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Decision support system for improving wheat grain quality in the Mediterranean area of Israel

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Abstract

The yield of dryland wheat in semi-arid and arid areas is limited by rainfall. Nitrogen application and rainfall distribution determine biomass production, soil water depletion, and grain quality. A precise base level of nitrogen fertilization is applied according to the annual rainfall, but in case of more rain, the higher biomass production would dilute the nitrogen and a low quality wheat would be harvested. On the other hand, under drought conditions, harvesting for hay or silage provides a greater income than leaving the crop for grain production. Our objective was to establish a quick and simplified decision support system (DSS) for decision making at heading. It was found that, at heading, flag leaf water concentration (FLW) and flag leaf total N concentration (FLN) data can be used to support agronomic decision making. In particular, these data can assist a decision to harvest early for hay or silage, since water stress exists and the test weight is expected to decline. In other cases these data can help to forecast the need for late nitrogen application to ensure sufficient protein levels. Our results show that the proposed DSS correctly forecasts wheat grain quality, test weight and protein content, in more than 80% of the 344 experimental plots, by monitoring flag leaves at heading. Therefore, application of the suggested simplified DSS would reduce the harvesting of shriveled grains, on the one hand, and would lead to improved grain protein, on the other hand, thus ensuring high-quality production.

Keywords: Crop monitoring; Heading; Nitrogen; Precision agriculture; Stress; Water; Spectroscopy

1. Introduction

Mediterranean areas of southern Europe and Australia are suitable for the production of high-quality bread-making wheat (*Triticum aestivum* L.), but to achieve a more consistent quality end product necessitates the simultaneous consideration of a large number of quality traits that are evaluated in several different growing environments. The established market adjustments for wheat are based on protein content and test weight, with premiums commonly paid for exceeding the baseline levels, and penalties imposed for falling below them. Efficient use of N fertilizer is important for economical wheat production; it is also

Abbreviations: DSS, decision support system; FLN, flag leaf total N concentration; FLW, flag leaf water concentration

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important for the quality of ground and surface waters, since the potential for nitrate enrichment of ground and surface waters also increases with excessive N fertilization (Raun and Johnston, 1999). Environmental constraints and economics are forcing farmers to be increasingly precise in determining the rate and date of nitrogen fertilizer application to crops. Insufficient N reduces wheat yield and profit, while excessive N results in wheat plants that are susceptible to water deficiency, disease and lodging, with consequently reduced quantity and quality of yield. Wheat producers in Israel typically use three options for applying N fertilizer: (i) apply all fertilizer in the fall, before sowing; (ii) apply some fertilizer in the fall, followed by a mid-winter or early spring topdressing; and (iii) the full quota of N applied in the fall, before sowing, followed by a topdressing application according to growing conditions. Although pre-sowing fertilizer applications decrease the potential for nutrient deficiencies in the early stages of growth, the presence of plant-available residual soil N from the previous season may pose a risk to the environment (leaching) or create growth problems. Excessive pre-sowing applications of N encourage vegetative growth and, therefore, the crop utilizes much water during that growth stage (Moore and Tyndale-Biscoe, 1999), leaving insufficient water during the grain-filling stage and, consequently, the production of poor-quality grain (Palta et al., 1994; Bonfil et al., 1999; Bonfil, unpublished data). Late-season foliar N applications, before or immediately following flowering, may significantly enhance the grain N content and, hence, the protein percentage in winter wheat; it may also reduce potential N losses caused by leaching or denitrification over the winter (Woolfolk et al., 2002). Thus, late-season augmentation of available N can be used to improve the wheat grain protein content, especially in irrigated fields. However, in practice, the N is frequently applied without knowledge of the amount needed, or the likelihood of significant protein enhancement.

Temperature, rainfall, solar radiation during grain-filling, soil N, and rate and timing of supplemental N application are the factors with the most marked effects on the protein concentration in wheat (Wuest and Cassman, 1992; Gooding and Davies, 1997; López-Bellido et al., 1998; Rharrabti et al., 2003b). Growing conditions that lead to long grain-filling periods (e.g., in northwestern Europe) normally result in well-filled grains with a low protein concentration (Gooding and Davies, 1997). In contrast, Mediterranean-type environments of southern Europe, Israel, and southern Australia are characterized by dry, hot summers alternating with wet, cold winters (Nahal, 1981; Palta et al., 1994; Acevedo et al., 1999), leading to a shorter grain-filling period, lower grain yields, and higher protein concentrations in the grain (Borghi et al., 1997; López-Bellido et al., 1998). The recently introduced payments according to wheat grain protein are intended to improve the marketability of the grain, and these payments have made the decisions on the application of fertilizer N to wheat more critical for profit (Palta et al., 2001). The grain protein concentration increases as N availability increases, but the question arises of how much N is required to produce both high yields and acceptable protein? Several studies have found that N applications combined with a better temporal distribution of N during the wheat cycle significantly improved the bread-making quality (Wuest and Cassman, 1992; Borghi et al., 1997; Gooding and Davies, 1997); they also found that delayed application of N within the growing season favors grain protein buildup over yield, and enhances the bread-making quality of the flour. There is a common perception that late-season moisture stress is essential for increasing protein up to acceptable levels, as moisture stress was found to increase mainly protein content and to reduce grain weight (Palta and Fillery, 1995a,b; Rharrabti et al., 2003a). However, severe drought often prevents starch accumulation in the grain, and the test weight of the grain declines. In that case, the harvested grain yield would be poor in quality, although the grain contained a high protein concentration. In that case, if the test weight is lower than a baseline (74 kg hl^{-1} in Israel) then the grains will be used only for animal feed, and the return will be much lower. Therefore, wheat growers in Israel sometimes harvest fields prematurely, for hay instead of grain, to increase their return and to ensure that they meet minimum market test weight levels.

