DIFFERENTIAL HARVESTING STRATEGY: TECHNICAL AND ECONOMIC FEASIBILITY

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Abstract

Differential Harvesting (DH) is performed to differentiate the product according to a precise quality standard in order to gain an economic advantage from temporal and spatial field variability. In agriculture this technique has been extensively applied in grape harvesting. There are fewer examples for extensive crops, since DH is mostly used for products with a value at harvest that differs depending on their quality characteristics. DH can be achieved through the use of sensors applied on the combine or through qualitative yield maps.

The aim of this paper is to compare the technical and economic feasibility of five DH methods identified in the literature and a new technique proposed by the authors. The analysis was conducted using yield and protein maps obtained in two years of experimentation growing durum wheat. Results highlight how management zone harvesting allows an increase of about 28 % of high-protein wheat, with a subsequent growth in gross revenue.

Key words: differential Harvesting, selective harvest, harvesting management, precision agriculture.

INTRODUCTION

Differential Harvesting (DH) is a harvesting approach performed to differentiate products according to predefined quality standards and allowing exploitation of economic advantages from the temporal and spatial field variability (BRAMLEY ET AL., 2005).

The first applications of DH were in the fishery and forestry sectors. In the fishery sector it is applied to improve the quality of the product by reducing the unintentional catching of undersized fish. In forestry it is used to limit damages caused to the forest and preserve the wood quality (ZILBERMAN ET AL., 1997). In agriculture this technique has been applied extensively in grape harvesting, where DH is achieved by simultaneously conveying the harvested grape into two or more hoppers with specific harvesting machines or through fractional grape harvesting. In the latter, the different zones are harvested at different times after analysis of vegetation indices performed with multispectral images derived from satellites or other platforms.

Implementing scalar harvesting enables to obtain different grape quality classes, resulting in the delivery of a product with homogeneous features. There are fewer DH examples for extensive crops as their value mostly different depending on their quality parameters at harvest-time (MEYER-AURICH ET AL., 2008). On the other hand, extensive crops as cereals take up an important role to satisfy the food demand and the food quality (PEZZUOLO ET AL., 2014; BASSO ET AL., 2016). By way of example, Durum wheat (Triticum durum Desf.) is the main cereal crop in several countries of the Mediterranean basin mainly used for pasta, bread, and couscous production. Durum wheat market constantly demands a grain protein content of 13.5 % or higher (CLARKE, 2001), since this trait represents the most important factor affecting pasta-making properties. However, for the farmer point of view, produce wheat with high protein levels allow a high income thanks to major market value and the premium price established by food companies.

This led to the idea of segregating wheat in different quality classes, achieved through the use of sensors mounted on combines (TAYLOR ET AL., 2005; LONG ET AL., 2013; MARINELLO ET AL., 2015) or qualitative yield maps (TOZER ET AL., 2007).

The aim of this paper is to define the technical and economic feasibility of the application of DH based methods. Different DH methods found in the literature are compared with the one proposed here (on-combine differential harvesting). The methods are tested using yield and protein maps obtained in two years of experimentation on durum wheat.

MATERIALS AND METHODS

Experimental site and climatic data

The grain yield and protein maps used in the present analysis were collected during the 2010/2011 and 2011/2012 wheat crops in a farm in the Venice Lagoon Watershed – Veneto – Italy (45°23'N; 12°09'E).

The experimental field measured 13.46 ha (520 m long and 260 m wide), with a soil defined as sandy according to the USDA classification. In terms of climate, most of the annual average rain falls in the months of April (90.6 mm), July (86.2 mm), October (119.4 mm) and November (82.8 mm). Temperatures peak in the summer months and daily average values are lower in the winter months (January and February), with mean values of 13 °C over the entire season. Durum wheat, cultivar Biensur (RAGT Semences – France), was managed with traditional agro-technical practices and the fertilization practice was applied using variable rate distribution techniques.

Homogeneous zone management

The three homogeneous zones were characterized by a different soil fertility (high, medium and low), on which different nitrogen fertilization levels were distributed (Fig. 1). In addition, each zone was split into two parts at flowering stage: one considered as control and the other treated with UAN (urea-ammonium-nitrate) solution (Tab. 1).

