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Indirect selection for grain yield in spring bread wheat in diverse nurseries worldwide using parameters locally determined in north-west Mexico

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SUMMARY

The relationships of normalized water index three (NWI-3) and canopy temperature (CT) with grain yield in north-west Mexico were determined in a set of wheat lines planted in multi-location yield trials. Advanced wheat lines developed by The International Maize and Wheat Improvement Centre (CIMMYT) were included and tested internationally in the trials including the 24th Elite Spring Wheat Yield Trial (ESWYT), the 11th Semi-Arid Wheat Yield Trial (SAWYT) and the 11th High Temperature Wheat Yield Trial (HTWYT). In north-west Mexico, NWI-3, CT and grain yield were determined in three growing seasons (2006, 2007 and 2008) and three environments (well irrigated, water-stressed and high-temperature), while grain yield was measured at international locations in the same advanced lines of the 24th ESWYT, the 11th SAWYT and the 11th HTWYT . The CIMMYT database was used to obtain grain yield from worldwide nurseries. The mean grain yield ranged from 0·8 to 12·7 t/ha for the 24th ESWYT (59 international sites), from 0·6 to 8·2 t/ha for the 11th SAWYT (28 international sites) and from 0·4 to 7·5 t/ha for the 11th HTWYT (26 international sites). NWI-3 and CT for the advanced lines in the three yield trials measured in north-west Mexico in distinct environments showed significant associations with the grain yield from a few international locations (0·12–0·23 of sites). Locations from Central Asia and North Africa had the best associations with NWI-3 and CT. The lack of more associations may be due to either an interaction of other factors (low rainfall and limited irrigations), which affected yield performance, or few of the advanced lines were well adapted to local growing conditions at each testing site, or a combination of these factors. The present results indicate that NWI-3 and CT have limited potential to predict yield performance at international sites.

INTRODUCTION

In a traditional crop breeding programme, elite lines are inter-crossed and then the highest yielding lines are selected. However, yield selection is empirical due to low heritability and a high genotype–environment interaction (Reynolds *et al.* 1999). It also requires the evaluation of a large number of advanced lines in field-yield trials over several years and locations (Ball & Konzak 1993). An indirect selection method that gives an early yield prediction is a potential alternative approach for screening large numbers of genotypes in breeding programmes for identifying and selecting high-yielding lines (Richards 1982; Shorter *et al.* 1991; Marti *et al.* 2007). However, the development of a selection index must integrate several traits, their interrelations and repeatability (high heritability) for predicting yield in breeding programmes (Baker 1986; Bouman 1995).

Yield prediction based on models derived from remotely sensed information can be used for this purpose because many genotypes are evaluated in a fast, cheap and accurate way, thereby reducing the time and effort required by breeders to select for high yield among thousands of lines in diverse environments (Reynolds *et al.* 2007). Spectral reflectance indices (SRIs) are frequently employed for assessing yield among genotypes under optimal and adverse

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growing conditions (Araus *et al*. 2001). The best known SRI is the normalized difference vegetation index (NDVI), which has been used to predict grain yield in wheat and maize under optimal and nitrogen deficient environments (Raun *et al*. 2001; Osborne *et al*. 2002). However, other SRIs also offer great potential for predicting yield, such as several water indices (WIs; the original WI and four normalized water indices (NWIs)), which are based on near infrared wavelengths ($WI = R_{970}/R_{900}$, $NWI\text{-}1 = R_{970} - R_{900}/R_{970} + R_{900}$, $NWI\text{-}2 = R_{970} - R_{850}/R_{970} + R_{850}$, $NWI\text{-}3 = R_{970} - R_{880}/R_{970} + R_{880}$ and $NWI\text{-}4 = R_{970} - R_{920}/R_{970} + R_{920}$) (Penuelas *et al*. 1993; Babar *et al*. 2006; Prasad *et al*. 2007). These WIs have been used for predicting the yield of wheat genotypes under well irrigated, water deficit stress and rainfed conditions in spring and winter wheat (Babar *et al*. 2006; Prasad *et al*. 2007) as well as in hot environments with spring wheat (Gutierrez *et al*. 2010*a*). WIs have been used as an alternative breeding tool for the indirect selection of high-yield potential and for predicting yield in different environments. Similarly, canopy temperature (CT) has demonstrated a strong relationship with grain yield among advanced wheat lines under well irrigated, water-stressed and hot conditions (Reynolds *et al*. 1999; Babar *et al*. 2006; Gutierrez *et al*. 2010*a*).

Since 1964, the wheat breeding programme at The International Maize and Wheat Improvement Center (CIMMYT) has selected advanced wheat lines that have been subsequently distributed via international nurseries around the world through diverse yield trials (Trethowan & Crossa 2007). The primary goal of CIMMYT associated with the distribution of advanced breeding materials to developing countries is to increase their adaptation to local conditions and to select for other desirable traits not present in Mexico (major genetic diversity) (Reynolds & Borlaug 2006). National programmes can choose from over 1500 new genotypes each year free of charge (Reynolds & Borlaug 2006). The advanced breeding lines are evaluated annually by diverse international cooperators who collect and send grain yield and other agronomic data to the CIMMYT database (Trethowan *et al*. 2002; Lillemo *et al*. 2005; Trethowan & Crossa 2007). Every nursery represents a specific agroclimate (i.e. dry and rainfed) and breeders can request those sets that are more appropriate for their environments in order to select well-adapted genotypes (Reynolds & Borlaug 2006). Three of these international yield trials are the Elite Spring Wheat Yield Trial (ESWYT), the Semi-Arid Wheat Yield Trial (SAWYT) and the High Temperature Wheat Yield Trial (HTWYT) (Trethowan & Crossa 2007; Lage *et al*. 2008). The ESWYT includes advanced breeding lines that are targeted for highly productive irrigated areas, the SAWYT includes advanced lines for semi-arid regions and the HTWYT is comprised of advanced lines for heat-stressed areas (Trethowan *et al*. 2001; Trethowan & Crossa 2007; Lage *et al*. 2008). These yield trials represent an important data feedback on how effective CIMMYT's targeting of germplasm is in terms of yield (international yield performance) by analysing how physiological or other traits are expressed across locations. It allows CIMMYT to evaluate the relevance of local requirements for future germplasm development and composition of international nurseries (Reynolds & Borlaug 2006).

Several studies involving international yield trials have been reported using grain yield data from the CIMMYT database (Peterson & Pfeiffer 1989; DeLacy *et al*. 1994; Trethowan *et al*. 2001, 2003; Lillemo *et al*. 2004, 2005). CIMMYT's germplasm has made important contributions to international wheat breeding by increasing yield, especially for developing countries (Dixon *et al*. 2006; Reynolds & Borlaug 2006). Trethowan *et al*. (2001) evaluated and examined the yield data of advanced lines included in the SAWYT at 122 locations that represented diverse environments over 6 years for grouping sites with similar growth conditions. The yield testing of advanced lines in diverse environments and/or regions is an important consideration to identify environmental factors that affect yield performance among lines (Lillemo *et al*. 2005). Yield progress across years for advanced lines in the ESWYT was explained by the amount of annual rainfall in dry areas (Trethowan *et al*. 2001). Reynolds *et al*. (2002) analysed the environmental data of diverse advanced wheat lines from the ESWYT to determine pre- or post-anthesis effects over the genotype due to environment interactions; they found that the post-anthesis conditions had greater effects to explain the genotype × environment interactions. Lage *et al*. (2008) grouped individual sites into clusters using a shifted-multiplicative model combining environmental data and grain yield (35 years average) and when several CIMMYT yield trials were compared, including the ESWYT, the SAWYT and the HTWYT, they found that 18 sites were similar and 23 sites were contrasting. Lage & Trethowan (2008) reported that the interspecific hybridization with *Triticum turgidum* ssp. and *Aegilops tauschii* have over time (10–15 years) improved the yield of the advanced lines in the SAWYT for rainfed environments.

North-west Mexico (Yaqui Valley) has been used extensively to develop and select advanced lines based on yield *per se* for irrigated, water-stressed and hot environments. These advanced materials are subsequently delivered to international cooperators around the world (Lillemo *et al.* 2005). Several studies have previously proposed the WIs and CT as indirect selection criteria to identify high-yielding lines over time for distinct environments, but most of these reports have originated from the same source location (Yaqui Valley) (Babar *et al.* 2006; Reynolds *et al.* 2007; Gutierrez *et al.* 2010*a*). In the present study, the main goal was to compare the expression of yield and two remotely sensed selection criteria, namely, water indices (WIs and NWIs) and CT measured in the selection environment of north-west Mexico (Yaqui Valley), with the expression of yield across a range of international target locations. Specific objectives were (i) to evaluate the ability of indirect selection criteria obtained from the WIs and CT to estimate genetic-yield potential of lines included in international nurseries and (ii) to determine the added value of using indirect selection criteria to select or target new breeding lines for international distribution.

MATERIALS AND METHODS

Advanced lines of yield trials

Advanced breeding lines developed by CIMMYT were used for the present study. The advanced lines corresponded to three international trials: ESWYT, comprising 25 lines developed for irrigation conditions; SAWYT, composed of 40 lines developed for reduced irrigation or semi-arid conditions; and HTWYT, containing 18 lines for high-temperature environments (previously reported in Gutierrez *et al.* 2010*a*). The advanced lines corresponded to the 24th ESWYT, the 11th SAWYT and the 11th HTWYT, which were evaluated for grain yield during three growing seasons (2006, 2007 and 2008) and in three environments (well irrigated, water-stressed and high-temperature) in north-west Mexico.

