Working Paper 25

Reliable high-throughput Phenotyping Tools to assess Adaptive Traits for Wheat in Drought Environments

- Delivering germplasm with enhanced productivity under drought to the Central and West Asia and North Africa region
- Developing innovative methodology to determine water soluble carbohydrates from standing crops using proximal hyperspectral sensing
- Building capability in phenotyping and trait selection

Acknowledgements
We are greatful to Greg Rebetzke (CSIRO) for contributing lines contrasting for tillering and early vigour and Bangyou Zheng and Scott Chapman (CSIRO) for help linking ground cover images to crop simulation and Amy Chan (CSIRO) for help with image analysis.
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ICARDA and the authors of this document would like to thank all those involved whose contributions have made this activity a success.

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ISBN: 92-9127-451-8

Key words: drought, wheat, CWANA, germplasm, NARS, phenotyping

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Executive Summary

This project successfully demonstrated the value of ICARDA's elite drought nurseries for the CWANA region and highlighted the opportunity to breed for specific adaptations. The great environmental diversity of the CWANA region, particularly weather and soil, underscores the importance of this work.

The following notable outcomes resulted from this project:

- The strength of ICARDA germplasm lines was demonstrated when the ICARDA lines outperformed local checks in Morocco, Ethiopia, and Syria.
    - As a result, 23 ICARDA lines are being used in Moroccan NARS breeders crossing blocks.
    - Ethiopian NARS breeders identified 15-20 lines with better performance under drought, and also stem and yellow rust resistance to the Ethiopian pathotypes. Crossing started in 2010 and selections have been tested in preliminary National Variety Trials.
- Great interest was stimulated by combining knowledge on the adaptive value of the traits and appropriate phenotyping technique, accompanied by field practice.
- The cutting-edge development of a methodology to determine water soluble carbohydrates from standing crops using proximal hyperspectral sensing.
- A proof of concept of how to link proximally sensed data and crop simulation modelling to deliver results on complex traits was developed using ground cover images to predict biomass as a case study.
- Capacity building training for NARS through two workshops held in May 1-5, 2010 and April 15-18, 2013 on field phenotyping for drought adaptive traits. Trainees were from Ethiopia, Morocco, Sudan, Syria and Tunisia

Understanding the specific traits behind the drought adaptation of ICARDA's wheat germplasm has the ability to have a positive impact on yields and improve adaptation to drought throughout the globe.

1. Introduction

Drought continues to be a major limiting factor to wheat crop production worldwide with often devastating consequences, especially in developing countries. While ongoing research focuses on understanding the wheat genome and its genetic variability with the aim of improving adaptation to drought, advances are limited by the lack of methods for reliable high-throughput phenotyping that allows the monitoring of complex traits. Such monitoring results in data on traits and trait combinations that is most relevant to different patterns of drought.

ICARDA is responsible for the improvement of bread wheat in the Central and West Asia and North Africa region (CWANA), covering a range of agro-ecological zones – continental, temperate and low latitude regions which count among the poorest with the most spatial and variable rainfall distribution pattern in the world. Understanding the specific traits behind the drought adaptation of ICARDA's spring wheat elite germplasm would facilitate exchange and deployment of germplasm with relevant National Agricultural Research Systems (NARS) and help focus molecular breeding efforts.

With the goal of enhancing wheat productivity under drought, the objectives of this project were to assess the relative impact of putative key traits on drought adaptation by comparing related lines contrasting in trait value in different drought mega-environments and develop and validate field-based, high-throughput phenotyping tools to assess traits relevant to water limited conditions. This knowledge was applied to characterize elite ICARDA lines and build capability in non-invasive phenotyping methods and the estimated value of different traits, particularly within CWANA.

2. Project Implementation

The relative impact of key physiological traits and the performance of elite ICARDA germplasm were tested in sites of contrasting drought patterns, representative of the main wheat growing mega-environments. All project lines were genotyped with whole genome profiling markers using Diversity Arrays Technology (DArT) plus markers linked to key developmental, e.g. vernalisation (VRN1) and photoperiod (PPD1), and other important agronomic genes.

Trials were grown in locations around the world representing three environments:

(1) **Summer dominant environments with terminal drought**: Ethiopia, Mexico and Northern Australia
(2) **Mediterranean type winter rainfall**: Syria, Lebanon, Morocco
(3) **Even rainfall distribution**: Southern Australia

Thirty-eight “location x year x management” combinations were tested between 2009 and 2012. A set of germplasm, consisting of about 200 elite ICARDA lines, were assessed together with related lines contrasting in trait value for transpiration efficiency, tillering, stem water soluble carbohydrates, early vigour and flowering, and a set of globally important checks.

3. Activities

3.1 Physiological and genotypic characterization of germplasm

In wheat, traits with successful impact under drought have the ability to increase water use, shift water use to critical crop periods, increase water use efficiency and/or influence biomass partitioning to the grains. To prioritize traits between regions and decide which ones would be most useful to combine, a comparative appraisal of their effects is required under contrasting water availability patterns.

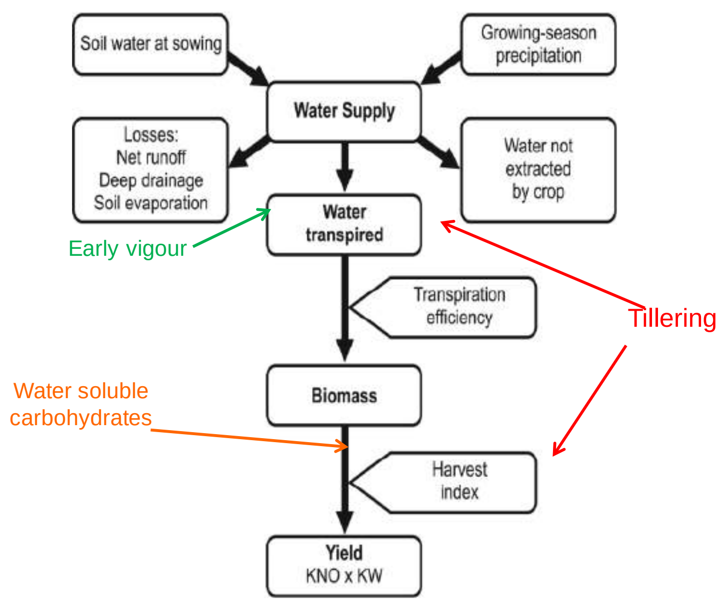
This activity aimed to quantify the relative impact of key physiological traits and the performance of ICARDA germplasm in regions of contrasting drought patterns, representative of the main wheat growing mega-environments. During 2009 to 2012, 38 trials took place in locations around the world representing summer dominant environments with terminal drought, Mediterranean type winter rainfall distribution, and even winter rainfall (Table 1).