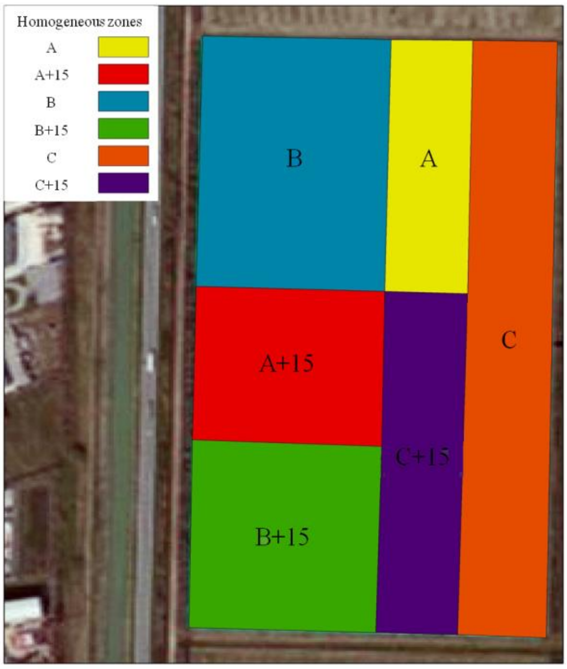

Fig. 1. – Homogeneous zones of the field trial during the wheat cropping seasons 2010/2011 and 2011/2012. The homogenous zones were identified according to soil fertility parameters.

Yield and protein mapping

Grain yield was recorded by a yield mapping system (Agrocom CL021) mounted on a combine harvester (Claas mbH *mod.* Lexion 460).

Consequently, protein content was measured with a Near Infrared Spectroscopy sensor (GraiNIT – RxGrains, Italy) associated to the mapping system GPS. As suggested by MORARI ET AL. (2013), NIRS accuracy was tested in 32 points of the field comparing the protein content measured by a NIRS used in laboratory and traditional Kjeldhal-method. Data were collected with a relatively high frequency (0.15-0.20 Hz), allowing high field resolution. Raw maps were post-processed in order to filter out points collected in correspondence of turn operations or in stationary combine conditions. Finally, data derived from maps were uploaded in a GIS software and interpolated using the Kriging-function (Fig. 2).

Differential harvesting strategy

Collected data were used in order to evaluate 4 different DH techniques (including a new method proposed by the authors) and compare with the uniform harvesting technique.

Uniform harvesting (UH): uniform harvesting of the field and undifferentiated unloading of wheat into the truck using a conventional combine without the possibility of segregating high-protein wheat.

Management zone harvesting (MZ): each homogeneous zone is harvested separately. Homogeneous areas within the field must be identified using GNSS (Global Navigation Satellite System) and the use of NIRS sensor is not necessary. Wheat yield is selected and unloaded on the basis of the protein content of the whole area.

On-truck differential harvesting (TD): the product is unloaded into two different trucks according to the average protein content found during the harvest. This strategy requires a NIRS sensor installed on the combine and information about the protein distribution in the field derived from the previous year protein maps.

On-combine differential harvesting (CD): the combine has two hoppers and the yield is differentiated on the basis of the indications of the NIRS sensor. Wheat with lower and higher protein concentrations falls into two different hoppers. This technique does not provide information about field protein, but it is important to check the right cut-off value. It is possible to assess the optimal cut-off value harvesting through a representative run of the field which allows to know the protein level present in the field. The basic requirement for successful application is a normal field distribution of protein. In this study a cut-off value of 13.5 % was considered.

Optimized on-combine differential harvesting (OCD): the hopper combine is divided into 8 equal parts of approximately 1 m^3 capacity. Each part is equipped with electrically controlled damper opening systems at the top and bottom. All the bottom openings convey into a pre-compartment where a screw allows the unloading operation. During the harvest operation wheat passes through the elevator and is conveyed into the different bins on the basis of protein content read by NIRS. In this way it is possible to know the protein level of each bin. In the unloading phase different bins are opened in order to mix the wheat and obtain a product with a protein content above the threshold. The control software is not limited to managing the protein content of the bin, but calculates the protein content of the truck at each unloading and determines the maximum quantity of low-protein wheat that can be mixed without falling below the threshold level.

Tab. 1. – Nitrogen fertilizer supply for each homogeneous zone

Fertilization practices (kg N·ha^{-1})	**Homogeneous zone**						**Date**		**Fertilizer**
	A	**A+15**	**B**	**B+15**	**C**	**C+15**	**2010/2011**	**2011/2012**	
	high	high	medium	medium	low	low			
Tillering fertilization	52	53	54	55	56	57	24/02/2011	02/03/2012	Ammonium nitrate (26%)
Stem extension fertilization	78	78	108	108	100	100	07/04/2011	06/04/2012	Urea (46%)
Stem extension fertilization					48	48	19/04/2011	27/04/2012	
Flowering stage fertilization		15		15		15	09/05/2011 17/05/2011	14/05/2012 24/05/2012	UAN
TOTAL	**130**	**145**	**160**	**175**	**200**	**215**			

Technical and economic analysis

Four parameters were calculated to evaluate the technical and economic feasibility of all the previously described DH strategies.