Growing conditions for north-west Mexico (Yaqui Valley)

The 24th ESWYT lines were grown under well-irrigated conditions, the 11th SAWYT lines under well irrigated and water-stressed conditions and the 11th HTWYT lines under well irrigated, water-stressed and high-temperature conditions (Gutierrez *et al.* 2010*a*). All advanced lines were planted at CIMMYT's experimental station in Ciudad (Cd.) Obregon, north-west Mexico (27°18′N, 109°54′W, 38 m asl) during three growing seasons (2006, 2007 and 2008), except the 11th HTWYT which was grown under water-stressed conditions only during 2007 and 2008. The seeding rate for each experiment was 78 kg/ha, and the advanced lines were fertilized with nitrogen (150 kg N/ha) and phosphorous (22 kg P/ha) in early January of each season, at the 3–4 leaf stage (growth stage (GS) 13–14; Zadoks *et al.* 1974). Field plots consisted of two raised beds, 5 m long and 0·8 m wide, 0·28 m apart, each containing two rows of wheat. The plots were arranged in an alpha lattice design with two replications.

Genotypes were planted in early November and plants reached booting (GS 39–47) and heading (GS 55–69) during February–March for the well irrigated and water-stressed conditions in each growing season. For the experiments under high-temperature conditions, lines were planted in early–mid February and reached heading in late April and May when temperatures were 30–40 °C.

Flood irrigation was applied every 20–25 days for well-irrigated treatments. In trials submitted to drought-stressed conditions, one irrigation was applied before seeding, providing 100 mm of available water, plus two additional irrigations of 50–70 mm prior to the booting stage. For the high-temperature trials, irrigations were also applied as required to prevent drought stress.

Grain yield was determined at maturity by harvesting the complete plot, excluding a 0·5 m border at each end in all experiments.

Spectral reflectance and CT measurements in north-west Mexico

Canopy reflectance was measured in the 350–1100 nm range using a FieldSpec spectroradiometer (Analytical Spectral Devices, Boulder, Colorado, USA). Data were collected during cloud-free days at solar noon (10·30 and 14·00 h) with a previous calibration using a white plate of barium sulphate ($BaSO_4$) that provides maximum reflectance (Labsphere Inc., North Sutton, New Hampshire, USA). Four measurements in each plot were taken at a height of 0·5 m above the canopy with a field of view of 25 °C

Table 1. *List of international locations where advanced lines of the 24th ESWYT, the 11th SAWYT and the 11th HTWYT were planted and evaluated*

Country	Site	Latitude	Longitude	Altitude (m asl)	Rainfall (mm)	Irrigation (mm where known)	International trial		
North-west Mexico (2006, 2007 and 2008)									
Mexico	Cd. Obregon	27°24′N	109°56′W	38	270	Irrigated	ESWYT	SAWYT	HTWYT
International locations (2003)									
1. Afghanistan	Behsud	34°26′N	70°02′E	570	⩽ 300	Irrigated			HTWYT
2. Afghanistan	Coll. of Agriculture	34°30′N	69°10′N	1800	⩽ 210	Irrigated	ESWYT		
3. Afghanistan	Darul	34°28′N	69°03′E	1841	151	Irrigated	ESWYT		
4. Afghanistan	Dehdadi	36°65′N	66°96′E	477	190	Irrigated	ESWYT	SAWYT	
5. Afghanistan	Khoja	34°04′N	32°01′E	1198	211	Irrigated		SAWYT	
6. Afghanistan	Kunduz R. Station	36°43′N	68°51′E	403	320	Irrigated	ESWYT		
7. Afghanistan	Shesham Bagh	34°42′N	70°74′E	552	180	Irrigated	ESWYT		
8. Afghanistan	Urdokhan	34°01′N	62°01′E	1096	244	Irrigated	ESWYT		
9. Algeria	El Khroub	36°15′N	06°41′E	496	580	Irrigated	ESWYT	SAWYT	
10. Angola	Humpata	15°01′S	13°22′E	1856	895	30	ESWYT		
11. Argentina	Marcos J.	32°42′S	62°07′W	110	640	Irrigated	ESWYT	SAWYT	
12. Argentina	Pergamino	33°53′S	60°34′W	56	1090	None	ESWYT	SAWYT	
13. Argentina	Tucuman-Obispo	26°48′S	65°30′W	460	678	Irrigated	ESWYT		
14. Canada	Aafc Glenlea F. St.	46°55′N	97°09′W	233	232	Irrigated	ESWYT		
15. Canada	Kernen Res. F.	52°08′N	106°32′W	510	300	Irrigated	ESWYT		HTWYT
16. Canada	Swift Current	50°17′N	107°47′W	818	398	Irrigated	ESWYT	SAWYT	HTWYT
17. Egypt	Ety-el	31°07′N	30°48′E	10	⩽ 200	Irrigated	ESWYT		
18. Egypt	Gemmeiza	31°07′N	30°47′E	9	187	Irrigated	ESWYT		
19. Egypt	Komombol	23°08′N	32°47′E	142	⩽ 200	Irrigated			HTWYT
20. Egypt	Mattana	25°04′N	32°04′E	90	200	Irrigated			HTWYT
21. Egypt	New Valley	25°41′N	32°39′E	81	⩽ 200	Irrigated			HTWYT
22. Egypt	Sakha	31°05′N	30°56′E	12	65	Irrigated	ESWYT		
23. Egypt	Shandawel	26°36′N	31°41′E	57	62	Irrigated	ESWYT		HTWYT
24. Egypt	Sids	30°43′N	31°31′E	26	8	Irrigated	ESWYT		
25. Hungary	Szeged	46°16′N	20°10′E	80	700	Unknown			HTWYT
26. India	Azad University	26°28′N	80°24′E	406	750	Unknown			HTWYT
27. India	Banaras H. U. V.	25°16′N	82°57′E	128	411	Irrigated			HTWYT
28. India	Bari	26°38′N	77°37′E	463	670	300	ESWYT	SAWYT	HTWYT
29. India	Bihar Agric. Coll. F.	25°07′N	86°30′E	43	1240	None			HTWYT
30. India	D. Plant Breeding	32°07′N	76°31′E	1472	234	Irrigated	ESWYT		
31. India	Durgapura	26°57′N	75°47′E	450	150	Irrigated	ESWYT		
32. India	Dwr-Karnal	15°42′N	76°07′E	638	580	Irrigated	ESWYT	SAWYT	HTWYT
33. India	Gwalior	26°12′N	78°13′E	150	1000	Irrigated	ESWYT		
34. India	IARI Genetics Div.	28°04′N	77°07′E	229	640	Irrigated	ESWYT	SAWYT	HTWYT
35. India	Indore	22°37′N	75°05′E	600	600	Irrigated	ESWYT		
36. India	Livestock Farm	23°00′N	79°58′E	412	1100	Irrigated	ESWYT		HTWYT
37. India	Nepz, Ubkv	25°57′N	88°25′E	43	2000	None	ESWYT		
38. India	Niphad	20°06′N	74°06′E	549	482	Irrigated			HTWYT
39. India	Pantnagar	29°00′N	79°30′E	243	1993	None	ESWYT		
40. India	Powarkheda	22°41′N	77°43′E	299	750	Irrigated		SAWYT	

Table 1. (*Cont.*)

Country	Site	Latitude	Longitude	Altitude (m asl)	Rainfall (mm)	Irrigation (mm where known)	International trial		
41. India	Pusa-IARI	25°51′N	85°47′E	51	765	Irrigated		SAWYT	
42. India	Vijapur	23°35′N	75°45′E	126	827	360	ESWYT		HTWYT
43. Iran	Ahwaz	31°17′N	48°40′E	20	195	Irrigated			HTWYT
44. Iran	Araghee Mohaleh	36°54′N	54°25′E	132	533	Irrigated	ESWYT		
45. Iran	Fars	39°02′N	47°05′E	50	336	240	ESWYT		HTWYT
46. Iran	Moghan	39°49′N	47°50′E	60	310	120	ESWYT		
47. Iran	Safiabad A. Res.	32°15′N	48°24′E	83	283	Irrigated	ESWYT		
48. Iran	Zargan	29°46′N	52°43′E	1603	351	350	ESWYT		
49. Italy	Montelibretti	47°07′N	12°42′E	80	433	Irrigated	ESWYT		
50. Kenya	Npbrc-Njoro	0°24′N	36°00′E	2163	940	Unknown	ESWYT	SAWYT	
51. Mexico	CIANO	27°24′N	109°56W	38	270	320		SAWYT	
52. Morocco	Marchouch	34°25′N	04°46′W	503	464	Irrigated	ESWYT	SAWYT	HTWYT
53. Morocco	Tassaout	29°49′N	08°34′W	1378	315	400	ESWYT	SAWYT	HTWYT
54. Nepal	Nwrp-Bhairahwa	27°30′N	83°27′E	105	1300	Irrigated	ESWYT		
55. Pakistan	Bannu	32°05′N	70°05′E	285	400	100		SAWYT	
56. Pakistan	Barani	32°05′N	72°05′E	490	240	Irrigated		SAWYT	
57. Pakistan	Dera	31°50′N	70°54′E	171	500	225		SAWYT	HTWYT
58. Pakistan	Jarm Res. S.	33°05′N	71°05′E	500	350	Irrigated		SAWYT	
59. Pakistan	Narc Islamabad	33°05′N	73°00′E	683	1143	Unknown	ESWYT	SAWYT	
60. Pakistan	Pirsabak	35°05′N	71°05′E	340	500	Irrigated	ESWYT	SAWYT	
61. Pakistan	Quetta Ari Sariab	26°33′N	62°25′E	1053	200	Irrigated		SAWYT	
62. Pakistan	Regional Agric. R.	28°24′N	71°40′E	170	60	225	ESWYT		
63. Pakistan	Sakrand	26°31′N	68°03′E	31	240	Irrigated	ESWYT		
64. Pakistan	Sariab	26°33′N	62°25′E	1053	$\leqslant 100$	225	ESWYT		
65. Pakistan	Wheat Res. I.	31°50′N	73°05′E	213	351	300	ESWYT	SAWYT	HTWYT
66. Poland	Danko-Choryn	52°02′N	16°46′E	66	540	Irrigated	ESWYT		
67. Poland	Radzikow P. Breed	52°07′N	22°30′E	174	500	Irrigated	ESWYT		
68. Portugal	P. Alentejo	38°08′N	07°09′W	208	600	60	ESWYT	SAWYT	HTWYT
69. Saudi Arabia	Tabuk Ars	28°21′N	36°37′E	725	100	940	ESWYT		
70. Serbia Montenegro	Kragujev	44°02′N	20°56′E	182	524	Irrigated		SAWYT	
71. South Africa	Pannar	29°04′S	30°34′E	1015	464	Irrigated	ESWYT	SAWYT	
72. Spain	Alameda O.	39°51′N	04°47′W	79	740	Irrigated	ESWYT		
73. Spain	Gimenells	41°35′N	0°32′E	290	370	200		SAWYT	
74. Spain	Tomejil	27°24′N	5°35′W	72	580	Irrigated	ESWYT		
75. Turkey	Aegean	38°04′N	27°00′E	10	600	200	ESWYT		
76. Turkey	SE Anatolian	37°54′N	40°12′E	660	450	Irrigated		SAWYT	HTWYT
77. Turkey	Univ. of Cukurova	35°01′N	37°01′E	90	549	Irrigated	ESWYT		HTWYT
78. Turkey	Ziraat	38°42′N	28°45′E	10	448	Irrigated	ESWYT		
79. Zambia	Golden Valley	15°00′S	28°30′E	1200	986	Irrigated	ESWYT		
80. Zimbabwe	Rattray	17°40′S	31°14′E	1300	787	385	ESWYT		
Total (considering just 2003 sites)						59	28	26	