Mechanistic crop growth models have many potential uses for crop management. These models can aid in preseason and within-season management practices such as fertilizer and irrigation applications. When making these management decisions, maximizing the yield and net return relative to inputs and production costs is one of the fundamental goals. Crop growth modeling techniques have been used to investigate the performance of a wheat crop over ranges of weather conditions, nitrogen application rates and soil types. Models of response to applied N can be useful for deriving improved N recommendations, and computer simulations have become powerful tools for investigating crop dynamics and solving practical problems. However, the input requirements for these models include many weather and soil conditions, plant characteristics, and crop management parameters (Sinclair and Amir, 1992; Jamieson and Semenov, 2000; Hunt et al., 2001). The complex data handling and parameterization of those models discourage their use in less monitored fields. Therefore, several indicators have been suggested for determining the N status of the crop. They include: the nitrate content of the stem base extracts (Papastyliano and Puckridge, 1981; Scaife and Stevens, 1983; Justes et al., 1997; Fox et al., 2001); leaf color charts (LCC), leaf reflectance (or transmittance) and crop reflectance (Raun et al., 2002; Yang et al., 2003); and the chlorophyll content of leaves (Yadava, 1986; Fox et al., 2001). These methods require several crop measurements. Spectroscopy, the process of acquiring information about objects from remote platforms such as ground-based booms, aircraft, or satellites, is a potentially important source of the data needed for decision-making (Shanahan et al., 2001).

Late-season N application has increased the grain protein content in many studies. In recent years, intensive management studies for winter wheat have shown that split topdressings of fertilizer N after spring green-up may improve N efficiency and increase yields. The chlorophyll meter and LCC based N management in rice suggest that N can be saved with no yield loss, by appropriately revising the blanket fertilizer recommendations by means of a simple and easily used tool (Singh et al., 2002). Plant N concentration was predicted by measurements of the reflectance in the red and green regions of the spectrum, and grain yield was estimated from the reflectance in the NIR region, with the specific wavelengths of importance changing with growth stage (Osborne et al., 2002). However, measurement of the flag leaf N at heading has not been consistently successful in predicting protein content, or its increase through the late-season application of N, on a commercial scale.

Past research in this area has focused primarily on N stress in crops. Other stresses and their interactions have not been fully evaluated, although water shortage is much more important than N content, especially in the Mediterranean region (Papastyliano and Puckridge, 1981; Borghi et al., 1997). Thus, strategies that allow decisions and expenditure on nitrogen fertilizer applications to be delayed until later in the season, when climatic conditions and yield potential are clearer, are essential for the management of grain protein in a Mediterranean-type environment (Palta et al., 2001). Deciding on the best end use for the crop—grain versus hay—and on the amount of N fertilizer for the March application at heading are more subjective, but may be more important. The present paper discusses the development of a novel DSS to help wheat producers in Mediterranean areas make more informed decisions about crop management.