Germplasm consisted of three groups of lines:

- (i) ICARDA lines from the elite drought nurseries (up to 200);
- (ii) Related lines (also called "training set") in one or more backgrounds contrasting in trait value for transpiration efficiency, tillering, stem water soluble carbohydrates, early vigour, and flowering (36 to 72 depending on trial); and
- (iii) A set of globally important checks.

Lines in group (ii) were chosen because of the potential impact of the trait on the processes underlying water productivity as described by Passioura and Angus (2010) (Figure 1). The maximum number of lines tested in any given trial was 200. During 2008, lines in group (ii) were sent to Mexico and ICARDA from CSIRO. In the same year, lines from group (i) were sent from ICARDA to CSIRO for multiplication. Consequently, trials sown and harvested in 2009 in Australia and sown in 2009 and harvested in 2010 in CWANA only had either group (i) or (ii) and the checks. Only group (ii) and (iii) were tested in Mexico.

Figure 1. Traits in training set of lines and their expected influence on different aspects of the water productivity scheme by Passioura and Angus (2010).



Multi-environment trial (MET) analyses of traits across locations and years were performed using the linear mixed model described by Oakey et al. (2007). This model is an extension of the factor analytic model by Smith et al. (2001) for MET analysis. This extension includes an additive relationships matrix in the mixed model with the objective of reflecting the expected degree of co-ancestry among the genotypes in the study (Mathews et al., 2007; Oakey et al., 2007), which in turn allows for the partitioning of the genetic effects of the genotypes into additive and residual non-additive effects (Oakey et al., 2006). Factor analytic model facilitates exploring the total genotype by environment (gxe) interaction (which can be partitioned into additive x environment and non-additive by environment interactions) through graphical displays such as heat-maps of the genetic correlation matrices. Cluster analysis can be applied to the genetic correlation matrices to identify groups of environments where genotypes performed similarly.

The trials encompassed a wide range of environmental conditions, with mean yields varying from less than 0.5 to 6.5 Mg ha^{-1} (Table 2). The average percentage of genetic variance explained by the factor analytic model with 2 factors was: 60.3%, ranging from 5.5 to 100%. Ranking of lines between pairs of sites showed specific adaptation for yield, as would be expected for locations with contrasting water availability and rainfall distribution (Figure 2). Examples are the clusters with Moroccan vs. Ethiopian (plus one Mexican) sites, as representative of in-season rainfall (Mediterranean) versus stored soil moisture (terminal drought) environments respectively.

Figure 2. Heat map of genetic correlations for total variance based on the pedigree model. Red means positive and blue negative correlations