Combine working times: including turning and unloading times. It considers the working width and the average working speed. Turning and unloading time were monitored during harvesting time.

Machine operating costs: a model was built encompassing all the operating costs that were added to the combine working time in order to obtain the operating cost of different techniques.

Grain Protein Concentration: evaluates the amount of collected product with a protein level higher than 13.5 % and the relative gross saleable production thanks to the protein maps of previous years obtained with NIRS sensor. Using the first three parameters the operating income was calculated, considering all other farming operations as constant. The different nitrogen rates applied to the different homogeneous zones were considered during the farming operation costs calculation.

Payback period: period needed for each DH technique considering the different technologies applied in each method.

Operating costs of the harvest for each DH strategy have been calculated using the ASABE standards (ASABE, 2011A; 2011B). Costs related to buying seeds, insecticides, fungicides and their application are the same for all the scenarios. On the other hand, it is assumed that the harvesting machines suitable for each DH method are available on the market and are not intended as experimental prototypes.

Gross revenues were determined for each year using price schedules of durum wheat on the AGER corn exchange of Bologna - Italy during the first week of July for both experimental years. The bonus payment for high-protein wheat was 15 EUR·t^{-1}, the threshold that distinguishes the product quality was 13.5 % for both the years (Tab. 2). The results of the various DH methods were compared with those of traditional harvesting.

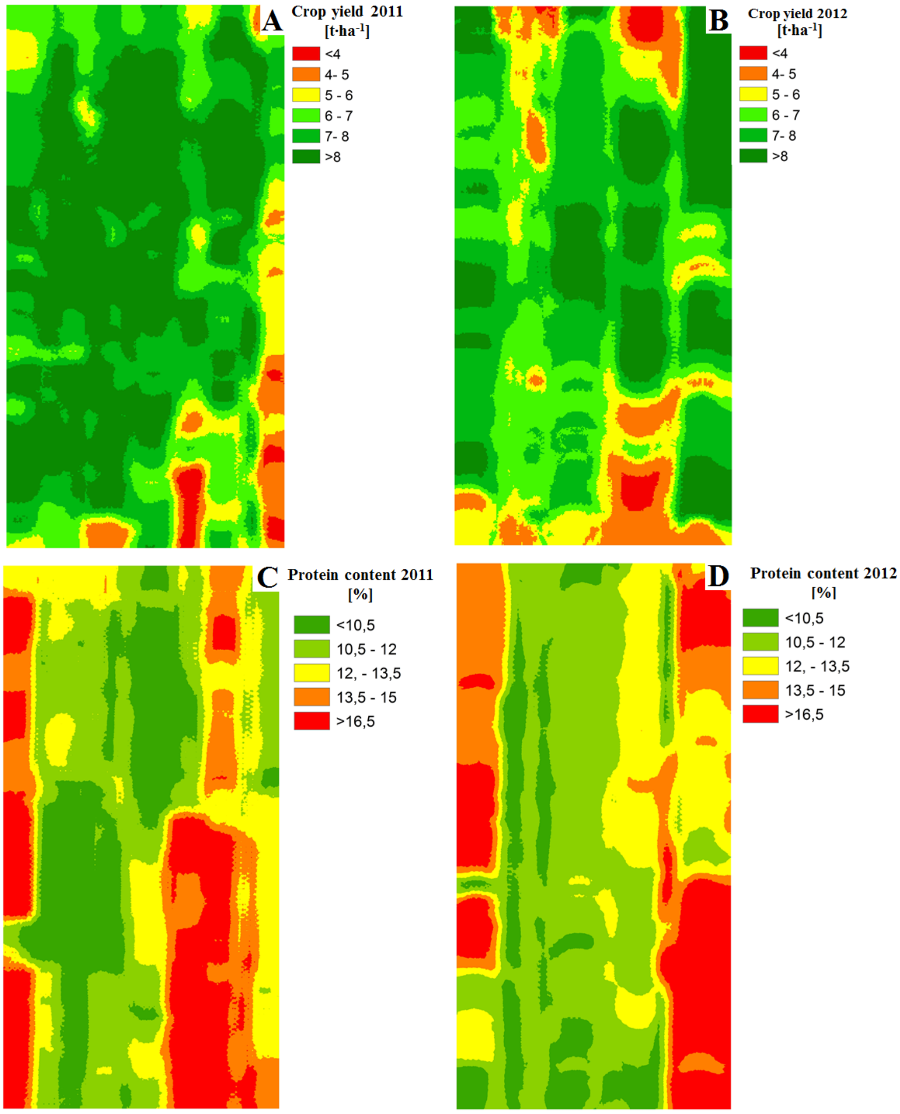

Fig. 2. – Grain yield and protein content maps of the field trial during the 2010/2011 (A; C) and 2011/2012 (B; D) wheat seasons