Table 2. *International locations distributed by regions where the advanced lines of the 24th ESWYT, the 11th SAWYT and the 11th HTWYT were planted and evaluated*

	Asia		Africa			Europe		America		
Trial	Central	West	North	Central	South	Southern	Central	North	South	Total
24th ESWYT	19	3	4	2	1	3	2	1	1	36
11th SAWYT	7	–	–	–	–	1	–	1	–	9
11th HTWYT	6	3	–	–		–	1	–	–	10
24th ESWYT & 11th SAWYT	3	–	1	1	1	1	–	–	2	9
24th ESWYT & 11th HTWYT	3	1	1	–	–	–	–	1	–	6
11th SAWYT & 11th HTWYT	2	–	–	–	–	–	–	–	–	2
24th ESWYT, 11th SAWYT & 11th HTWYT	4	–	2	–	–	1	–	1	–	8
Total	44	7	8	3	2	6	3	4	3	80

Table 3. *Minimum, maximum, mean grain yield (t/ha), standard error (S.E.) and significance level (P) among advanced lines (n=24) of the 24th ESWYT planted in NW Mexico (2006, 2007 and 2008) and at international locations (2003)*

Country	Mean	Min.	Max.	S.E.	*P*
*North-west Mexico**	*24th ESWYT*				
Well irrigated	6·63	5·93	7·21	0·08	$\leqslant$ 0·01
International locations†					
2. Afghanistan, C. Agric.	5·45	4·15	6·24	0·10	$\leqslant$ 0·01
3. Afghanistan, Darul	1·22	0·46	2·38	0·13	$\leqslant$ 0·01
4. Afghanistan, Dehdadi	4·64	3·93	5·29	0·12	$\leqslant$ 0·05
6. Afghanistan, Kunduz	4·69	3·97	5·24	0·08	$\leqslant$ 0·05
7. Afghanistan, Shesham	4·02	3·29	4·69	0·11	NS
8. Afghanistan, Urdokhan	3·03	1·98	3·74	0·12	$\leqslant$ 0·01
9. Algeria, El Khroub	5·27	1·49	7·78	0·43	$\leqslant$ 0·01
10. Angola, Humpata	3·12	1·87	4·45	0·21	$\leqslant$ 0·05
11. Argentina, Marcos J.	4·20	2·39	5·09	0·16	$\leqslant$ 0·01
12. Argentina, Pergamino	3·90	3·14	4·54	0·09	$\leqslant$ 0·01
13. Argentina, Tucuman	1·50	1·14	2·11	0·06	$\leqslant$ 0·01
14. Canada, Aafc	3·53	2·88	4·35	0·08	$\leqslant$ 0·01
15. Canada, Kernen	2·64	1·90	3·19	0·09	$\leqslant$ 0·01
16. Canada, Swift	1·57	0·71	2·41	0·09	$\leqslant$ 0·01
17. Egypt, Ety-el	8·92	7·49	10·00	0·13	$\leqslant$ 0·05
18. Egypt, Gemmeiza	10·60	8·90	12·26	0·19	NS
22. Egypt, Sakha	6·81	3·96	9·18	0·19	$\leqslant$ 0·01
23. Egypt, Shandawel	10·91	8·79	12·72	0·16	$\leqslant$ 0·05
24. Egypt, Sids	7·15	5·31	9·95	0·28	NS
28. India, Bari	3·07	2·15	3·95	0·14	$\leqslant$ 0·05
30. India, D. Plant B.	7·13	4·57	9·37	0·30	$\leqslant$ 0·01
31. India, Durgapura	1·38	1·13	1·65	0·04	NS
32. India, Dwr-Karnal	3·74	2·79	5·08	0·14	$\leqslant$ 0·01
33. India, Gwalior	4·86	3·86	5·71	0·11	$\leqslant$ 0·01
34. India, IARI	4·36	3·79	5·24	0·10	$\leqslant$ 0·05
35. India, Indore	7·87	7·20	8·64	0·14	$\leqslant$ 0·01
36. India, Livestock	3·02	1·84	3·68	0·13	$\leqslant$ 0·05
37. India, Nepz	3·58	2·70	4·32	0·09	$\leqslant$ 0·01
39. India, Pantnagar	4·16	3·35	5·00	0·12	$\leqslant$ 0·01
42. India, Vijapur	3·87	2·73	4·91	0·15	$\leqslant$ 0·01
44. Iran, Araghee	4·08	1·23	5·64	0·25	$\leqslant$ 0·01

Table 3. (*Cont.*)

Country	Mean	Min.	Max.	S.E.	*P*
45. Iran, Fars	5·36	4·00	6·68	0·22	NS
46. Iran, Moghan	5·09	2·39	7·10	0·28	⩽ 0·01
47. Iran, Safiabad	5·61	4·44	6·70	0·12	⩽ 0·01
48. Iran, Zargan	6·05	5·08	7·25	0·13	⩽ 0·01
49. Italy, Montelibretti	6·44	4·61	7·49	0·14	⩽ 0·01
50. Kenya, Npbrc	0·75	0·38	1·24	0·07	⩽ 0·01
52. Morocco, Marchouch	5·85	4·68	7·72	0·16	⩽ 0·01
53. Morocco, Tassaout	6·24	5·06	7·15	0·19	NS
54. Nepal, Nwrp	2·50	2·03	2·92	0·08	⩽ 0·01
59. Pakistan, Narc	3·09	2·16	3·62	0·11	NS
60. Pakistan, Pirsabak	4·43	3·06	5·12	0·12	NS
62. Pakistan, Reg. Agric.	3·17	2·20	4·16	0·10	⩽ 0·01
63. Pakistan, Sakrand	2·66	1·50	3·59	0·13	NS
64. Pakistan, Sariab	2·72	2·27	4·22	0·14	⩽ 0·05
65. Pakistan, Wheat R.I.	3·74	3·13	4·26	0·08	⩽ 0·01
66. Poland, Danko	6·84	5·78	8·13	0·15	⩽ 0·01
67. Poland, Radzikow	2·94	2·32	3·47	0·12	⩽ 0·01
68. Portugal, P. Alentejo	4·13	3·11	5·03	0·18	NS
69. Saudi Arabia, Tabuk	8·52	4·96	10·83	0·46	⩽ 0·01
71. South Africa, Pannar	9·00	7·29	10·02	0·20	⩽ 0·05
72. Spain, Alameda	5·58	3·41	7·32	0·23	⩽ 0·01
74. Spain, Tomejil	4·29	2·64	5·72	0·16	⩽ 0·01
75. Turkey, Aegean	7·28	4·97	8·70	0·23	⩽ 0·05
77. Turkey, U. Cukurova	7·39	5·74	9·24	0·38	NS
78. Turkey, Ziraat	2·51	1·61	3·17	0·15	NS
79. Zambia, Golden V.	6·49	3·68	8·44	0·27	NS
80. Zimbabwe, Rattray	7·22	3·03	8·99	0·33	⩽ 0·01
Overall mean	4·86				

* Average of 3 years (2006, 2007 and 2008).
† Average of 1 year (2003).
NS: not significant.

during heading and grain filling (see Gutierrez *et al.* 2010*a*).