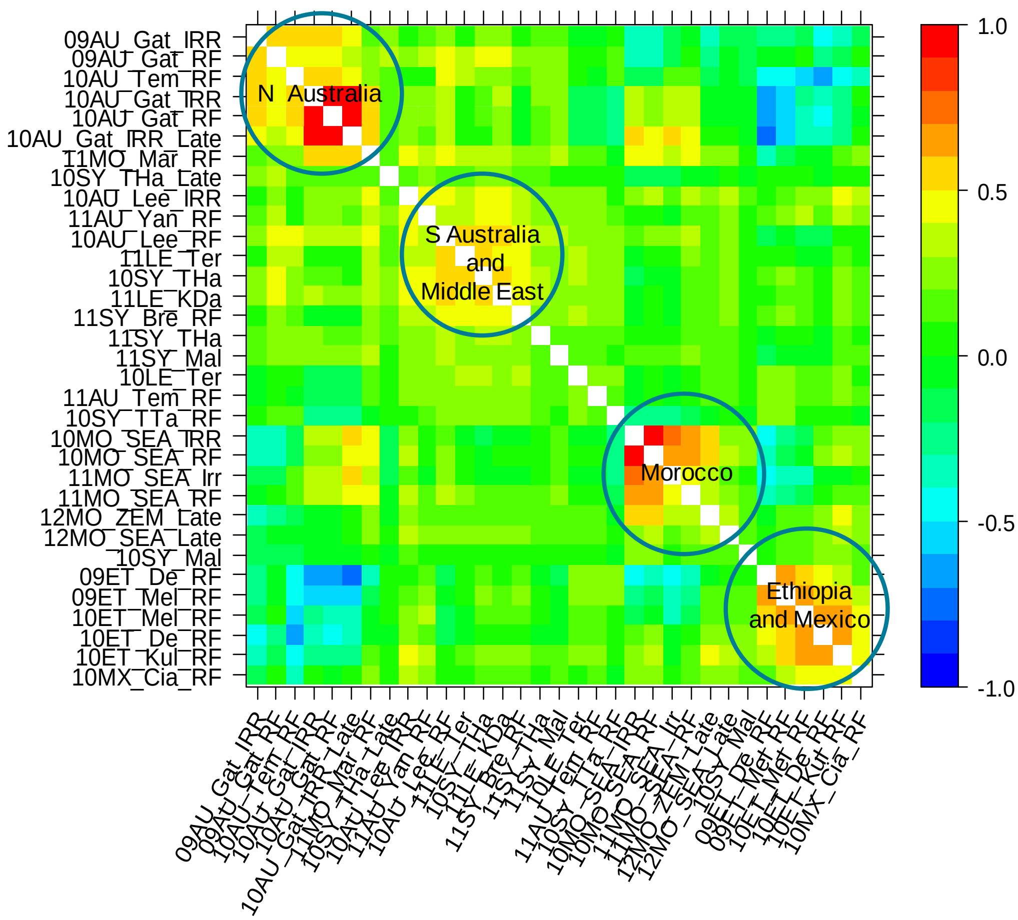


Table 1. Trial location, coordinates, acronym, and target management

Country	Site	Latitude (decimal)	Longitude (decimal)	Altitude (m asl)	Trial acronym	Management	
						Water	Sowing Date
Syria	Tel Hadya	36.01	36.93	284	10SY_THa	Rainfed	Normal
					10SY_THa_Late	Irrigated	Late
					11SY_THa	Rainfed	Normal
	Breda	35.93	37.17	300	11SY_Bre_RF	Rainfed	Normal
	Al Malikiya	37.16	42.13	500	10SY_Mal	Rainfed	Normal
					11SY_Mal	Rainfed	Normal
	Tel Tair	37.02	40.70	436	10SY_TTa_RF	Rainfed	Normal
Australia	Gatton	-27.54	152.34	89	09AU_Gat_IRR	Irrigated	Normal
					09AU_Gat_IRR_Late	Irrigated	Late
					09AU_Gat_RF	Rainfed	Normal
					10AU_Gat_IRR	Irrigated	Normal
					10AU_Gat_IRR_Late	Irrigated	Late
					10AU_Gat_RF	Rainfed	Normal
	Leeton	-34.55	146.40	151	10AU_Lee_IRR	Irrigated	Normal
					10AU_Lee_RF	Rainfed	Normal
	Yanco	-34.62	146.43		11AU_Yan_RF	Rainfed	Normal
	Temora	-34.41	147.52	270	10AU_Tem_RF	Rainfed	Normal
					11AU_Tem_RF	Rainfed	Normal
Ethiopia	Dera	8.32	39.32	1680	09ET_De_RF	Rainfed	Normal
					10ET_De_RF	Rainfed	Normal
	Melkassa	8.24	39.21	1550	09ET_Mel_RF	Rainfed	Normal
					10ET_Mel_RF	Rainfed	Normal
	Kulumsa	8.00	39.15	1850	10ET_Kul_RF	Rainfed	Normal
Morocco	Sydi el Aydi	33.12	-7.63	253	10MO_SEA_IRR	Irrigated	Normal
					10MO_SEA_RF	Rainfed	Normal
					11MO_SEA_Irr	Irrigated	Normal
					11MO_SEA_RF	Rainfed	Normal
					12MO_SEA_Late	Irrigated	Late
	Marchouch	33.56	-6.69	446	11MO_Mar_RF	Rainfed	Normal
	Zemamra	31.90	-7.10	656	12MO_ZEM_Late	Rainfed	Late
Mexico	Ciano, Obregon	27.35	-109.33	38	09MX_Cia_IRR	Irrigated	Normal
					10MX_Cia_IRR	Irrigated	Normal
					10MX_Cia_RF	Rainfed	Normal
					11MX_Cia_IRR	Irrigated	Normal
					11MX_Cia_RF	Rainfed	Normal
Lebanon	Kfr Dahn	34.02	36.05	1080	11LE_KDa	Rainfed	Normal
	Terbol	33.82	35.98	890	10LE_Ter	Rainfed	Normal
					11LE_Ter	Rainfed	Normal

Table 2. Trial location and summary statistics of yield

Country	Site	Trial acronym	Yield (Mg ha^{-1})	SE predicted value	Number of lines
Syria	Tel Hadya	10SY_THa	2.99	0.18	200
		10SY_THa_Late	1.34	0.14	200
		11SY_THa	3.25	0.22	200
	Breda	11SY_Bre_RF	2.77	0.18	200
	Al Malikiya	10SY_Mal	1.96	0.60	200
		11SY_Mal	4.86	0.49	200
	Tel Tair	10SY_TTa_RF	0.36	0.08	200
Australia	Gatton	09AU_Gat_IRR	6.25	0.56	72
		09AU_Gat_IRR_Late	5.62[A]	-	72
		09AU_Gat_RF	5.20	0.40	72
		10AU_Gat_IRR	5.89	0.97	128
		10AU_Gat_IRR_Late	5.00	0.64	72
		10AU_Gat_RF	5.89	0.88	131
	Leeton	10AU_Lee_IRR	4.01	0.27	72
		10AU_Lee_RF	3.65	0.27	72
	Yanco	11AU_Yan_RF	5.54	0.45	64
	Temora	10AU_Tem_RF	5.45	0.66	72
		11AU_Tem_RF	3.91	0.47	64
Ethiopia	Dera	09ET_De_RF	0.35	0.10	200
		10ET_De_RF	2.25	0.29	200
	Melkassa	09ET_Mel_RF	0.76	0.21	200
		10ET_Mel_RF	2.31	0.45	200
	Kulumsa	10ET_Kul_RF	3.58	0.55	200
Morocco	Sydi el Aydi	10MO_SEA_IRR	1.88	0.43	200
		10MO_SEA_RF	1.79	0.39	200
		11MO_SEA_Irr	4.23	0.76	200
		11MO_SEA_RF	4.47	0.66	200
		12MO_SEA_Late	2.23	0.88	200
	Marchouch	11MO_Mar_RF	3.22	0.55	200
	Zemamra	12MO_ZEM_Late	2.45	0.59	200
Mexico	Ciano, Obregon	09MX_Cia_IRR	4.11[B]	0.51	47
		10MX_Cia_IRR	6.50[B]	0.76	47
		10MX_Cia_RF	2.99	0.50	47
		11MX_Cia_IRR	5.54[B]	0.70	47
		11MX_Cia_RF	1.18[B]	0.29	47
Lebanon	Kfr Dahn	11LE_KDa	3.98	0.35	200
	Terbol	10LE_Ter	3.06	0.40	200
		11LE_Ter	4.89	0.41	200

