capacity) to verify the field performance, lifting and manual weighing of successive 10 m lengths of a single row of sugar beet at twenty-five meter intervals along 300-400 m lengths of the field. After that, a sugar beet harvester placed the load on the trailer. Comparisons of the single row and trailer harvest yield data obtained for four strips across the field revealed a maximum difference of 2.3%. Other yield mapping systems based on load cells have shown a precision of 5% or less for the weighing system (Rawlins *et al.,* 1995; Walter *et al.* 1996; Missoten *et al.,* 1997).

There are yield variations in the field ranging from 0 to 18 Mg ha^{-1}. Large yield variations in a field have been found in many other crops (Godwin and Wheeler, 1997). Fig. 6 shows that 34.6% of total area yields less

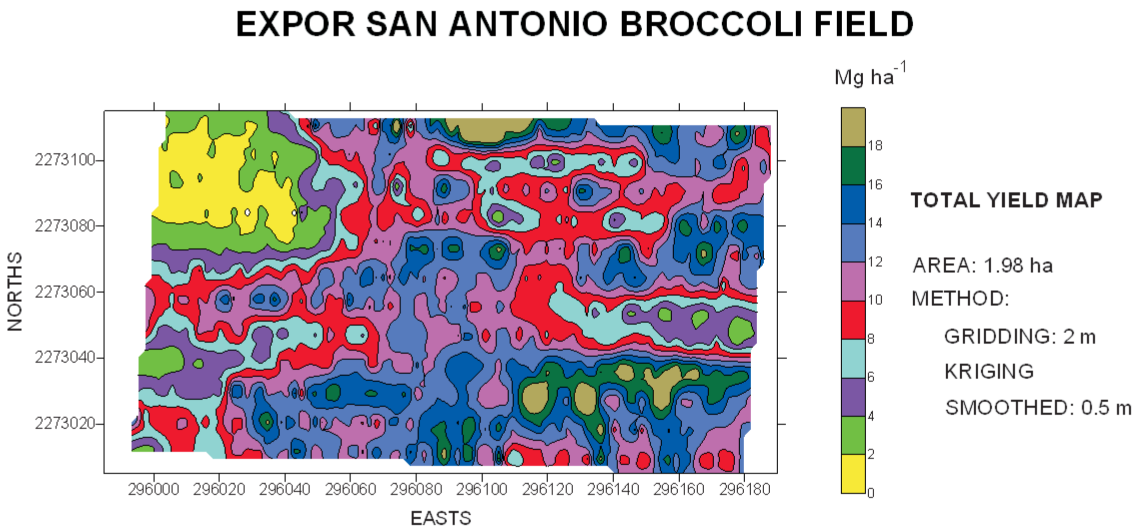

Figure 6. Total yield map developed by summing weight data for each trip through the field to calculate yield on coincident grids with a classification for yield by 2 Mg ha^{-1} increments.

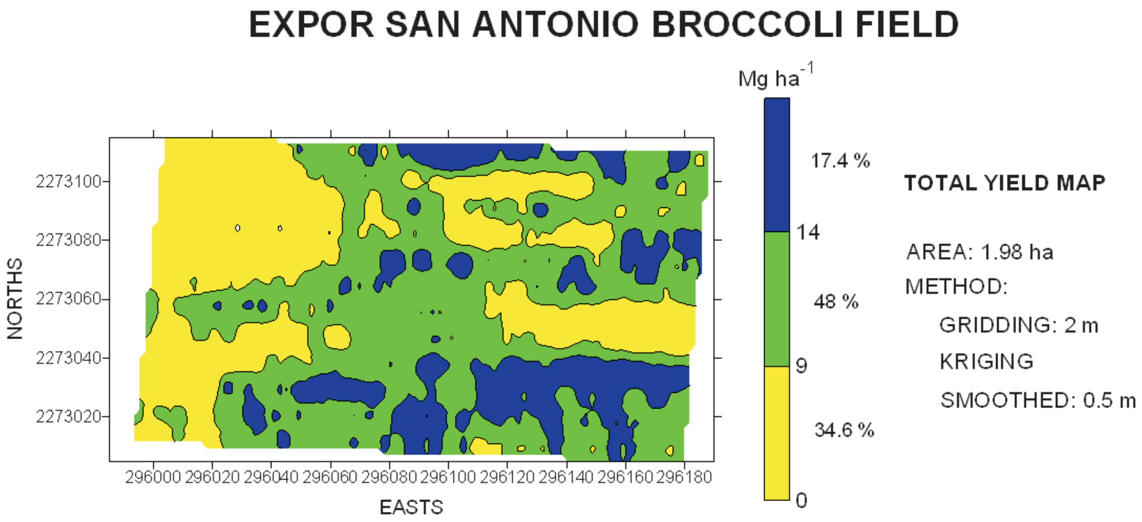

Figure 7. Total yield map developed by summing weight data for each trip through the field to calculate yield on coincident grids with three yield ranges.

than 9 Mg ha^{-1}; 48% of total area yields from 9 to 14 Mg ha^{-1}; and only 17.4% of total area yields more than 14 Mg ha^{-1}. From this information, the potential of the field (where tests were carried out) can be estimated by assuming a uniform average yield over the field of 14 Mg ha^{-1}. This estimation results in a productivity increment of 38%. Also, when the tests were done it was observed that areas with a low yield were areas with problems of weeds, waterlogging and restricted growth or without plants. From the way that position data and yield data were recorded by the yield mapping system, it was possible to calculate and summarize other important information shown in Table 4.

A tendency can be observed from data in Table 4 in that the effective field capacity diminishes as the yield increases. This can be explained by the fact that a high yield means that field workers have to select and pick up more broccoli and the speed of travel must be reduced. Also, other important information can be derived from Table 4. For example, the total work time for the seven harvest days was 52 hours, but due to starting time, finishing time and time lost, this was reduced to only 28 hours, corresponding to 51% of the total time. Recording this data continuously could enable the field manager to implement some changes in the procedures that could improve the performance of the harvesting workers and equipment. This can be considered as an additional benefit of using the yield mapping system.

According to yield maps presented in Fig. 5, it can be seen that there were no visual differences and also the same yield range areas are presented in the same position. In addition, results presented in Table 5 show that the greater differences in area with the same yield range between maps is only 1.1% (in the 1-1.5 Mg ha^{-1} range). Therefore, GPS1000 is as useful as GPS4100 for the yield mapping system developed in this work.

For yield mapping validation, errors for weighing measurements were below 2.69%; which is low compared with the yield variation shown in yield maps. In yield mapping system tests, the system worked properly without interfering with the harvesting methodology.

Comparison of maps obtained with the two GPS used revealed a difference no greater than 1.1% in areas presented in yield maps, thus the less precise and low-cost GPS can be used to map yield.

The yield mapping system can be used to study and manage the performance of field worker groups, by analyzing time and position data.

From the yield maps obtained it can be inferred that by identifying causes of low yield in some areas and taking corrective actions, productivity can be potentially improved by around 38%.

Future work could use the yield mapping system to identify yield variability and to study causes of this variability.

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