Canopy spectral reflectance was measured during the three seasons at heading (mid February for water-stress, early March for well irrigated and late April–early May for high-temperature conditions), and at grain filling (early March for water-stress, late March for well irrigated and mid–late May for high-temperature) according to the growth conditions in each experiment. Five WIs were computed as follows: $WI = R_{970}/R_{900}$, $NWI\text{-}1 = R_{970} - R_{900}/R_{970} + R_{900}$, $NWI\text{-}2 = R_{970} - R_{850}/R_{970} + R_{850}$, $NWI\text{-}3 = R_{970} - R_{880}/R_{970} + R_{880}$ and $NWI\text{-}4 = R_{970} - R_{920}/R_{970} + R_{920}$ (Penuelas *et al.* 1993; Babar *et al.* 2006; Prasad *et al.* 2007).

CT was determined in the same yield trials and growth conditions in north-west Mexico during grain filling (early March for water-stress, late March for well irrigated and mid-late May for high-temperature) using a hand-held infrared thermometer (Mikron M90 Series, Mikron Infrared Instrument Co. Inc., Oakland, New Jersey, USA).

Grain yield data for international locations

CIMMYT's database for the advanced lines of the 24th ESWYT, the 11th SAWYT and the 11th HTWYT corresponded to the year 2003 when these three yield trials were evaluated for grain yield at many international locations. The database contained yield data, latitude, longitude, altitude, seasonal rainfall and irrigations reported by collaborators at each testing site. However, the information provided by many collaborators was incomplete, especially for the amount of irrigation, annual or seasonal rainfall and fertilizers applied.

All advanced breeding lines were planted in an alpha lattice design with two replications at each location/country. Seeds of all trials were packaged

Table 4. *Minimum, maximum, mean grain yield (t/ha), standard error (s.e.) and significance level (P) among advanced lines (n=24) of the 11th SAWYT planted in NW Mexico (2006, 2007 and 2008) and at international locations (2003)*

Country	Mean	Min.	Max.	s.e.	*P*
*North-west Mexico**	*11th SAWYT*				
Well irrigated	6·42	4·51	7·12	0·09	⩽ 0·01
Water-stress	2·20	1·49	2·77	0·05	⩽ 0·01
International locations†					
4. Afghanistan, Dehdadi	2·05	1·46	3·35	0·02	⩽ 0·05
5. Afghanistan, Khoja	0·70	0·30	0·97	0·24	⩽ 0·01
9. Algeria, El Khroub	5·21	1·10	7·12	0·12	⩽ 0·01
11. Argentina, Marcos J.	3·46	1·48	4·77	0·07	⩽ 0·01
12. Argentina, Pergamino	2·61	1·46	3·45	0·05	⩽ 0·01
16. Canada, Swift	1·59	0·83	1·97	0·10	⩽ 0·01
28. India, Bari	3·37	2·35	4·25	0·14	⩽ 0·01
32. India, Dwr-Karnal	4·03	2·91	5·54	0·06	⩽ 0·01
34. India, IARI	1·30	0·67	1·81	0·12	NS
40. India, Powarkheda	5·90	4·84	7·26	0·13	⩽ 0·01
41. India, Pusa	2·84	0·81	4·15	0·05	⩽ 0·01
50. Kenya, Npbrc	0·64	0·22	1·33	0·11	⩽ 0·01
51A. Mexico, CIANO	5·54	3·36	6·66	0·08	⩽ 0·01
51B. Mexico, CIANO	4·85	3·79	5·78	0·13	⩽ 0·01
52. Morocco, Marchouch	5·61	3·38	7·25	0·18	⩽ 0·01
53. Morocco, Tassaout	5·70	3·32	7·50	0·09	⩽ 0·01
55. Pakistan, Bannu	1·79	0·50	2·47	0·07	⩽ 0·01
56. Pakistan, Barani	2·21	1·50	3·00	0·06	⩽ 0·01
57. Pakistan, Dera	1·36	0·84	2·04	0·28	⩽ 0·01
58. Pakistan, Jarm	3·36	1·70	5·30	0·10	NS
59. Pakistan, Narc	3·43	2·56	4·37	0·09	⩽ 0·05
60. Pakistan, Pirsabak	3·25	2·29	4·17	0·04	⩽ 0·05
61. Pakistan, Quetta	0·62	0·37	0·95	0·08	NS
65. Pakistan, Wheat R.I.	3·02	1·97	4·14	0·11	⩽ 0·01
68. Portugal, P. Alentejo	4·26	3·05	5·45	0·17	⩽ 0·01
70. Serbia Mont, Kragujev	8·26	5·69	9·80	0·09	⩽ 0·01
71. South Africa, Pannar	1·25	0·22	2·04	0·15	⩽ 0·01
73. Spain, Gimenells	8·17	6·05	9·39	0·07	⩽ 0·05
76. Turkey, SE Anatolian	3·79	2·89	4·49	0·03	⩽ 0·01
Overall mean	3·53				

* Average of 3 years (2006, 2007 and 2008).
† Average of 1 year (2003).
NS: not significant.

and randomized at CIMMYT and grown under local agronomic practices for every testing site.

Annual rainfall

Average annual rainfall data for each testing site were obtained through several websites such as World Climate (http://www.worldclimate.com, verified 14 April 2011), Falling Rain Genomics (http://www.fallingrain.com/world/index.html, verified 14 April 2011) and The National Oceanic and Atmospheric Administration website (http://www.ncdc.noaa.gov, verified 14 April 2011). Longitude, latitude and altitude for several international locations were completed using the CropForge website (http://www.CropForge.org, verified 14 April 2011), which reports the majority of the CIMMYT testing sites.

Statistical analysis

Grain yield data for the advanced lines at international locations in each yield trial were analysed by SAS using Proc Mixed and the adjusted means were obtained according to the alpha lattice design (SAS

Table 5. *Minimum, maximum, mean grain yield (t/ha), standard error (S.E.) and significance level (P) among advanced lines (n=24) of the 11th HTWYT planted in NW Mexico (2006, 2007 and 2008) and at international locations (2003)*

Country	Mean	Min.	Max.	S.E.	*P*
*North-west Mexico**	*11th HTWYT*				
Well irrigated	6·42	5·64	7·17	0·11	⩽ 0·01
Water-stress	2·40	2·17	2·64	0·03	NS
High-temperature	2·69	1·94	3·31	0·09	⩽ 0·01
International locations†					
1. Afghanistan, Behsud	4·69	3·51	5·48	0·14	NS
15. Canada, Kernen	2·76	2·08	3·19	0·09	⩽ 0·01
16. Canada, Swift	1·57	1·01	2·13	0·09	⩽ 0·01
19. Egypt, Komombol	6·88	5·00	8·40	0·21	⩽ 0·05
20. Egypt, Mattana	7·48	5·60	8·60	0·23	⩽ 0·05
21. Egypt, New Valley	4·64	3·40	5·40	0·16	⩽ 0·05
23. Egypt, Shandawel	6·61	4·90	7·80	0·22	⩽ 0·05
25. Hungary, Szeged	4·27	2·99	5·11	0·16	⩽ 0·01
26. India, Azad	4·14	3·34	5·52	0·17	⩽ 0·01
27. India, Banaras	3·40	2·77	3·91	0·10	⩽ 0·01
28. India, Bari	3·54	2·64	4·04	0·10	⩽ 0·01
29. India, Bihar	2·71	2·00	3·30	0·17	NS
32. India, Dwr-Karnal	3·48	2·27	4·32	0·24	NS
34. India, IARI	2·78	2·14	3·24	0·10	⩽ 0·01
36. India, Livestock	3·67	2·83	4·54	0·12	⩽ 0·05
38. India, Niphad	1·58	1·08	2·26	0·11	NS
42. India, Vijapur	3·16	2·07	4·19	0·18	⩽ 0·01
43. Iran, Ahwaz	4·84	3·55	5·73	0·25	NS
45. Iran, Fars	6·97	5·42	8·13	0·22	NS
52. Morocco, Marchouch	5·66	4·73	6·75	0·19	NS
53. Morocco, Tassaout	5·66	4·24	7·28	0·27	⩽ 0·05
57. Pakistan, Dera	0·41	0·26	0·71	0·03	⩽ 0·01
65. Pakistan, Wheat R. I	2·65	1·91	3·31	0·11	⩽ 0·01
68. Portugal, P. Alentejo	3·39	2·81	4·15	0·21	⩽ 0·05
76. Turkey, SE Anatolian	3·86	2·99	4·55	0·11	⩽ 0·01
77. Turkey, U. Cukurova	6·98	4·32	9·20	0·37	⩽ 0·05
Overall mean	4·10				

* Average of 3 years (2006, 2007 and 2008).
† Average of 1 year (2003).
NS: not significant.

Institute 2001). Pearson correlation coefficients were used to estimate the phenotypic relationships of the WIs, CT and yield in north-west Mexico with grain yield at the international locations.