2. Materials and methods

2.1. Wheat growth

The research was based on the same experimental plots and leaves that were listed previously (Bonfil et al., 2004). Spring wheat (*T. aestivum*) cv. Galil was sown at the Gilat Research Center for all experiments, using two fields—Gate and fixed (Fixed is a permanent long-term experiment field with fixed sub-plots and treatments (Bonfil et al., 1999)). In both fields, wheat was grown as rainfed (Dry) in half of the field and under supplemental irrigation (Irr) in the other half. The fixed study examined wheat growth under various crop management systems such as different soil tillage and mulching regimes, crop rotations and fertilization with N (0, 50, 100 or 150 kg ha^{-1}) and phosphorus (0 or 10 kg ha^{-1}). The fertilization treatments were established 27 years ago as base applications. During the three seasons of this study (2000–2002), four rates of N application were maintained, but were modified from the original scheme to applications of $0+0$, $50+0$, $50+50$ and $100+50$ kg ha^{-1} as base and topdressing at heading, respectively. The applied N was incorporated fully into the soil by either irrigation (in Irr plots) or natural rainfall (in Dry plots). In 2000 and 2002, solid urea was used for topdressing at heading, whereas in 2001 the rainfed plots (Dry) received only 24 kg N ha^{-1} as liquid urea and the irrigated plot received only 42 kg N ha^{-1} as liquid urea and ammonium nitrate (1:1). In 2002, another experiment was established in the Gate experimental field. This experiment includes six N applications prior to heading, with N at $0 + 0$, $0 + 50$, $50 + 0$, $50 + 50$, $100 + 0$, and $100 + 0$ kg ha^{-1} for base/early top dressing, respectively. Several sub-plots in all treatments received an additional 50 kg ha^{-1} N (solid urea) at heading. In 2002, there was no rainfall for more than 30 days after heading, therefore rainfed plots in both fields did not receive the late N application. A total of 344 sub-plots were analyzed from the two experiments in this study. Grain yield was determined from 30 or 51 m^2 area, harvested with a combine. Grain test weight was measured on a 250 g sample and expressed as kg hl^{-1}. Grain protein content was determined by the Kjeldhal method; the percentage of protein was calculated after multiplying the Kjeldhal nitrogen by 5.7 and was expressed on a 10% water content basis.

In addition to yield quantity and quality data, this study used measurements of flag leaf water (FLW) and flag leaf N (FLN) contents during heading. The development of the decision support system was based on the ‘‘wet determination’’ of flag leaf water content and the total N (Kjeldhal) concentration, and on the calibration of the reflectance within the NIR region (1100–2498 nm) as measured with the Foss NIR System model 5000 (Bonfil et al., 2004). Descriptive statistics and ANOVA were applied by means of the SAS statistical package.

2.2. Decision support system (DSS)—concept

Annual precipitation in the region of the study varied between 200 and 450 mm. In addition to the rainfall quantity variation, the starting point of the rainy season varies from year to year, but sowing is usually around mid-November. Since growth conditions could negatively affect wheat production if they result in later emergence, the starting point is very important. In the northern Negev, the study region, base nitrogen fertilization can be commercially applied without danger of nitrogen leaching, but larger amounts of nitrogen application encourage vegetative growth, so that the crop utilizes much more water during that growth stage. The main result of this is insufficient water during the grain-filling stage and, consequently, production of poor-quality grain. Therefore, smaller amounts of nitrogen than would be needed in heavy-rainfall seasons should be used for base application. The same logic discourages the use of topdressing in the period from tillering to elongation. Nevertheless, in case of more rain, higher biomass production would dilute the nitrogen within the plant, and a low quality of grain, containing low protein levels, would be harvested. In such a situation a late topdressing could be applied to ensure suitable protein content in the grain. In the present study, after booting-heading the rain amount varied from zero to more than 100 mm, and in many years this is a significant amount of rain that could be the carrier for a late nitrogen application.

At heading the main questions that arise are: ‘‘should N be applied?’’ and ‘‘would hay/silage be a better end use, since under water stress harvesting for hay or silage could increase income?’’. A rapid and simplified DSS is needed for such decision-making, without any need for a within-field reference.

The hypothesis of the present DSS is that the plant itself would be the best source of the information that is needed to support decisions. The flag leaf was taken as a model for this information, since at this growth stage reflectance data could be collected by spectroscopic techniques. Furthermore, this is a simple fixed sampling technique that could be repeated by every farmer.

The proposed DSS requires only three input parameters: (1) expected rain in the next several (3–5) days, (2) FLW and (3) FLN. The local meteorological service as well as the various available forecasting models could be used by farmers to forecast rain. Reflectance spectra analysis could represent FLW and FLN (Bonfil et al., 2004), and were considered suitable for the DSS as well as wet procedures for FLW and FLN analysis. The DSS compiles data and provides one of three recommendations to farmers: harvest hay (or silage); leave for grain harvest; or leave for grain harvest but apply nitrogen as close as possible prior to the expected rain, as listed below.

3. Results

3.1. Wheat growth

Precipitation conditions varied from year to year and from one field to another (Table 1); no rain fell during the months June–September. The driest condition occurred in the Fixed-rainfed field in 2001, with 222 mm rainfall available to the crop, and the grain-filling period being dry. The Gate-irrigate field (2002) reached the best condition: about 488 mm were available to the crop, and the plants received 210 mm of it during the grain-filling period. All seasons had similar temperature, humidity, and radiation without any remarkable or unusual events. Since supplemental irrigation (which varied between 95 and 210 mm, depending on the rainfall) was used, there was no problem in applying any N fertilizer formulation, solid or liquid, at heading in the irrigated fields. However, the late application of N top dressing to rainfed plots was problematic: in 2001, in the absence of carrier rain, these plots received smaller amounts of in the form of a liquid for foliar application. This fertilization caused some scorching damage to the flag leaf. Therefore, in the following season, the topdressing was limited to solid urea application. In 2002, the only rain that fell after heading occurred about one month after it, therefore the late N application could not be done in the rainfed plots.