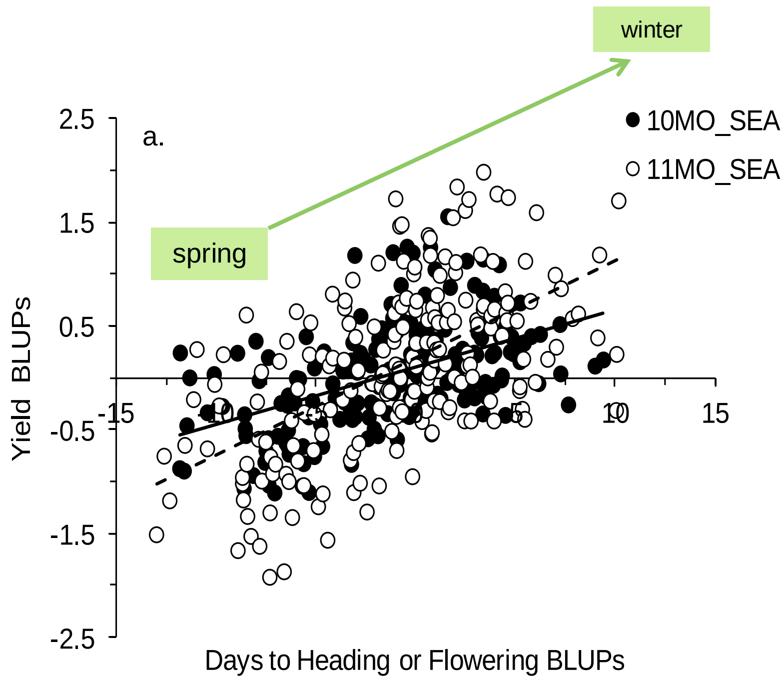
[A] This was not included in the MET analysis as it did not have additive genetic variance

[B] Information on these trials arrived at a later stage and was analysed separately

3.1.1 Results in Morocco

In Morocco, for Sidi El Aydi, yields ranged from 1-3 to 2-6 t ha^{-1} in 2010 and 2011 respectively. Yield was associated with a longer cycle to heading or flowering (Figure 3a) and was correlated to biomass, harvest index and grain number per unit area (data not shown). The spread of flowering dates was underpinned by changes in the allelic composition of the vernalisation gene VRN1, i.e. VRN1A, VRN1B and VRN1D, from spring to winter types. Capital letters indicate lower vernalisation requirement, and hence shorter time to flowering, as seen in spring lines. Interestingly, ICARDA germplasm had lines with abundance of A1a, a very strong spring allele with a promoter insertion, but also lines with need for vernalisation (e.g. abD form). Flowering occurred later with the following order in terms of allelic combinations of VRN1: A1aBD<A1aBd=A1abD<aBD=abD. It was also clear from the survey of allelic variation of development genes that the vast majority of lines were insensitive to photoperiod in Ppd1.

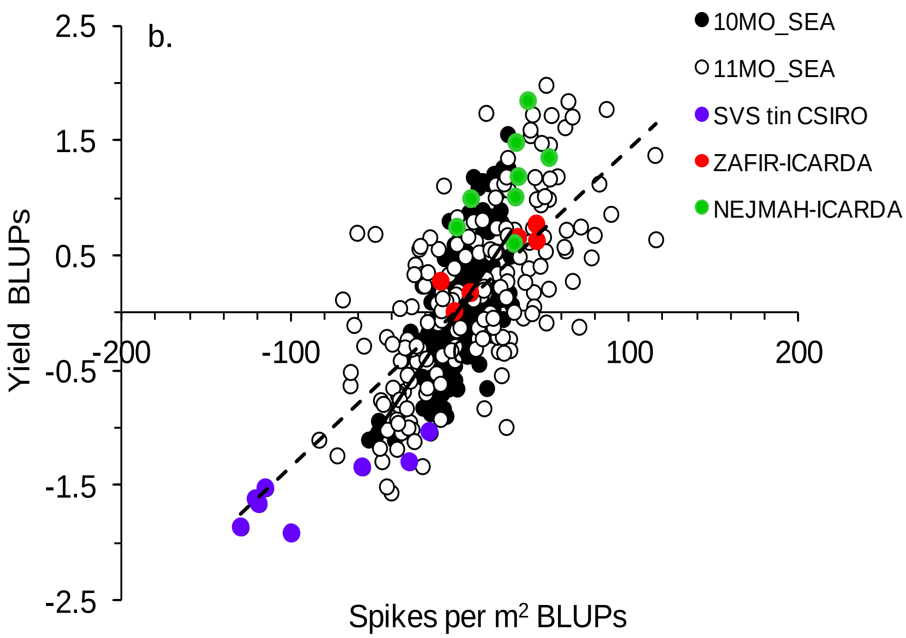
Figure 3. Yield best linear unbiased prediction (BLUPs) versus days to flowering or heading BLUPs in Trials in Sidi El Aydi, Morocco in 2010 and 2011. The spring to winter signs indicate the spread of lines with less to more vernalisation requirement.



In Sidi El Aydi, yield was positively associated with spike production per unit area, across flowering dates. To illustrate this point, Figure 4 presents different colouring for Silverstar lines, an Australian spring early flowering background with or without tin gene (CSIRO); and the Zafir (A1aBd) and Nejmah (aBD) families from ICARDA's nursery, with some vernalisation requirement. Silverstar derivatives flowered approximately seven days earlier and ICARDA lines less than a day later compared to the site average.

Hence longer cycles and higher spike number production were desirable traits under the Moroccan conditions at two different yield levels. Sensitivity to photoperiod could be further exploited at this latitude as means of fine-tuning flowering and increasing the length of the stem elongation period, conducive to higher grain number production (Miralles et al., 2000).

Figure 4. Yield BLUPs versus number of spikes per unit area BLUPs in Trials in Sidi El Aydi, Morocco in 2010 and 2011. Sets of lines have been highlighted that contrast for flowering date and have a spread of spike number.