Tab. 2. – Wheat price at different protein content

Protein content (%)	Durum wheat market price (EUR·t^{-1})	
	2010/2011	2011/2012
< 13,5	297,5	256,5
≥ 13,5	312,5	271,5

RESULTS AND DISCUSSION

Harvesting costs

UH presents lower harvesting costs due to no need for additional investment, and greater field capacity of the combine (Tab. 4).

All DH methods have a low field capacity due to more turns or extra unloading times and the difference in price compared to a machine used for the UH ranges between EUR 10.000 (for the GNSS components required for MZ or for the installation of NIRS used by TD) and EUR 20.000 (required to install the additional bins necessary for CD and OCD).

Separating the combine bins leads to a reduction in the autonomy of the combine and an increase in the unloading time. All these factors affect the field capacity of the harvesting machine: field capacity for UH was estimated to be 2.06 ha·h^{-1}, whereas there were reductions of 7 and 13 % respectively for MZ and OCD.

Harvesting costs were estimated to range from 141 EUR·ha^{-1} in the case of UH, to 188 EUR·ha^{-1} in the case of CD and automatic harvesting determines cost increases of 31.1 % compared to UH. Despite the higher initial investment, OCD does not determine significant cost increases (19.4 %) compared to UH.

Tab. 4. – Harvesting costs for the differential harvesting strategy

Economics parameters	UH		MZ		TD		CD		OCD	
Initial investment (EUR)	272.000		282.000		282.000		292.000		292.000	
Operating or turning time (h·ha^{-1})	0.03		0.07		0.03		0.03		0.03	
Unloading time (h·ha^{-1})	0.058		0.055		0.058		0.192		0.128	
Actual field capacity (ha·h^{-1})	2.06		1.92		1.84		1.61		1.80	
Harvesting cost (EUR·ha^{-1})	141		155		161		188		168	
Experimental year	**2011**	**2012**	**2011**	**2012**	**2011**	**2012**	**2011**	**2012**	**2011**	**2012**
Cultivation cost (EUR·ha^{-1})	667	673	667	673	666	673	666	673	666	673
Total cost (EUR·ha^{-1})	808	814	821	828	828	834	854	861	835	841

High-protein wheat segregation capacity

The amount of segregated high-quality wheat is related to different characteristics of the methods. Total wheat production was 90.2 tons in 2011 and 86.9 tons in 2012 year. The UH has supplied a product with an average protein content of 12.3 % in the first year and 12.4 % in the second, therefore below the threshold of 13.5 %.

All DH methods have allowed a high-protein product differentiation but at different levels. Because of the quantity and distribution of protein in the field, each scenario has segregated different quantities of wheat with high protein content (Tab. 5). OCD is the best technique in segregating wheat with a high protein content (47.2 % and 43.6 % in the two experimental years).

As reported by LONG ET AL. (2013), all other harvesting methods succeed in segregating approximately 30 % of high-protein product. Gross revenues have been calculated on the base of the high-protein wheat collected by each DH method.

Tab. 5. – Percentage of high-protein wheat segregated by each differential harvesting strategy

DH Strategy	2010/2011		2011/2012	
	Average yield (t·ha^{-1})	**Segregated fraction (%)**	**Average yield (t·ha^{-1})**	**Segregated fraction (%)**
UH	6.7	0	6.4	0
MZ	6.7	32.8	6.4	23.8
TD	6.7	30.2	6.4	35.7
CD	6.7	31.3	6.4	28.7
OCD	6.7	47.2	6.4	43.6

Gross revenues

Wheat with a protein content higher than 13.5 % obtains the bonus payment of 15 EUR·t^{-1}.

Gross revenues are therefore higher in the DH method that can collect a larger quantity of high-protein wheat. DH techniques allow to increase gross revenue of 28 EUR·ha^{-1} (+ 1.5 %) and 45 EUR·ha^{-1} (+ 2.5 %) respectively for MZ and OCD compared to UH.

Gross revenues obtained from different DH scenarios do not appear to be consistent. This is probably due to the “low bonus” awarded to the product with high protein content.