Variations in growing conditions resulted in differences in grain yield and quality (Table 2). Grain yield varied from 440 to 7040 kg ha^{-1}, which represents almost the whole yield potential spectrum of the growing region. The test weight of most samples

Table 1
Rain and irrigation (mm) accumulation in the experimental fields

Year	Field	October	November	December	January	February	March	April	May	Head[a]	Total
2000	Fixed-Irr	2.4	4.1	83.8	118.9	7.7	30.0	70.6	0.0	95	318
2001	Fixed-Dry	20.9	1.1	77.1	72.7	58.0	4.2	4.6	5.8	10	244
2001	Fixed-Irr	20.9	56.1	107.1	72.7	73.0	54.2	4.6	5.8	120	394
2002	Fixed-Dry	5.0	15.0	57.1	98.1	25.1	35.4	7.6	0.0	40	243
2002	Fixed-Irr	5.0	45.0	57.1	98.1	65.1	120.4	7.6	0.0	130	398
2002	Gate-Dry	5.0	75.0	57.1	108.1	60.1	35.4	7.6	0.0	43	348
2002	Gate-Irr	5.0	75.0	57.1	108.1	100.1	135.4	7.6	0.0	210	488

[a] Rain and irrigation amounts that accumulated after heading and were relevant for late N application. In dry fields of 2002 the 40 mm of rain fell 30 days after heading, therefore could not be used for topdressing.

Table 2
Grain yield and yield quality of the 344 sub-plots from different experiment fields that were used for DSS development

Year	Field	Late N	Number	Grain yield (kg ha^{-1})			Test weight (kg hl^{-1})			Protein content (%)		
				Mean	S.E.	Range	Mean	S.E.	Range	Mean	S.E.	Range
2000	Fixed-Irr	No	37	1581	82.8	1950	82.4	0.11	2.5	13.8	0.13	3.1
2000	Fixed-Irr	Yes	32	1410	92.4	1810	82.1	0.09	1.8	14.3	0.14	3.6
2001	Fixed-Dry	No	36	1416	76.4	1940	73.4	0.65	14.6	14.0	0.37	8.0
2001	Fixed-Dry	Yes	36	1345	80.3	1670	70.6	0.47	10.4	16.2	0.24	6.3
2001	Fixed-Irr	No	39	1986	97.2	2690	80.9	0.17	4.4	10.5	0.13	3.6
2001	Fixed-Irr	Yes	32	2271	118.3	2180	80.3	0.21	5.0	11.0	0.15	3.8
2002	Fixed-Dry	No	48	2398	145.5	4520	82.1	0.22	5.4	10.3	0.24	5.5
2002	Fixed-Irr	No	12	2676	294.7	3280	83.3	0.42	4.6	8.7	0.12	1.4
2002	Fixed-Irr	Yes	12	3332	236.2	2430	83.0	0.32	3.0	10.2	0.23	2.4
2002	Gate-Dry	No	10	3047	365.3	3370	79.4	0.69	5.7	12.0	0.33	2.9
2002	Gate-Dry	Yes	10	3566	340.3	3290	79.0	0.55	5.8	12.3	0.40	4.2
2002	Gate-Irr	No	14	5884	159.8	1810	82.5	0.16	2.1	10.0	0.15	1.9
2002	Gate-Irr	Yes	26	5650	137.6	2960	82.0	0.15	2.7	10.7	0.12	3.2

was above 79 kg hl^{-1} (Fig. 2), but lower test weight of about 63.9 kg hl^{-1}, shows that some plots were water deficient during the grain-filling, resulting in the production of shriveled grains. Grain protein content varied widely from 7.7 to 19.3%. These results show that grain yields and quality can be greatly affected by the variability of the weather in the Mediterranean climate and by crop management. Experimental treatment factors, crop management, and fertilization all significantly affected grain yield and quality parameters in each experimental field. Since the DSS development was based on only 344 out of 1106 sampled plots, specific treatment effects are not shown here. However, it can be seen (Table 2) that N application at heading could increase the yield in some cases (Fixed-irrigated and Gate-dry 2002 fields), that it usually had no effect on test weight, and that it increased the grain protein content. This improvement in protein content was limited to increases of up to 1% in four fields, and two fields showed a greater effect. However, in one of these two (the 2001 Fixed-dry field) this increase must be related to the lower test weight achieved. Flag leaf water content and N concentration at heading also show wide variations among these 344 plots (Bonfil et al., 2004).