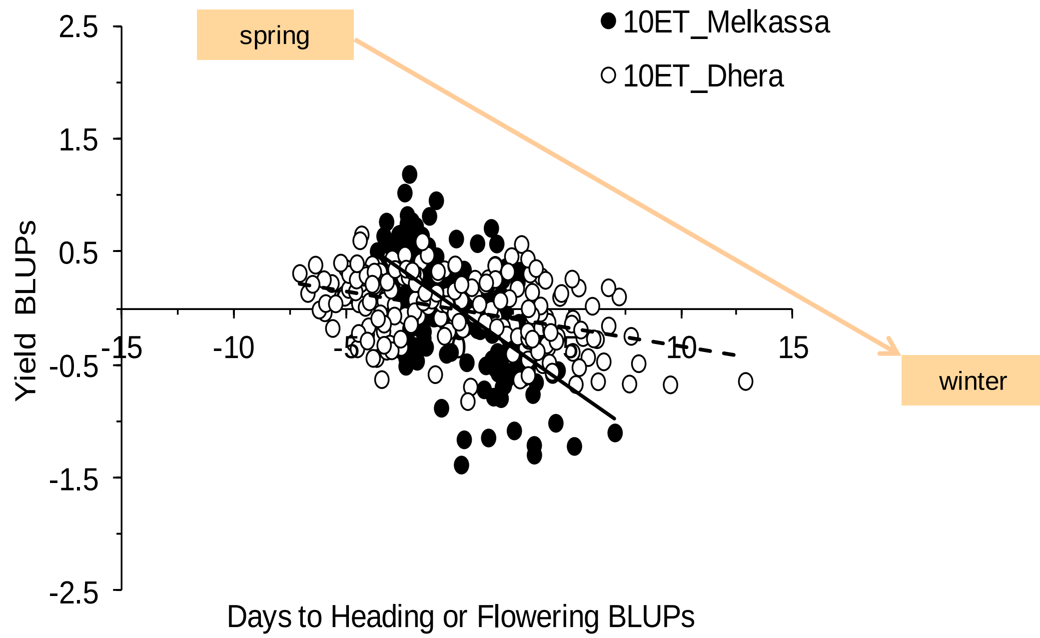
As a result of ICARDA lines outperforming their best line (Arrehane), 23 ICARDA lines are being used in Moroccan NARS breeders crossing blocks.

3.1.2 Results in Ethiopia

In Ethiopian environments with terminal drought due to a combination of poor water retention capacity of the soils and lack of rainfall during grain filling, early maturing lines, featuring low vernalisation requirements, did better in terms of yield (Figure 5). Yield was correlated with grain number (data not shown) but there was little variation in spike number per unit area (10ET_De_RF: 765, SE= 6.2; 10ET_Mel_RF: 518, SE=2.9), with grains per spike being the most important component. Genotypic variation in the earliness per se response and a higher rate of spikelet production could be investigated as traits that could underpin early maturing lines with higher grains per spike production. In terms of water saving traits, lines with high carbon isotope discrimination ability that were part of the training set of lines did comparatively better (25% higher yield) than their counterparts in these environments.

As a corollary of these activities, Ethiopian NARS breeders identified 15-20 lines with better performance under drought, and also stem and yellow rust resistance to the Ethiopian pathotypes. Crossing started in 2010 and selections have been tested in preliminary National Variety Trials.

Figure 5. Yield BLUPs versus days to flowering or heading BLUPs in trials in Melkassa and Dhera, Ethiopia, 2010. The spring to winter signs indicate the spread of lines with less to more vernalisation requirement.



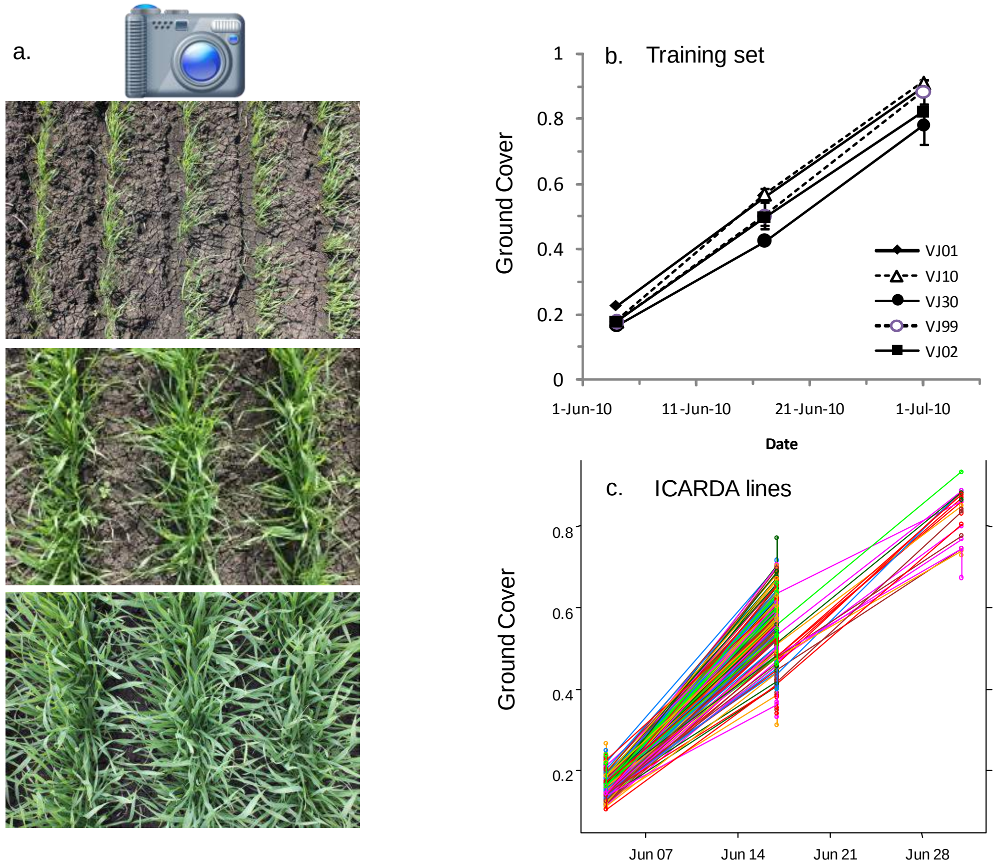
3.2 Field remote sensing methodologies

An array of field remote sensing methodologies were applied and/or developed to survey the phenotypic variation in the material under study. This report showcases particular aspects of target traits.

3.2.1 Early growth and cover

Early vigour has been referred to as a trait useful for Mediterranean type rainfall environments (winter rainfall) as potentially contributing to shift the balance between evaporation from the soil in favour of transpiration by the crop in seasons with medium to high rainfall and for better weed competitiveness (Botwright et al., 2002; Rebetzke et al., 2004). In trials conducted at Gatton, Australia, digital imaging was utilised as a cheap technology to quantify ground cover quantitatively, both in the set of isolines from the training set differing in early vigour (from G. Rebetzke, *pers. comm.)* and in ICARDA lines. The images were analysed using proprietary software developed by CSIRO (P. Jackaway *pers. comm*.), but commercial software could be used. ICARDA lines exhibited greater variation in early ground cover than that observed in the training set (Figure 6(a) and (b)).