RESULTS

Geographic and rainfall diversity among international locations

The advanced lines of the 24th ESWYT, the 11th SAWYT and the 11th HTWYT were evaluated in 80 international locations, which were widely distributed in Asia, Africa, Europe and America (Tables 1 and 2). The 24th ESWYT was evaluated at 59 sites, the 11th SAWYT at 28 sites and the 11th HTWYT at 26 sites. Some international locations evaluated only one-yield trial, but others combined two- or three-yield trials at the same site (Table 2). The 24th ESWYT was evaluated singly at 36 sites, the 11th SAWYT at nine sites and 11th HTWYT at 10 sites. The 24th ESWYT and the 11th SAWYT trials were evaluated together at nine sites, the 24th ESWYT and the 11th HTWYT at six sites, the 11th SAWYT and the 11th HTWYT at two sites and the three yield trials were evaluated together at eight sites. Central Asia was the region with the highest number of

Table 6. *Correlation coefficients between the NWI-3 measured under well-irrigated conditions in north-west Mexico and grain yield from international locations for advanced lines of the 24th ESWYT*

		North-west Mexico well irrigated		
		NWI-3		
24th ESWYT	Average yield (t/ha)	2006	2007	2008
Central Asia				
India, Bari	3·07	NS	NS	$P \leqslant 0{\cdot}01$ (+)*
India, Durgapura	1·38	$P \leqslant 0{\cdot}05$ (−)	$P \leqslant 0{\cdot}05$ (−)	$P \leqslant 0{\cdot}05$ (−)
India, Dwr-Karnal	3·74	$P \leqslant 0{\cdot}05$ (+)	NS	NS
India, IARI	4·36	$P \leqslant 0{\cdot}05$ (+)	NS	NS
India, Livestock	3·02	NS	NS	$P \leqslant 0{\cdot}05$ (+)
Iran, Safiabad	5·61	NS	$P \leqslant 0{\cdot}05$ (−)	NS
Nepal, Nwrp	2·50	NS	NS	$P \leqslant 0{\cdot}01$ (+)
West Asia				
Turkey, Aegean	7·28	NS	$P \leqslant 0{\cdot}05$ (−)	NS
Turkey, U. Cukurova	7·39	NS	$P \leqslant 0{\cdot}05$ (−)	NS
Turkey, Ziraat	2·51	$P \leqslant 0{\cdot}05$ (−)	NS	NS
North Africa				
Egypt, Ety-el	8·92	NS	$P \leqslant 0{\cdot}05$ (−)	$P \leqslant 0{\cdot}05$ (−)
Egypt, Sakha	6·81	$P \leqslant 0{\cdot}05$ (−)	$P \leqslant 0{\cdot}05$ (−)	NS
South Africa				
South Africa, Pannar	9·00	$P \leqslant 0{\cdot}05$ (−)	$P \leqslant 0{\cdot}05$ (−)	$P \leqslant 0{\cdot}05$ (−)
Zimbabwe, Rattray	7·22	$P \leqslant 0{\cdot}05$ (−)	NS	NS
Southern Europe				
Italy, Montelibretti	6·44	$P \leqslant 0{\cdot}01$ (−)	$P \leqslant 0{\cdot}01$ (−)	$P \leqslant 0{\cdot}05$ (−)
Spain, Alameda	5·58	$P \leqslant 0{\cdot}05$ (−)	NS	NS
Spain, Tomejil	4·29	NS	NS	$P \leqslant 0{\cdot}05$ (−)
South America				
Argentina, Marcos J.	4·20	NS	NS	$P \leqslant 0{\cdot}05$ (−)
Argentina, Pergamino	3·90	NS	NS	$P \leqslant 0{\cdot}05$ (−)
Total		7 (−)	8 (−)	7 (−)

* Sign in parentheses indicates negative or positive significant correlations.
NS: no significant correlation.

locations for evaluating one, two or three yield trials (44 locations), while the other regions (West Asia, North, Central and South Africa, Southern and Central Europe, and North and South America) showed less than 10 locations each (Table 2).

The geographic diversity among international locations was responsible for considerable variations in annual rainfall (Table 1). Few locations had very low rainfall (six sites with ⩽100 mm) and few had very high rainfall (two sites with ⩾1900 mm) (Table 1). Most of the international locations displayed low to moderate annual rainfall (⩽ 800 mm in 69 sites) and the others had moderately high rainfall (>800 mm in 11 sites). Irrigation was commonly employed in sites with low, intermediate and high rainfall and only four locations were reported as non-irrigated. This means that rainfall was absent or minimal during the cropping season in the majority of the international locations (Table 1).

Grain yield diversity among international locations

There was considerable variation in the average grain yield of the advanced lines from the 24th ESWYT, the 11th SAWYT and the 11th HTWYT among the testing sites (Tables 3–5). The average grain yield ranged from 0·8 to 12·7 t/ha for the 24th ESWYT entries, from 0·6 to 8·2 t/ha for the 11th SAWYT entries and from 0·4 to 7·5 t/ha for the 11th HTWYT entries. The average yield of the advanced lines from the 24th ESWYT was higher (4·9 t/ha) than the 11th SAWYT lines (3·5 t/ha) and the 11th HTWYT lines (4·1 t/ha) when all sites were combined for each yield trial. There were genotypic differences in most locations and the genotype by

Table 7. *Correlation coefficients of CT measured under well-irrigated conditions in north-west Mexico and grain yield from international locations for advanced lines of the 24th ESWYT*

		North-west Mexico well irrigated		
		CT		
24th ESWYT	Average yield (t/ha)	2006	2007	2008
Central Asia				
Afghanistan, Darul	1·22	NS	$P \leqslant 0{\cdot}01$ (−)	NS
India, Bari	3·07	NS	NS	$P \leqslant 0{\cdot}05$ (+)*
India, Nepz	3·58	NS	$P \leqslant 0{\cdot}01$ (+)	NS
Nepal, Nwrp	2·50	NS	NS	$P \leqslant 0{\cdot}01$ (+)
Pakistan, Wheat R.I.	3·74	$P \leqslant 0{\cdot}05$ (−)	NS	NS
West Asia				
Saudi Arabia, Tabuk	8·52	$P \leqslant 0{\cdot}05$ (−)	$P \leqslant 0{\cdot}05$ (−)	NS
North Africa				
Morocco, Tassaout	6·24	$P \leqslant 0{\cdot}05$ (+)	NS	$P \leqslant 0{\cdot}05$ (−)
Southern Europe				
Spain, Alameda	5·58	NS	$P \leqslant 0{\cdot}01$ (−)	$P \leqslant 0{\cdot}05$ (−)
Spain, Tomejil	4·29	NS	NS	$P \leqslant 0{\cdot}05$ (−)
Central Europe				
Poland, Danko	6·84	$P \leqslant 0{\cdot}05$ (−)	NS	NS
North America				
Canada, Kernen	2·64	$P \leqslant 0{\cdot}01$ (−)	NS	NS
South America				
Argentina, Tucuman	1·50	$P \leqslant 0{\cdot}05$ (−)	NS	NS
Total		5 (−)	3 (−)	3 (−)

* Sign in parentheses indicates negative or positive significant correlations.
NS: no significant correlation.

environment interaction was highly significant ($P \leqslant 0{\cdot}01$) (data not shown).

Association of the north-west Mexico parameters with grain yield of international locations

Grain yield from international locations showed significant associations with the five WIs (one WI and four NWIs) measured in north-west Mexico under stressed and non-stressed conditions. There were minor differences among the five indices (data not shown), but NWI-3 consistently gave the strongest correlations of the five WIs, and it will be presented in the current study to illustrate the relationship of the WIs and their utility to predict yield at international locations. Similarly, CT determined in north-west Mexico also showed significant associations with grain yield at international locations. For both parameters, NWI-3 and CT were only considered to have good predictive potential if the grain yield from international locations was associated during 2 or 3 years with these two parameters (tested during 3 years in north-west Mexico).

NWI-3, CT and grain yield determined in north-west Mexico showed significant relationships with the grain yield of the advanced lines from the 24th ESWYT, the 11th SAWYT and the 11th HTWYT, displaying both negative and positive correlation values (Tables 6–14). The negative association of NWI-3 and CT with grain yield from international locations was the primary interest in order to find sites with similar yield performance, which could be reaffirmed with positive associations between the grain yield from north-west Mexico and the grain yield from international sites.

NWI-3, which was determined during three growing seasons in north-west Mexico, gave a few significant negative associations ($P \leqslant 0{\cdot}05$ and 0·01) in all worldwide regions for the 24th ESWYT (Table 6). One location with low grain yield in India (1·4 t/ha), and two locations each with high grain yield in Italy (6·4 t/ha) and South Africa (9 t/ha), showed significant negative associations ($P \leqslant 0{\cdot}05$ and 0·01) with NWI-3 during 3 years. Two locations with high grain yield in Egypt (6·8 and 8·9 t/ha) also showed significant negative associations ($P \leqslant 0{\cdot}05$) with NWI-3 during 2 years. CT only showed negative associations ($P \leqslant 0{\cdot}05$

Table 8. *Correlation coefficients between grain yield measured under well-irrigated conditions in north-west Mexico and grain yield from international locations for advanced lines of the 24th ESWYT*

		North-west Mexico well irrigated		
		Yield		
24th ESWYT	Average yield (t/ha)	2006	2007	2008
Central Asia				
Afghanistan, Dehdadi	4·64	$P \leqslant 0·05$ (+)*	NS	$P \leqslant 0·05$ (+)
Afghanistan, Shesham	4·02	$P \leqslant 0·01$ (+)	NS	NS
India, Durgapura	1·38	NS	NS	$P \leqslant 0·05$ (+)
India, Indore	7·87	$P \leqslant 0·05$ (+)	NS	$P \leqslant 0·05$ (+)
Iran, Zargan	6·05	$P \leqslant 0·05$ (+)	NS	NS
West Asia				
Saudi Arabia, Tabuk	8·52	$P \leqslant 0·05$ (+)	NS	NS
North Africa				
Egypt, Ety-el	8·92	NS	NS	$P \leqslant 0·01$ (+)
Egypt, Gemmeiza	10·60	$P \leqslant 0·01$ (+)	$P \leqslant 0·01$ (+)	NS
Egypt, Sakha	6·81	$P \leqslant 0·01$ (+)	$P \leqslant 0·05$ (+)	$P \leqslant 0·01$ (+)
Egypt, Shandawel	10·91	$P \leqslant 0·01$ (+)	NS	NS
Egypt, Sids	7·15	$P \leqslant 0·01$ (+)	NS	NS
Morocco, Marchouch	5·85	$P \leqslant 0·01$ (+)	$P \leqslant 0·05$ (+)	NS
South Africa				
South Africa, Pannar	9·00	$P \leqslant 0·05$ (+)	NS	$P \leqslant 0·01$ (+)
Zambia, Golden V.	6·49	$P \leqslant 0·05$ (+)	NS	NS
Zimbabwe, Rattray	7·22	NS	NS	$P \leqslant 0·01$ (+)
Southern Europe				
Italy, Montelibretti	6·44	$P \leqslant 0·05$ (+)	NS	$P \leqslant 0·01$ (+)
Spain, Alameda	5·58	$P \leqslant 0·05$ (+)	$P \leqslant 0·05$ (+)	$P \leqslant 0·05$ (+)
Central Europe				
Poland, Danko	6·84	$P \leqslant 0·05$ (+)	$P \leqslant 0·05$ (+)	$P \leqslant 0·05$ (+)
Poland, Radzikow	2·94	$P \leqslant 0·01$ (+)	NS	NS
South America				
Argentina, Marcos J.	4·20	NS	NS	$P \leqslant 0·05$ (+)
Argentina, Pergamino	3·90	NS	NS	$P \leqslant 0·05$ (+)
Argentina, Tucuman	1·50	NS	$P \leqslant 0·05$ (−)	NS
Total		16 (+)	5 (+)	12 (+)