3.2. Development of decision support system

The DSS procedure was built as a hierarchical tree of conditions (Fig. 1). The first answer needed, is whether the field would receive rain and/or irrigation (at least 30 mm) soon. Thereafter, FLW and FLN values would lead to one of the three suggestions. The leaf values that the model uses as limits differ for each precipitation condition, and the model results are only qualitative answers. The efficiency of late N application is low and there is a limit to the amount that can be applied; it is always between 30 and 50 kg N ha^{-1}.

After FLW and FLN determination, the DSS provided a recommendation for each plot. Then, part of the plots received a topdressing of N, application, according to the experiment design, and irrespective of the DSS suggestion. The relation between the DSS suggestions (that were based on data from the 2000 and 2001 seasons) and grain quality is shown in Fig. 2. There are three main quality groups: (1) high quality with test weight above 79 kg hl^{-1} and protein content above 11.5%; (2) low quality with test weight under 79 kg hl^{-1}, and especially where it is under 74 kg hl^{-1}; (3) low quality with protein content under

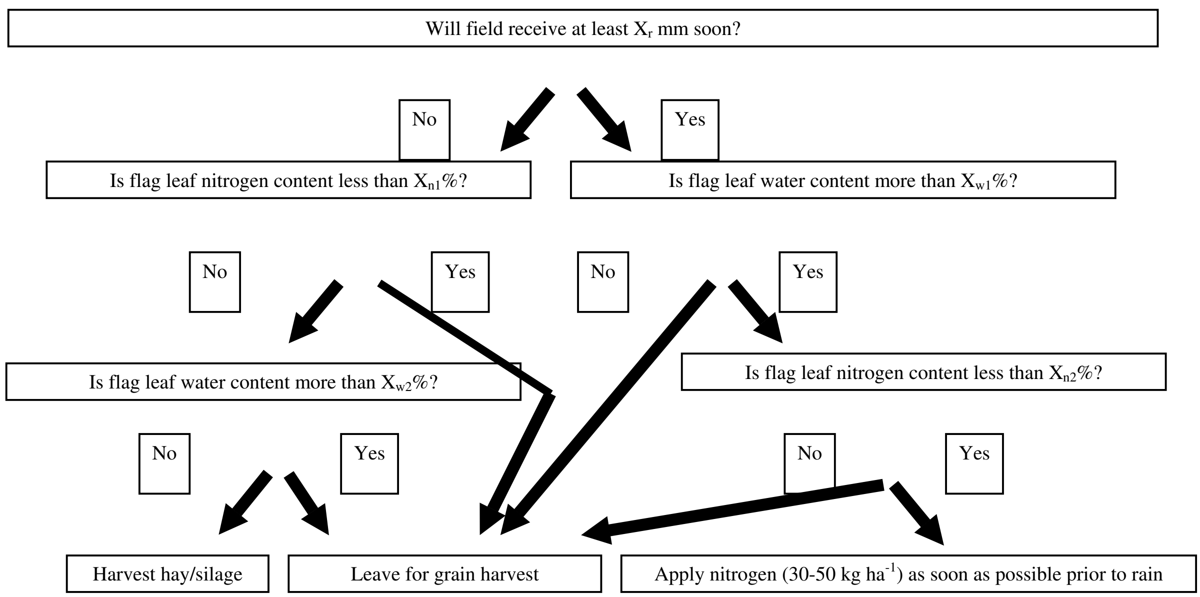

Fig. 1. DSS model: determining the requirement for late nitrogen fertilization and end use for wheat at harvest. X represents the coefficient of: r, rain and irrigation; w, FLW; n, FLN.