Figure 6. (a) Progression of images showing differences in early cover in the same plot over time. (b) Ground cover calculated from digital images in the early vigour training set and the ICARDA lines. Vertical bars are 2xSE.



3.2.2 Quantitative remote sensing monitoring of stem water soluble carbohydrates (WSC) in the field

Development of a high-throughput, field-applicable, phenotyping technique would benefit agronomy/physiology applications and also help its quantification in wheat breeding programs. Leveraging on data from a previous project, we concentrated on developing the methodology. Additional data collected on the germplasm in this project will be used for validation after the method is published.

The aim was to evaluate if it was possible to estimate the concentration (WSCc, mg g^{-1}) and amount (WSCa, g m^{-2}) of stem WSC in wheat canopies in situ non-destructively using a hyperspectral sensor, as opposed to currently available labour intensive laboratory methods. In two successive years, hyperspectral reflectance data was proximally obtained (Figure 7) at varying developmental stages from the canopy of wheat trials with a limited number of related genotypes growing under a range of management treatments.

Further data was also collected for technique validation, including surveying ICARDA lines. The data was calibrated, firstly independently for each year and then jointly, to provide a measure of stem water soluble carbohydrate, using partial least square regression on wavelengths in the range of 350-1290 nm. Pre-treated spectra (second derivative) enabled calibrations for the combined years with WSC concentration (WSCc, mg g^{-1}) (r^2 = 0.90) and WSC amount (WSCa, g m^{-2}) (r^2 = 0.88) of water soluble carbohydrate in the stems (Figure 8).

Figure 7. (a) View of the equipment mounted on the quadbike. (b) Schematic overview of the field of view of the instrument, which is centered in a section on row 4 of the 7-row, 8m long plot.

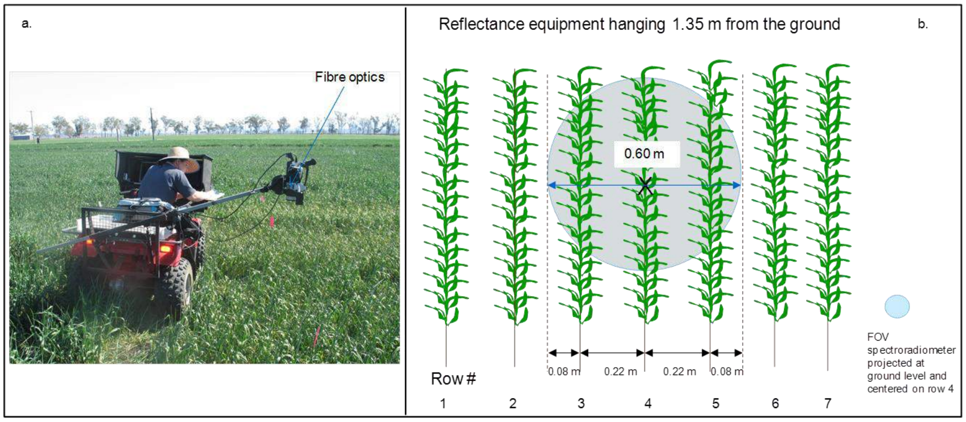
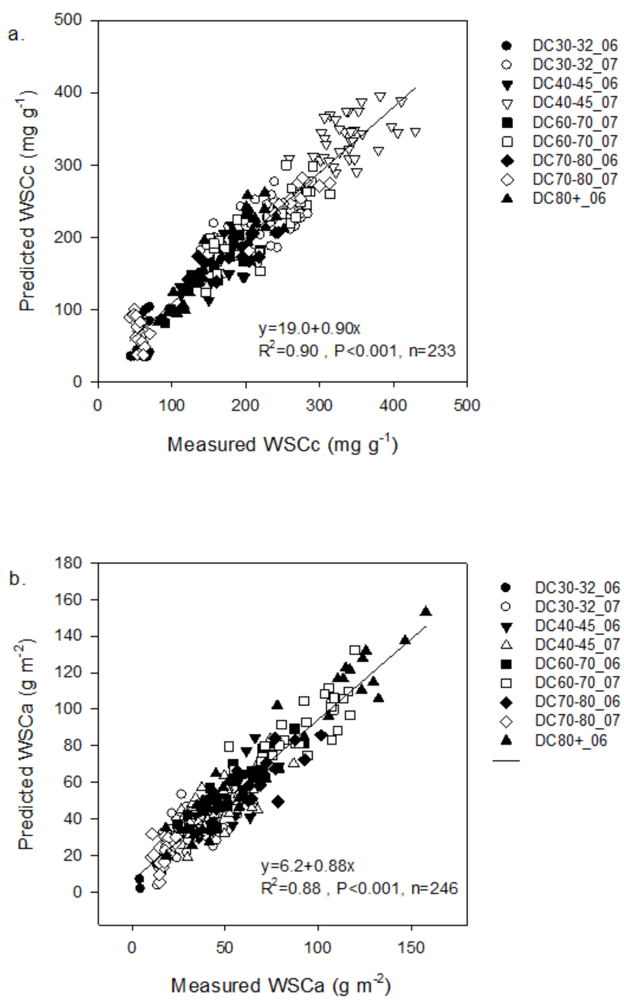


Figure 8. Partial Least Square (PLS) regression calibration plots of NIR (ranges A (350-988 nm) and B (1010-1290 nm) combined) predicted vs. measured WSCc for 2006 and 2007 (a) and predicted vs. measured WSCa for 2006 and 2007(b).



Crop phenological stages were recorded using the decimal code (DC) of Zadoks et al. (1974), with anthesis diagnosed when 50% of the spikes had anthers extruded (DC65). Across trials, samples were taken at one or more of the following stages (1) from start of stem elongation till the swelling of the second node was detectable (DC30-32), (2) from early to full boot, i.e. when the spike is enclosed in the sheath of the flag leaf (DC40-45), (3) once spike emergence was complete, from the beginning of flowering to the beginning of grain growth (DC60-70), (4) during the “milk” stage or active grain filling (DC70-80) and (5) during the “dough” stage of grain filling, when grains have increasingly higher content of solids (DC80+).