* Sign in parentheses indicates negative or positive significant correlations.
NS: no significant correlation.

and 0·01) during 2 years with locations of high grain yield in Saudi Arabia (8·5 t/ha) and Spain (5·6 t/ha) (Table 7). Grain yield from north-west Mexico gave several significant correlations with grain yield at international locations (positively associated at $P \leqslant 0·05$ and 0·01) during 2 and 3 years in central Asia, north and south Africa and central and southern Europe, and some of these locations were the same locations associated with NWI-3 and CT (Table 8).

NWI-3 determined in the well-irrigated environment in north-west Mexico for the 11th SAWYT trial displayed negative associations ($P \leqslant 0·05$ and 0·01) with two locations in Morocco, one with high grain yield (5·7 t/ha) and one with low grain yield (1·8 t/ha), which were correlated during 3 and 2 years, respectively (Table 9). CT showed a negative association ($P \leqslant 0·05$) during 2 years with one site in India with low grain yield (3·4 t/ha) (Table 10). For water-stressed environments, NWI-3 displayed a negative association ($P \leqslant 0·05$) during 2 years with one location in India with low grain yield (1·3 t/ha), while CT only showed negative associations ($P \leqslant 0·05$) during 1 year for two locations (Tables 9 and 10). Grain yield in north-west Mexico under irrigated and water-stressed conditions showed several positive correlations ($P \leqslant 0·05$ and 0·01) with the grain yield at international locations, but few corresponded to the same locations associated with NWI-3 and CT (Table 11).

Table 9. *Correlation coefficients between the NWI-3 measured under well irrigated and water-stressed conditions in north-west Mexico and grain yield from international locations for advanced lines of the 11th SAWYT*

		North-west Mexico					
		Well irrigated			Water-stress		
	Average yield	NWI-3			NWI-3		
11th SAWYT	(t/ha)	2006	2007	2008	2006	2007	2008
Central Asia							
Afghanistan, Dehdadi	2·05	NS	NS	NS	NS	$P \leqslant 0{\cdot}05$ (–)*	NS
Afghanistan, Khoja	0·70	$P \leqslant 0{\cdot}05$ (+)	NS	NS	NS	NS	NS
India, Powarkheda	5·90	NS	NS	NS	NS	NS	$P \leqslant 0{\cdot}05$ (+)
India, Pusa	2·84	NS	NS	NS	NS	$P \leqslant 0{\cdot}05$ (–)	NS
India, IARI	1·30	NS	NS	NS	$P \leqslant 0{\cdot}05$ (–)	NS	$P \leqslant 0{\cdot}05$ (–)
Pakistan, Dera	3·36	NS	NS	NS	$P \leqslant 0{\cdot}05$ (+)	NS	NS
West Asia							
Turkey, SE Anatolian	3·79	NS	NS	NS	NS	$P \leqslant 0{\cdot}01$ (–)	NS
North Africa							
Morocco, Marchouch	5·70	$P \leqslant 0{\cdot}05$ (–)	$P \leqslant 0{\cdot}01$ (–)	$P \leqslant 0{\cdot}05$ (–)	NS	NS	NS
Morocco, Tassaout	1·79	$P \leqslant 0{\cdot}05$ (–)	$P \leqslant 0{\cdot}05$ (–)	NS	$P \leqslant 0{\cdot}05$ (+)	NS	$P \leqslant 0{\cdot}05$ (+)
South Africa							
South Africa, Pannar	1·25	NS	NS	NS	NS	$P \leqslant 0{\cdot}01$ (–)	NS
North America							
Mexico, CIANO	5·61	NS	NS	NS	NS	$P \leqslant 0{\cdot}05$ (+)	NS
Total		2 (–)	2 (–)	1 (–)	1 (–)	4 (–)	1 (–)

* Sign in parentheses indicates negative or positive significant correlations.
NS: no significant correlation.

NWI-3 and CT for the 11th HTWYT were measured in north-west Mexico in three environments (irrigated, water-stressed and high-temperature) (Tables 12–14). The NWI-3 obtained from the well-irrigated environment showed negative associations ($P \leqslant 0{\cdot}05$ and 0·01) during 2 and 3 years for locations with low grain yield in India (2·8 t/ha) and Turkey (3·9 t/ha) and high grain yield in Turkey (7·0 t/ha) and Egypt (6·9 and 7·2 t/ha) (Table 12). CT only displayed significant negative associations ($P \leqslant 0{\cdot}05$) during 1 year for several international locations (Table 13). For the north-west Mexico parameters determined under water-stress (2007 and 2008 seasons), neither NWI-3 nor CT showed any significant associations (Tables 12 and 13). Finally, NWI-3 and CT determined in the high-temperature environment displayed significant negative association ($P \leqslant 0{\cdot}05$ and 0·01) with one location with high grain yield in Egypt (6·9 t/ha) and with one low grain yield in Pakistan (2·7 t/ha) during 2 years. Grain yield from north-west Mexico measured in the three environments displayed significant correlations (positively associated at $P \leqslant 0{\cdot}05$ and 0·01) during 2 years in several international locations and only two corresponded to the same locations associated with NWI-3 and CT (Table 14).

DISCUSSION

Annual rainfall of international locations

Apparently, local weather conditions such as low annual rainfall in several international locations were the primary reason for evaluating more than one CIMMYT yield trial. The cooperators probably assumed that this would improve the chance of finding lines well adapted to the local conditions, although

Table 10. *Correlation coefficients between CT measured under well irrigated and water-stressed conditions in north-west Mexico and grain yield from international locations for advanced lines of the 11th SAWYT*

		North-west Mexico					
		Well irrigated			Water-stress		
	Average yield	CT			CT		
11th SAWYT	(t/ha)	2006	2007	2008	2006	2007	2008
Central Asia							
India, Dwr-Karnal	4·03	NS	NS	NS	NS	$P \leqslant 0{\cdot}05$ (−)*	NS
India, Bari	3·37	NS	$P \leqslant 0{\cdot}05$ (−)	$P \leqslant 0{\cdot}05$ (−)	NS	NS	NS
Pakistan, Jarm	3·43	$P \leqslant 0{\cdot}05$ (+)	NS	NS	NS	$P \leqslant 0{\cdot}05$ (−)	NS
Pakistan, Narc	3·25	$P \leqslant 0{\cdot}01$ (+)	NS	NS	NS	NS	NS
Pakistan, Bannu	2·21	NS	NS	NS	NS	$P \leqslant 0{\cdot}05$ (+)	NS
Pakistan, Pirsabak	0·62	$P \leqslant 0{\cdot}05$ (+)	NS	NS	NS	NS	NS
West Asia							
Turkey, SE Anatolian	3·79	NS	$P \leqslant 0{\cdot}05$ (−)	NS	NS	NS	NS
North Africa							
Morocco, Tassaout	1·79	NS	NS	NS	NS	$P \leqslant 0{\cdot}05$ (+)	$P \leqslant 0{\cdot}01$ (+)
South Africa							
South Africa, Pannar	1·25	$P \leqslant 0{\cdot}01$ (−)	NS	NS	NS	NS	NS
Southern Europe							
Serbia Mont., Kragujev	8·26	$P \leqslant 0{\cdot}05$ (+)	NS	$P \leqslant 0{\cdot}01$ (+)	NS	NS	NS
Spain, Gimenells	8·17	NS	NS	NS	NS	NS	$P \leqslant 0{\cdot}01$ (+)
Portugal, P. Alentejo	4·26	NS	NS	NS	$P \leqslant 0{\cdot}05$ (+)	NS	NS
North America							
Canada, Swift	1·59	NS	$P \leqslant 0{\cdot}05$ (−)	NS	NS	NS	NS
Total		1 (−)	3 (−)	1 (−)	0 (−)	2 (−)	0 (−)

* Sign in parentheses indicates negative or positive significant correlations.
NS: no significant correlation.

most of the international testing sites employed some irrigation during the cropping season (Tables 1 and 2). Out of 80 testing sites in Asia, Africa, Europe and America, 60 had less than 800 mm of annual rainfall, indicating that many sites were irrigated dry sites (Table 1).