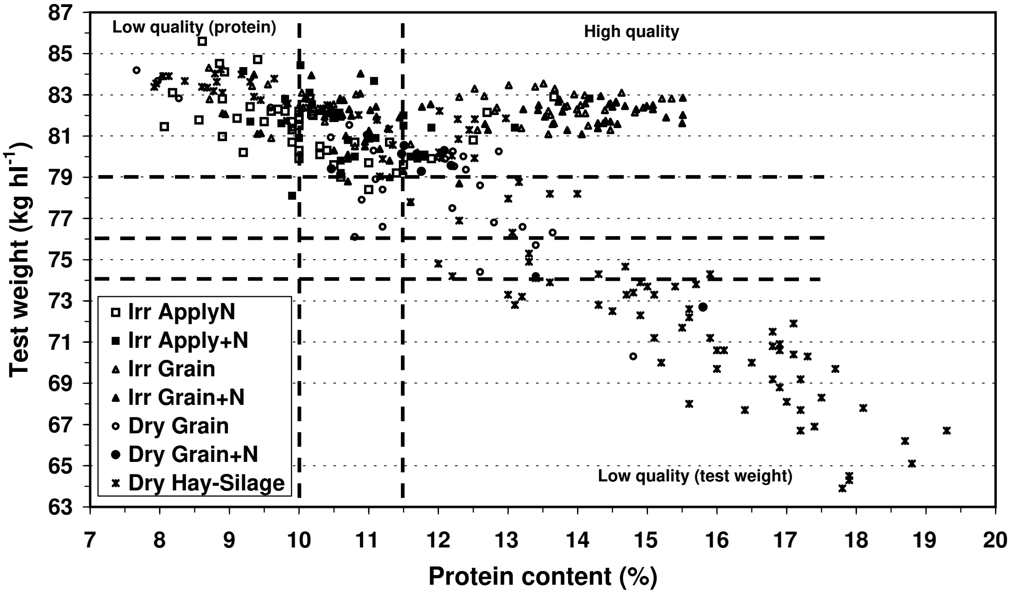

Fig. 2. DSS recommendations based on FLW and FLN at heading and grain quality parameters of rainfed (Dry) and irrigated (Irr) wheat. DSS algorithm based on data from only the two seasons 2000 and 2001. Groups marked with close symbols (+N) received N application after heading, regardless of the DSS recommendation. Broken lines represent premium and penalty baselines.

11.5%, and especially where it is under 10%. The premium or penalty for wheat grain marketing in Israel reflects this classification. In Fig. 2, it is obvious that many sub-plots needed the late nitrogen application. Indeed, the late application increased the grain protein content. However, since most plots were under the conditions of a long-term fixed experiment, there were some with soil nitrogen content was so low that although late fertilization was applied the grain still had a low protein content. According to the DSS rules none of the irrigated plots were recommended for early harvest for hay, and indeed all plots could fill grains (test weight above 79 kg hl^{-1}). Since another rule ensured that none of the dry plots was recommended to receive additional nitrogen, many plots that could fill grains showed protein deficiency. However, although they produced adequate test weight, many plots were recommended to be harvested earlier for hay.

Grain yield is the highest economic priority for farmers, and harvesting for hay must be restricted to fields that suffer drought and cannot fill grains. The rain distribution (Table 1) could be one reason for the wrong DSS recommendations. Since the fields received at least 40 mm of rain after heading in the 2002 season, all the plants could fill grain. However, since this rain occurred only one month later than heading, the DSS used the option that no rain was forecast, therefore wrong decisions were made. When the DSS was run after the precipitation expected for the 2002 dry field was changed from false to true, this problem was solved (as shown in Fig. 3). Fig. 3 shows that this modification indeed restricted hay harvest to driest fields. However, the results in Fig. 3 raised a protein problem: there were too many plots that were recommended to be left for the grain harvest, but these plots were N deficient and yielded grain containing less than 11.5% protein. As the DSS must cover the full ranges of yield quantity and quality, the DSS procedure (Fig. 1) and wheat results (Figs. 2 and 3) ignore grain yield quantity. Better recommendations were achieved after the procedure had been modified according to yield level (Fig. 4). It is difficult to forecast the expected yield precisely, even at heading, but it is much simpler to judge whether to expect a high or a medium–low yield. Hence, the modified procedure needs as input a true/false answer to the question: is the grain yield expected to be higher than