Income

As shown in Tab. 6, MZ allows higher operating profit compared to UH due to higher gross revenues. Despite this type of harvesting method requires a preliminary preparation of the field for each homogeneous zone, harvesting costs are slightly higher than UH one. The automatic DH methods using separate bins have high gross revenues, demonstrating how this is a viable technique to differentiate large quantities of wheat with high protein content. On the other hand, the operating income of this scenario is lower than that of the UH due to high harvesting costs that undermine higher revenues.

High harvesting costs come from the lower capacity of the bin, due to its division into two sections. Consequently, a decrease of bins operative efficiency is observed with a consequent decrease in field capacity of the combine. OCD can partially lessen problems that characterize DH methods using separated bins. Indeed, OCD optimizes the segregation of high-protein wheat. The high flexibility of the hopper capacity, high gross revenues and moderate harvesting costs allow economic feasibility of this method.

Tab. 6. – Analysis of operating income deriving from DH scenarios examined

DH Strategy	Incomes ($EUR \cdot ha^{-1}$)			Operating income ($EUR \cdot ha^{-1}$)			Operating income gap (compared UH)		
	2011	2012	mean	2011	2012	mean	2011	2012	mean
UH	1994	1658	1826	1186	843	1015	-	-	-
MZ	2027	1681	1854	1205	853	1029	19.05	9.13	14.09
TD	2025	1693	1858	1197	858	1027	10.29	14.55	12.42
CD	2026	1686	1856	1171	824	998	-15.23	-18.92	-17.08
OCD	2042	1700	1871	1207	858	1032	20.31	14.96	17.63

Payback period

Considering a durum wheat harvesting season of 20 days and the field capacity of the different DH methods, the maximum harvestable area does not exceed 300 $ha \cdot year^{-1}$. In this situation the payback period is less than 2 years for MZ and TD and 3 and 4 for OCD and CD respectively.

If a payback period of 5 years is considered, the minimum annual areas to harvest are approximately 100 ha for TD MZ, 125 ha for OCD and 200 ha for CD (Fig. 5).

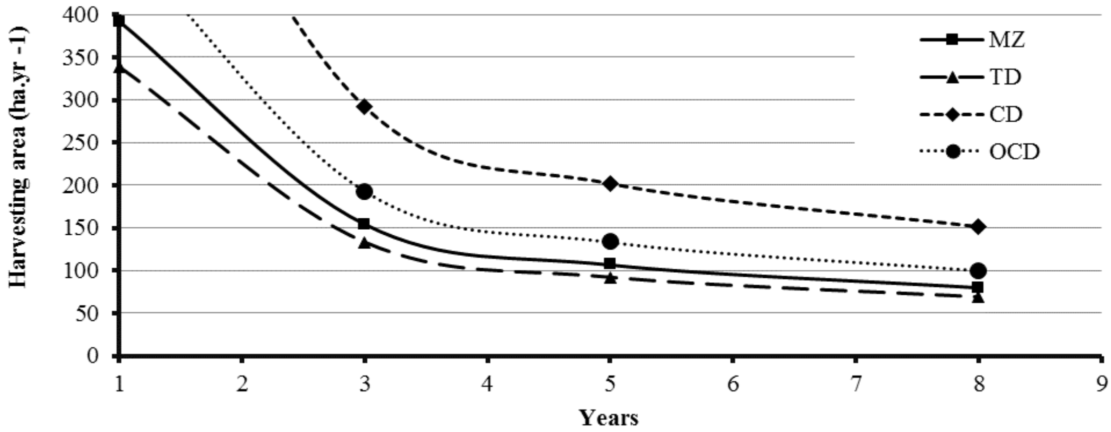

Fig. 5. – Minimum area harvested to pay off the technology applied to machines for the different DH strategy

CONCLUSIONS

The aim of this paper is to evaluate the technical and economic feasibility of DH methods found in the literature and the technique proposed by the authors for durum wheat harvesting, on the basis of protein content.

In this specific study case characterized by small field size, small homogeneous zones and a moderate bonus payment (15 $EUR \cdot t^{-1}$), a different behaviour distinguishing the different DH strategies was observed. MZ, as discussed also by TOZER ET AL. (2007), seems to be advantageous due to the regularity and size of the six zones found in the field. However, to obtain an economic advantage from this technique it is essential to have big differences in terms of potential protein between homogeneous zones. DH on-truck methods using NIRS can generate more profits if the distribution of the protein in the field and the field measures are adequate.

The high harvesting costs related to on-combine DH methods are moderated by OCD. The hopper divided into 8 sections can be more effective that the one divided into 2. This allows to enhance the bin operative efficiency, and consequently an increase in the combine field capacity.

Moreover, the software able to optimize the truck protein content at each unloading can segregate large amounts of high-protein wheat obtaining higher income.

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