Association between north-west Mexico parameters and grain yield of international sites

In a previous study conducted during three growing seasons (2006, 2007 and 2008) in north-west Mexico (Gutierrez *et al.* 2010*a*), NWI-3 and CT determined in three environments showed significant negative associations with grain yield of the advanced lines from the 24th ESWYT (well irrigated), the 11th SAWYT (well irrigated and water-stress) and the 11th HTWYT (well irrigated, water-stress and high-temperature). Better associations with grain yield were obtained when heading and grain filling determinations were combined for NWI-3 and when CT determinations were taken at grain filling. Both remote sensing parameters demonstrated high genetic gain and heritability across years, which indicated their high potential as indirect selection approaches to detect, identify and select high-yielding lines in the three environments. In the current study, NWI-3 and CT measured from north-west Mexico (reported by Gutierrez *et al.* 2010*a*) showed significant negative associations ($P \leqslant 0{\cdot}05$ and 0·01) with grain yield at international locations, indicating that WIs and CT can predict the yield performance of advanced yielding lines in some international sites (Tables 6–14). The negative associations of NWI-3 and CT with grain yield at international locations signifies that the same low- and high-yielding lines across international locations performed in a similar fashion as in north-west Mexico (Yaqui Valley), which is widely employed to develop

Table 11. *Correlation coefficients between grain yield measured under well irrigated and water-stressed conditions in north-west Mexico and grain yield from international locations for advanced lines of the 11th SAWYT*

		North-west Mexico					
		Well irrigated			Water-stress		
	Average yield	Yield			Yield		
11th SAWYT	(t/ha)	2006	2007	2008	2006	2007	2008
Central Asia							
Afghanistan, Dehdadi	2·05	NS	NS	NS	NS	$P \leqslant 0.05$ (+)*	$P \leqslant 0.05$ (+)
India, Dwr-Karnal	4·03	NS	NS	NS	NS	$P \leqslant 0.01$ (+)	NS
India, Pusa	2·84	NS	NS	NS	NS	$P \leqslant 0.05$ (+)	NS
India, IARI	1·30	NS	NS	NS	NS	NS	$P \leqslant 0.05$ (+)
Pakistan, Wheat R.I.	4·26	NS	NS	NS	NS	$P \leqslant 0.05$ (+)	NS
West Asia							
Turkey, SE Anatolian	3·79	$P \leqslant 0.05$ (+)	NS	NS	NS	NS	NS
North Africa							
Morocco, Marchouch	5·70	$P \leqslant 0.01$ (+)	$P \leqslant 0.01$ (+)	$P \leqslant 0.01$ (+)	NS	NS	NS
Morocco, Tassaout	1·79	$P \leqslant 0.01$ (+)	NS	$P \leqslant 0.01$ (+)	NS	NS	NS
Central Africa							
Kenya, Npbrc	0·64	NS	NS	NS	NS	$P \leqslant 0.01$ (+)	$P \leqslant 0.01$ (+)
Southern Europe							
Spain, Gimenells	8·17	$P \leqslant 0.01$ (+)	NS	$P \leqslant 0.01$ (+)	NS	NS	NS
North America							
Mexico. CIANO	5·54	$P \leqslant 0.05$ (+)	NS	$P \leqslant 0.05$ (+)	NS	NS	$P \leqslant 0.05$ (+)
Mexico, CIANO	4·85	NS	NS	NS	$P \leqslant 0.05$ (+)	$P \leqslant 0.01$ (+)	$P \leqslant 0.05$ (+)
South America							
Argentina, Marcos J.	3·46	$P \leqslant 0.05$ (+)	NS	$P \leqslant 0.05$ (+)	NS	NS	NS
Total		6 (+)	1 (+)	5 (+)	1 (+)	6 (+)	5 (+)

* Sign in parentheses indicates negative or positive significant correlations.
NS: no significant correlation.

advanced wheat lines for well irrigated, water-stressed and hot environments (Lillemo *et al.* 2005). The significant negative associations occurred for 1, 2 or 3 years, respectively, but the better potential for predicting yield at international sites was when the significant associations occurred for 2 or 3 years (Tables 6–14). The variations of NWI-3 and CT from one year to another caused the lack of association for the same testing sites. The negative association of grain yield at international locations with NWI-3 and CT was sometimes supported with positive associations with the grain yield from north-west Mexico in the three yield trials.

The 24th ESWYT represented advanced lines selected for high-yield potential in irrigated environments (Trethowan *et al.* 2003). In the present study, grain yield of seven testing locations (i.e. 0·12 of the total number of sites) in central and west Asia, north and south Africa and southern Europe showed significant negative associations for 2 or 3 years with NWI-3 and CT (Tables 6 and 7). The advanced lines in the 11th SAWYT, which were selected by CIMMYT breeders for high yield in semi-arid regions (Trethowan *et al.* 2001), were evaluated under both well-irrigated and water-stressed conditions in north-west Mexico (Gutierrez *et al.* 2010a). NWI-3 and CT determined under both environments during 2 or 3 years gave only four negative significant associations (0·14 of sites) with testing sites in central Asia and northern Africa (Tables 9 and 10). The advanced lines of the 11th HTWYT were selected for high yield in heat-stressed environments (Lillemo *et al.* 2005) and were

Table 12. *Correlation coefficients between NWI-3 measured under well irrigated, water-stressed and high-temperature conditions in north-west Mexico and grain yield from international locations for advanced lines of the 11th HTWYT*

		North-west Mexico							
		Well irrigated			Water-stress		High-temperature		
	Average yield	NWI-3			NWI-3		NWI-3		
11th HTWYT	(t/ha)	2006	2007	2008	2007	2008	2006	2007	2008
Central Asia									
India, Banaras	3·40	NS	NS	$P \leqslant 0{\cdot}05$ (–)*	NS	NS	NS	NS	NS
India, Bari	3·54	NS	NS	NS	NS	$P \leqslant 0{\cdot}01$ (–)	NS	NS	NS
India, Dwr-Karnal	3·48	NS	NS	$P \leqslant 0{\cdot}01$ (–)	NS	NS	NS	$P \leqslant 0{\cdot}05$ (–)	NS
India, IARI	2·78	$P \leqslant 0{\cdot}05$ (–)	$P \leqslant 0{\cdot}05$ (–)	$P \leqslant 0{\cdot}05$ (–)	NS	NS	NS	NS	NS
India, Vijapur	3·16	NS	NS	NS	$P \leqslant 0{\cdot}05$ (+)	NS	NS	NS	NS
Iran, Ahwaz	4·84	$P \leqslant 0{\cdot}05$ (–)	NS	NS	NS	$P \leqslant 0{\cdot}05$ (–)	NS	NS	NS
Pakistan, Dera	0·41	$P \leqslant 0{\cdot}05$ (–)	NS	NS	NS	NS	$P \leqslant 0{\cdot}05$ (–)	NS	NS
Pakistan, Wheat R. I	2·65	NS	NS	$P \leqslant 0{\cdot}05$ (–)	NS	NS	NS	NS	$P \leqslant 0{\cdot}05$ (–)
West Asia									
Turkey, SE Anatol.	3·86	$P \leqslant 0{\cdot}01$ (–)	$P \leqslant 0{\cdot}05$ (–)	NS	NS	$P \leqslant 0{\cdot}05$ (–)	NS	NS	NS
Turkey, U. Cukurova	6·98	$P \leqslant 0{\cdot}05$ (–)	$P \leqslant 0{\cdot}05$ (–)	NS	NS	NS	NS	NS	NS
North Africa									
Egypt, Komombol	6·88	$P \leqslant 0{\cdot}05$ (–)	$P \leqslant 0{\cdot}01$ (–)	NS	NS	NS	$P \leqslant 0{\cdot}05$ (–)	NS	$P \leqslant 0{\cdot}05$ (–)
Egypt, New Valley	4·64	NS	NS	$P \leqslant 0{\cdot}05$ (–)	NS	NS	NS	NS	NS
Egypt, Shandawel	6·61	NS	NS	NS	NS	NS	$P \leqslant 0{\cdot}05$ (+)	NS	NS
Egypt, Sid	7·15	NS	$P \leqslant 0{\cdot}05$ (–)	$P \leqslant 0{\cdot}05$ (–)	NS	NS	NS	NS	NS
Morocco, March.	5·66	$P \leqslant 0{\cdot}05$ (–)	NS	NS	NS	NS	NS	NS	NS
Southern Europe									
Portugal, P. Alentejo	3·39	$P \leqslant 0{\cdot}01$ (+)	NS	NS	NS	NS	NS	NS	NS
Central Europe									
Hungary, Szeged	4·27	NS	NS	NS	$P \leqslant 0{\cdot}05$ (–)	NS	NS	NS	NS
Total		7 (–)	5 (–)	6 (–)	1 (–)	3 (–)	2 (–)	1 (–)	2 (–)

* Sign in parentheses indicates negative or positive significant correlations.
NS: no significant correlation.

Table 13. *Correlation coefficients between CT measured under well irrigated, water-stressed and high-temperature conditions in north-west Mexico and grain yield from international locations for advanced lines of the 11th HTWYT*

		North-west Mexico							
		Well irrigated			Water-stress		High-temperature		
	Average yield	CT			CT		CT		
11th HTWYT	(t/ha)	2006	2007	2008	2007	2008	2006	2007	2008
Central Asia									
India, Dwr-Karnal	3·48	NS	NS	$P \leqslant 0{\cdot}05$ (–)*	NS	$P \leqslant 0{\cdot}05$ (–)	NS	NS	$P \leqslant 0{\cdot}05$ (–)
India, IARI	2·78	NS	NS	NS	NS	NS	NS	NS	$P \leqslant 0{\cdot}05$ (–)
Pakistan, Dera	0·41	NS	$P \leqslant 0{\cdot}05$ (–)	NS	NS	NS	NS	NS	NS
Pakistan, Wheat R. I	2·65	$P \leqslant 0{\cdot}05$ (+)	NS	NS	NS	$P \leqslant 0{\cdot}01$ (–)	NS	$P \leqslant 0{\cdot}05$ (–)	$P \leqslant 0{\cdot}01$ (–)
North Africa									
Egypt, Mattana	7·48	NS	NS	NS	$P \leqslant 0{\cdot}01$ (+)	NS	NS	NS	NS
Egypt, New Valley	4·64	NS	NS	$P \leqslant 0{\cdot}01$ (–)	NS	NS	NS	NS	NS
Morocco, Tassaout	5·66	NS	NS	NS	$P \leqslant 0{\cdot}05$ (+)	NS	NS	NS	NS
Total		0 (–)	1 (–)	2 (–)	0 (–)	2 (–)	0 (–)	1 (–)	3 (–)

* Sign in parentheses indicates negative or positive significant correlations.
NS: no significant correlation.