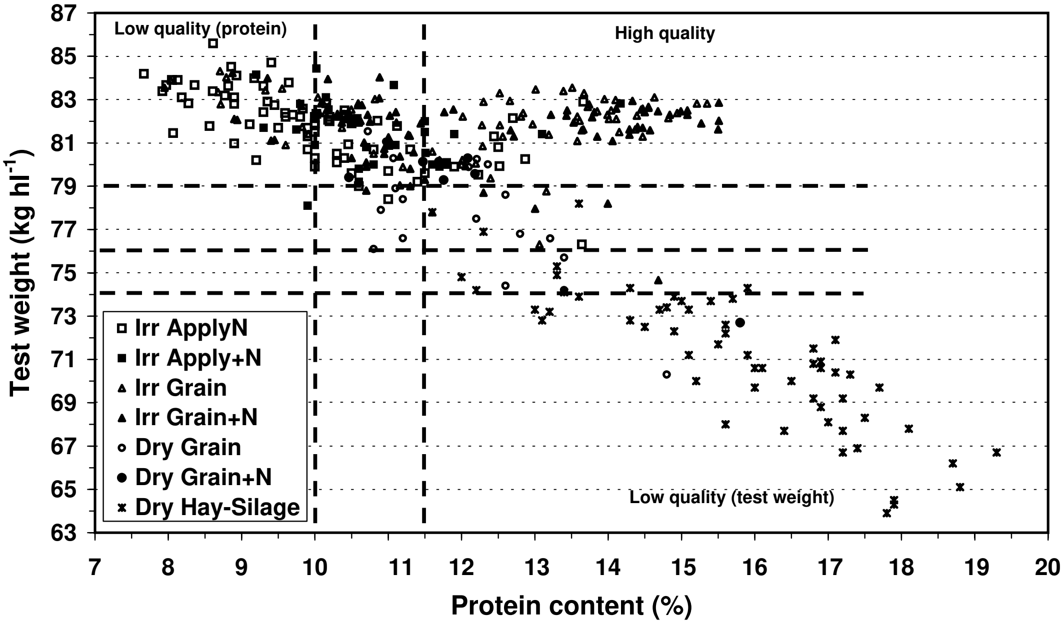

Fig. 3. DSS recommendations based on FLW and FLN at heading and grain quality parameters of rainfed (Dry) and irrigated (Irr) wheat. DSS algorithm based on data from only the first two seasons (2000 and 2001), but 2002 plots were modified to be considered as if the forecast for rain were correct. Groups that are marked with closed symbols (+N) received N application after heading, regardless of the DSS recommendation. Broken lines represent premium and penalty baselines.

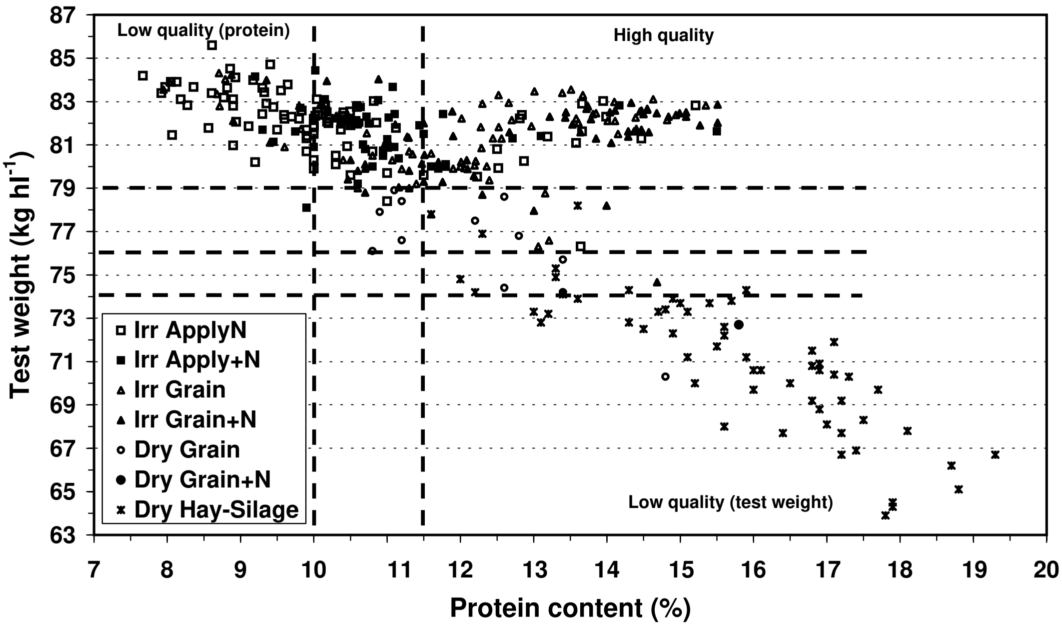

Fig. 4. DSS recommendations based on FLW and FLN at heading and grain quality parameters of rainfed (Dry) and irrigated (Irr) wheat. DSS algorithm based on plot data from all seasons, with yield level consideration. Groups marked with closed symbols (+N) received N application after heading, regardless of the DSS recommendation. Broken lines represent premium and penalty baselines.

Table 3
DSS recommendations based on FLW and FLN estimated directly or by flag leaf NIR reflectance, accuracy for each decision[a]

DSS recommendation	Late N application	Wet estimation		NIR estimation	
		True	False	True	False
Harvest hay	No	20	4	22	9
	Yes	35	0	36	0
Harvest grain, rainfed wheat	No	9	3	5	0
	Yes	0	1	0	0
Harvest grain, irrigated wheat	No	53	19	61	25
	Yes	49	15	49	11
Harvest grain but apply N at heading	No	73	15	68	6
	Yes	40	8	44	8
Total		279	65	285	59

[a] True or false scores have been assigned according to guiding principles listed in the text.

5000 kg ha^{-1}? For each yield level, the DSS procedure is the same as in the first version (Fig. 1), but FLW and FLN limit values are different for each condition.