In addition, the same measurement could be used to simultaneously predict other canopy properties, such as leaf area index and canopy water content (data not presented). This study has shown that calibration models from canopy level data can robustly predict the dynamics of WSC throughout crop stages and treatments, while including variation in indices diagnostic of crop water and cover status, such as the Water Index (Penuelas et al., 1993) and Enhanced Vegetation Index (Huete et al., 1994). Promising WSC prediction using spectral data below 1000 nm needs to be investigated further, in order to harness the impact potential of this approach

3.2.3 Linking remote sensing and dynamic crop simulation to predict complex traits
Remote sensing information can be used as input to a crop simulation model to deliver improved predicted values of complex traits that are impractical to measure in breeding trials but may provide a better understanding of seasonal dynamics, e.g. biomass and water use of probe genotypes.

Remote sensing information for ground cover estimates, in combination with the model APSIM Wheat 7.4 (Agricultural Production Simulator, www.apsim.info), can be used to test if total biomass, and eventually water use, could be predicted. An experiment was set up with six genotypes, in pairs contrasting for phenology, protein production and tillering, in combination with two levels of N availability to create differences in early growth. Ground cover was photographed at regular intervals and matched with harvests where plants were partitioned. Leaf area and biomass was measured and leaf area index (LAI m^2 leaves m^{-2} ground) calculated. Phenology observations were taken to enhance the model's reliance on accurate information. Parameterisation regarding the extinction coefficient (kl) and specific leaf area was optimised to fit the calculated ground cover with minimal error. Model outputs regarding ground cover, LAI and biomass are shown in Figure 9.

The evolution of ground cover and biomass for all treatments was successfully predicted (Figure 10), which is a solid first step towards proving that the idea of predicting complex traits, such as water uses, is viable. This type of information developed on probe genotypes could help characterize the stress pattern of a particular site, further informing GxE interactions. In addition, deviations between a probe genotype and unknown ones could be used to generate genotypic rankings/clusters based on a complex phenotype.

Figure 9. Images used as input to APSIM for prediction of ground cover, LAI and total biomass. Data (points) and simulations (lines) for high (red) and low (blue) N levels in the Long season genotype

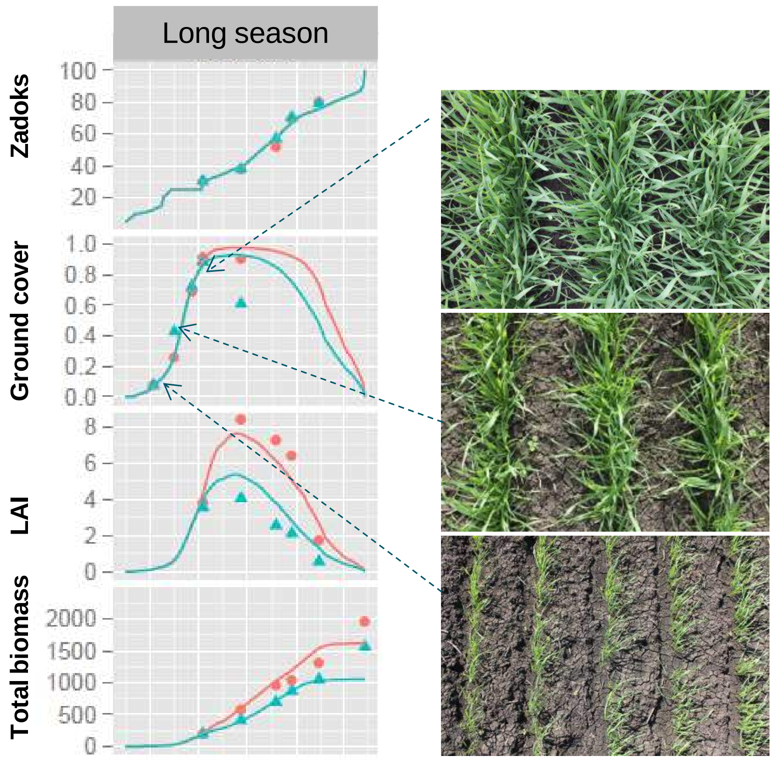
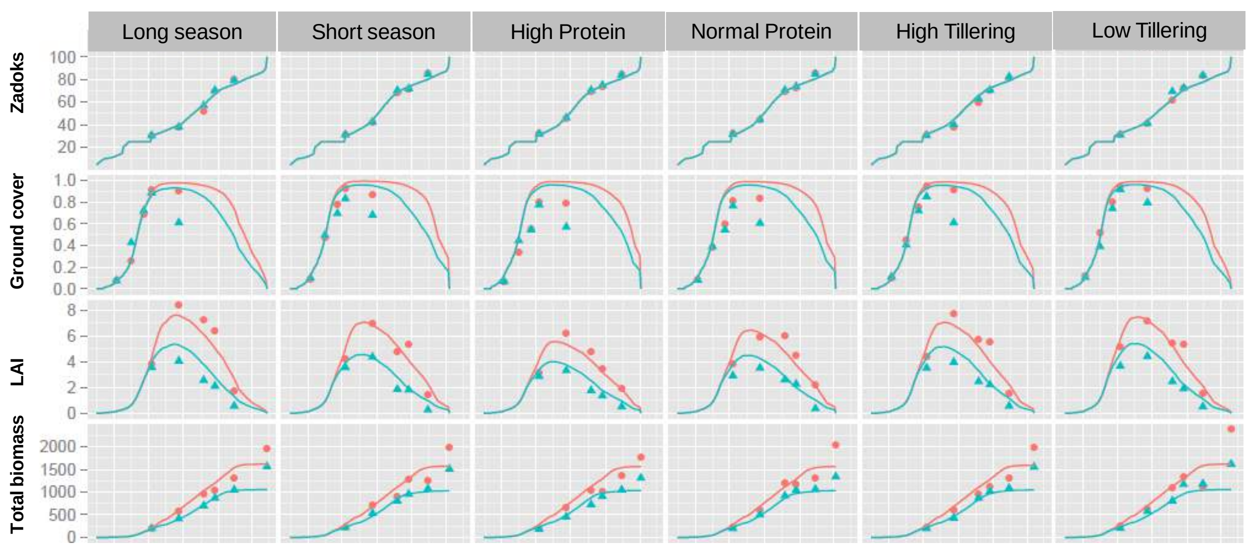


Figure 10. Data (points) and simulations (lines) for high (red) and low (blue) N levels in the genotypes tested, using ground cover images for validation and the simulation framework described in this section.