3.3. Accuracy of the decision support system

The DSS recommendations and grain quality (Fig. 4) showed clear differentiation among the three main groups: high-quality grains, low-test weight quality, and low protein quality. To test the accuracy of the DSS recommendations for each decision, true/false scores were assigned according to the following three guiding principles. Hay harvest was a correct decision if the harvested grains had a test weight less than 75 kg hl^{-1}, and incorrect above this limit. This baseline (75 kg hl^{-1}) is a little higher than for grain (74 kg hl^{-1}), as profit declines steeply at 74 kg hl^{-1}, and we would like to minimize harvest of grain from these questionable fields as much as possible. Harvesting the grain was a correct decision if the harvested grains had a test weight above 74 kg hl^{-1}, and their protein content was above 11%. Leaving the field for subsequent grain harvest but applying N fertilization at heading was the correct decision if the harvested grains had a test weight above 74 kg hl^{-1} and their protein content was under 11.5% (or under 11.75% for plots that did receive a late N application, since they had increased protein content). Use of FLW and FLN data based on wet determination results, resulted in 279 correct and 65 incorrect decisions (Table 3). Almost the same results were achieved when DSS was based on reflectance data: 285 correct and 59 incorrect decisions. Hence, irrespective of the FLW and FLN determination method, more than 80% of the recommendations produced by the DSS were correct.

4. Discussion

The DSS procedure was able to distinguish between plots at heading and to relate their differences to expected yield quality. This procedure requires just a few input parameters. This DSS has a marked advantage over any crop growth model that needs as input many parameters that are not available for most commercial fields. The FLW and FLN must be determined for each field. Usual laboratory procedures can supply these data within 48 h, and advanced equipment can do so in less than 1 h. The possibility of obtaining these data from reflectance spectra opens the possibility that in the future FLW and FLN data would be obtained by remote sensing means such as satellite or aerial hyperspectral imaging, without the need for field sampling. This would yield data relevant to a wide area very quickly.

Flag leaf N content was reported to provide a reasonable indication of the extent to which late-season N could increase grain protein. This DSS deals with the complicated water-nitrogen interaction that affects crop growth and yield production. This interaction leads to different interpretations of FLN, so that a given FLN can lead to any of the three possible DSS recommendations. Correct data interpretations enable correct decision making for hay harvesting, to our knowledge, no tool that assists this decision is available yet. Therefore, among the many fields that are harvested for hay in dry seasons are fields that could produce good grain yields, which would provide a higher income than hay. At heading, the farmer receives the DSS recommendation based on FLW and FLW for all four combinations of precipitation and yield forecast. Therefore, farmers can delay their decisions and finalize them according to real conditions as they change for each field. This delay would increase profitability since accurate data on heat stress, rain, foliar disease, etc. would be involved in decision making.

The DSS could be improved, and some important points must be considered in the next development stage. First, the DSS development was based on only one cultivar growing in experimental plots, and, since the reflectance from leaves of different cultivars may differ, the ability to use reflectance information must be tested. Moreover, different cultivars differ in many parameters, such as phenology, grain-filling rate, FLN, late N absorption and translocation to grain, that could necessitate the designation of specific FLN and FLW limits for each cultivar. Our hypothesis is that all cultivars can be classified into two or three groups according to these parameters, and this must be proved by further work. Another point to be checked is the effect of atmospheric interference on the option of obtaining FLN and FLW data by spectroscopic methods. The most important work that should be done is validation in commercial fields. It is planned to do this in the coming growth seasons. However, since the development of the DSS procedure was based on a very wide range of grain yield and grain quality data, that included yield data for regular fields, it is expected that accuracy would be high for commercial fields as well. At least, the suggested DSS would be suitable for about 50% of Israeli fields that were sown with cv. Galil, the cultivar that was used for the DSS development.

The DSS was developed for spring wheat grown under Mediterranean-type environments of the northern Negev in Israel. In about 1 out of 4 years, a sufficient amount of rain falls after heading to enable a late N application in dryland fields, although the total rain quantity is low. Hence, using DSS is not restricted to fields that receive supplemental irrigation. Moreover, in regions where rainfall occurs more frequently during grain-filling, the DSS can be used to determine the possibility of late fertilization in more seasons. This DSS can be used for dryland fields and soils with low water retention capacity; it is thus suited for considering water shortage situations, where decision making would be focused mainly on early harvesting for hay instead late fertilization. These decision combinations make the DSS powerful and useful for growth conditions in many regions. DSS adaptation and tuning to other regions would be affected by several factors, including cultivars, soil types and field management. All these data would affect the FLN and FLW level used by the DSS, which can be useful in many regions with Mediterranean climates.

5. Conclusions

The ability to monitor changes in wheat plant growth conditions according to changes in the FLW and FLN, directly or by means of near-infrared reflectance, could lead to a considerable improvement in crop management. In the present study we demonstrated that FLW and FLN data can be used to support agronomic decision making. In particular, these data can assist the decision to harvest early for hay or silage, when water stress is detected and the test weight is expected to decline. In other cases, these data could help forecast the need for late nitrogen application, in order to ensure sufficient protein levels. This DSS provided correct forecasts of grain quality parameters (test weight and protein) for more than 80% of 344 plots, by testing just the flag leaves at heading. Therefore, application of the suggested simplified DSS would reduce the harvesting of shriveled grains, on the one hand, and would lead to improved grain protein, on the other hand, thus ensuring high-quality production.

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