4. Capacity Building

Two workshops were held during the lifetime of the project. The first workshop took place from May 1-5, 2010, at ICARDA's headquarters in Syria. There were twelve participants from Australia (2), Morocco (2), Ethiopia (2), and Syria (6), the later comprising of two NARS each from Sudan and Syria respectively. Theory, protocols and field experiments were discussed and practised and activities coordinated. Part of the group also travelled to Morocco to visit field sites and discuss further activities.

The second workshop was held in Rabat, Morocco, April 16-18, 2013, with nine participants from Morocco, Sudan, Tunisia, Australia, and Ethiopia. The main topics discussed include traits for increased water productivity, non-invasive high throughput phenotyping, FIGS, and breeding methodologies. The workshop also included a trip to Sidi El Aydi Experimental Station (field practical) and Marchouch Experimental Station (overview ICARDA and INRA breeding program wheat/barley).

Figure 11. Participants at the Rabat-held meeting during a phenotyping field practice session

5. Conclusion

This project quantified the relative impact of key physiological traits and the performance of ICARDA germplasm in regions of contrasting drought patterns, representative of the main wheat growing mega-environments. Different traits were highlighted for sites relying on in-season rainfall (e.g. spike number production in Morocco) compared to areas with stored soil moisture (e.g. grains per spike production and transpiration efficiency in Ethiopia). In both cases, opportunities continue for breeding programs to further explore and introduce new genetic variation related to optimizing water use and production of yield components. For example, photoperiod sensitivity could be introduced for Moroccan-type environments and a faster spikelet development rate could be considered in low latitude Ethiopian highlands.

In terms of phenotyping, the combination of knowledge on the adaptive value of the traits and appropriate phenotyping technique, accompanied by field practice, was of great interest to course attendees and project participants. The development of a methodology to determine water soluble carbohydrates from standing crops using proximal hyperspectral sensing and the attempts to link ground cover and simulation modelling to predict seasonal course of biomass are extremely innovative.

NARS breeders have recognised the value of some of the tested ICARDA germplasm by incorporating lines in their crosses. A follow up to this investigation in drought prone CWANA (or other water limited areas in SE Asia) could successfully combine dynamic crop simulation modelling in a larger number of sites in the region using historical weather data to highlight trait combinations with the highest value proposition. These ideas can then be tested in past/current nursery data and advance crosses with targeted combination of traits could occur.

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6. Annexes: Conference and Journal papers published from the results of this project

Conference papers

Makdis F, Abdalla O, Hakim MS, Ogbonnaya FC (2009). Characterization of drought adaptive traits for the improvement of bread wheat in Mediterranean environments. In: 3rd International on integrated approaches to improve crop production under drought-prone environments (InterDrought III), 11-10 October 2009, Shanghai, China.

Makdis F, Ogbonnaya FC, Baum M and Abdalla O (2010). Grain yield performance of synthetic backcross derived wheat in rain-fed Mediterranean environments. In N.I. Dzyubenko (Ed.) 8th International Wheat Conference N.I. Vavilov Research Institute of Plant Industry (VIR) 1–4 June 2010 St. Petersburg, Russia.

Dreccer MF, Condon AG, Makdis F, Barnes L, Ouabbou H, Eticha F, Reynolds M, Borgognone MG, Rebetzke G, Ogbonnaya FC. (2013) Assessment of the relative impact of key physiological traits on adaptation to drought in different mega-environments. InterDrought-IV, Sept 2-6, Perth. Invited for special issue journal.

Dreccer MF, Condon AG, Barnes L, Meder R (2013) Using spectral reflectance to discriminate for drought relevant traits. InterDrought-IV, Sept 2-6, Perth. Poster.

Dreccer MF, Chapman SC, Ogbonnaya F, Condon AG, Matthew Reynolds. (2012) In-season wheat phenotyping for breeding and agronomy applications. Crop Science Society of America International Annual Meeting, Oct. 21-24, Cincinnati, OH. Symposium: Field-based high throughput phenotyping. Invited speaker.

Dreccer MF, Chapman SC, Ogbonnaya F, Condon AG, Reynolds M. (2011) Applications of remote sensing in wheat breeding. Crop Science Society of America International Annual Meeting, Oct. 16-19, San Antonio, TX. Oral.

Journal papers

Ogbonnaya FC, Abdalla O, Mujeeb-Kazi A, AG Kazi, Xu Steven, Gosman N, Lagudah ES, Bonnett D, Sorells ME and Tsujimoto H (2013). Synthetic hexaploids: Harnessing species of primary gene pool for wheat improvement. Plant Breeding Reviews 37:35-122.

Dreccer MF, Barnes LR, Meder R. Quantitative dynamics of stem water soluble carbohydrates in wheat can be monitored in the field using hyperspectral reflectance. Field Crops Research 6-1-14.

About ICARDA and the CGIAR

Established in 1977, ICARDA is one of the 15 centers supported by the CGIAR. ICARDA's mission is to improve the livelihoods of the resource-poor in dry areas through research and partnerships dedicated to achieving sustainable increases in agricultural productivity and income, while ensuring efficient and more equitable use and conservation of natural resources.

ICARDA has a global mandate for the improvement of barley, lentil and faba bean, and serves the non-tropical dry areas for the improvement of on-farm water use efficiency, rangeland and small ruminant production. In Central Asia, West Asia, South Asia, and North Africa regions, ICARDA contributes to the improvement of bread and durum wheats, kabuli chickpea, pasture and forage legumes, and associated farming systems. It also works on improved land management, diversification of production systems, and value-added crop and livestock products. Social, economic and policy research is an integral component of ICARDA's research to better target poverty and to enhance the uptake and maximize impact of research outputs.

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