Table 14. *Correlation coefficients between grain yield measured under well irrigated, water-stressed and high-temperature conditions in north-west Mexico and grain yield from international locations for advanced lines of the 11th HTWYT*

		North-west Mexico							
		Well irrigated			Water-stress		High-temperature		
	Average yield	Yield			Yield		Yield		
11th HTWYT	(t/ha)	2006	2007	2008	2007	2008	2006	2007	2008
Central Asia									
India, Azad	4·14	NS	$P \leqslant 0{\cdot}01$ (–)*	NS	$P \leqslant 0{\cdot}05$ (–)	NS	NS	NS	NS
India, Banaras	3·40	NS	NS	$P \leqslant 0{\cdot}05$ (+)	NS	NS	NS	NS	NS
India, Bari	3·54	$P \leqslant 0{\cdot}05$ (+)	NS	NS	NS	$P \leqslant 0{\cdot}05$ (+)	$P \leqslant 0{\cdot}05$ (+)	NS	NS
India, Dwr-Karnal	3·48	NS	NS	$P \leqslant 0{\cdot}05$ (+)	NS	NS	NS	$P \leqslant 0{\cdot}05$ (+)	$P \leqslant 0{\cdot}05$ (+)
India, Vijapur	3·16	NS	NS	NS	NS	$P \leqslant 0{\cdot}05$ (+)	$P \leqslant 0{\cdot}05$ (+)	NS	NS
Pakistan, Wheat R. I	2·65	NS	NS	$P \leqslant 0{\cdot}05$ (+)	$P \leqslant 0{\cdot}05$ (–)	NS	$P \leqslant 0{\cdot}05$ (+)	NS	$P \leqslant 0{\cdot}01$ (+)
North Africa									
Egypt, Komombol	6·88	NS	$P \leqslant 0{\cdot}05$ (+)	NS	NS	$P \leqslant 0{\cdot}05$ (+)	$P \leqslant 0{\cdot}05$ (+)	NS	$P \leqslant 0{\cdot}05$ (+)
Egypt, New Valley	4·64	$P \leqslant 0{\cdot}05$ (+)	NS	$P \leqslant 0{\cdot}01$ (+)	NS	$P \leqslant 0{\cdot}05$ (+)	NS	NS	NS
Egypt, Sid	7·15	NS	NS	$P \leqslant 0{\cdot}05$ (+)	NS	$P \leqslant 0{\cdot}05$ (+)	NS	NS	NS
Morocco, March.	5·66	$P \leqslant 0{\cdot}05$ (+)	NS	NS	$P \leqslant 0{\cdot}05$ (+)	$P \leqslant 0{\cdot}05$ (+)	NS	NS	NS
Morocco, Tassaout	5·66	$P \leqslant 0{\cdot}05$ (+)	NS	NS	NS	NS	NS	NS	NS
North America									
Canada, Kernen	2·76	NS	$P \leqslant 0{\cdot}05$ (–)	NS	NS	NS	NS	NS	NS
Canada, Swift	1·57	NS	NS	NS	NS	$P \leqslant 0{\cdot}05$ (+)	NS	NS	NS
Total		4 (+)	1 (+)	5 (+)	1 (+)	7 (+)	4 (+)	1 (+)	3 (+)

* Sign in parentheses indicates negative or positive significant correlations.
NS: no significant correlation.

evaluated under well irrigated, water-stressed and high-temperature conditions in north-west Mexico. The highest significant associations for NWI-3 and CT with grain yield from north-west Mexico were found in the high-temperature environment (Gutierrez *et al.* 2010*a*). In the present study, the highest number of negative associations of NWI-3 with grain yield at international testing sites was found for the determinations conducted from the well-irrigated environment. Six locations (0·23 of sites) with low and high yield in central and west, and north Africa gave significant correlations with NWI-3 (Table 12). In all yield trials, CT showed a lower association than NWI-3 with grain yield at the international locations.

North-west Mexico (Yaqui Valley) has been widely employed as a site for evaluating and selecting advanced lines for high yield for well irrigated, water-stressed and high-temperature environments (Lillemo *et al.* 2005). Lage *et al.* (2008) grouped individual sites into clusters using a shifted multiplicative model based on environmental data and grain yield (35 years average) and found that 18 sites were similar and 23 sites were contrasting when ESWYT, SAWYT and HTWYT data were analysed together. Lage *et al.* (2008) found that Yaqui Valley site was similar to six nursery sites in western and central Asia (southwest Turkey, north-east and north-west Pakistan and Syria). Trethowan *et al.* (2003) found that some nurseries from Egypt and Pakistan were also associated with yields from north-west Mexico for the ESWYT trial. Similarly, Trethowan & Crossa (2007) reported that other nurseries located in north Africa, western Asia and South America (Argentina) were also similar to north-west Mexico when advanced lines of ESWYT, SAWYT and HTWYT were evaluated. In the present study, grain yield from some dry and irrigated locations, mainly in central Asia (India and Pakistan), west Asia (Saudi Arabia and Turkey) and north Africa (Egypt and Morocco), showed stronger associations with the three parameters measured in north-west Mexico (Tables 6–14).

Power of the north-west Mexico parameters for indirect selection of high yielding lines

Plant breeders have repeatedly considered the potential of developing new selection indices that integrate several traits with high repeatability (genetically linked) for predicting yield in breeding programmes at relatively low cost (Baker 1986; Milligan *et al.* 2003). Previous studies (Babar *et al.* 2006; Gutierrez *et al.* 2010*a*) indicated that NWI-3 and CT offered great potential for the indirect selection of high yielding lines under optimal and adverse growth conditions (well irrigated, water-stressed and high-temperature) and also demonstrated high genetic gain and heritability for the same selection site (Yaqui Valley, north-west Mexico). It has been demonstrated using advanced wheat lines that NWI-3 and CT are related to the canopy water content (lower leaf water potentials), cooler CTs (high transpiration rates) and enhanced root capacity for tapping water in deeper soil layers under water-stressed conditions (Gutierrez *et al.* 2010*b*). The hypothesis for the present study was that by using the two remote sensing parameters determined in north-west Mexico, yield performance of advanced lines could be predicted at international testing sites. However, NWI-3 and CT measurements taken in north-west Mexico were associated with grain yield at only a few testing sites for the 24th ESWYT (0·12), the 11th SAWYT (0·14) and the 11th HTWYT (0·23) (Tables 6–14). The majority of international locations did not show strong associations with the north-west Mexico parameters, indicating that probably other factors (i.e. drought) were involved in the yield performance of the advanced lines, thereby reducing the association with NWI-3 and CT. Many international locations had low grain yield (average grain yield was 4·9 t/ha for the 24th ESWYT, 3·5 t/ha for the 11th SAWYT and 4·1 t/ha for the 11th HTWYT), indicating that rainfall and irrigations were probably limited and drought may have occurred during the cropping season in many international locations. Trethowan *et al.* (2001) established that drought was a common event in many testing sites and sometimes reduced/eliminated yield performance of advanced lines, especially in semi-arid sites.

The parameters (NWI-3 and CT) measured in north-west Mexico measured in three environments gave the opportunity to explore a wider range of international locations associated with NWI-3 and CT, but the number of associated testing sites were low (Tables 6–14). The lack of association could also indicate that few advanced lines were well adapted to local growth conditions in each location. Mohammadi *et al.* (2009) reported that 20 genotypes evaluated in 19 testing sites were differently adapted to warmer and cooler environments of Central Asia (Iran). Dwarf and early maturating genotypes with low to medium yields were better adapted to warmer environments, which were clearly distinctive of genotypes adapted to cooler environments. Data on the weather (ambient temperature and precipitation) and amount of irrigation during the cropping season for each location required to make major inferences in respect to the yield performance of lines across testing sites were lacking in the present study.

NWI-3 and CT presented several limitations for the yield prediction of international locations because few of them showed significant associations (Tables 6–14). The grain yield for one year (2003) for all international testing sites was considered in relation to NWI-3, CT and yield measurements in north-west Mexico, while other studies have analysed the genetic improvement across years for the SAWYT, ESWYT and HTWYT genotypes (i.e. 35 years analysis reported by Lage *et al*. 2008). The multiple year analysis made it easier to establish and identify the parameters that were influencing yield. Sener *et al*. (2009) found that the genetic improvement in yield among wheat cultivars delivered in the Mediterranean region (representing 23 years) were caused by changes in some physiological traits, such as higher harvest index, grain weight and grain number per spike.

Breeders are continuously looking for new indirect selection parameters for screening among genotypes to detect yield differences and to find strong associations with yield, such as stomatal conductance among wheat genotypes under rainfed conditions (Condon *et al*. 2004), chlorophyll fluorescence among triticale winter genotypes (Hura *et al*. 2009), water potential to screen plant water status (drought resistance) among wheat genotypes under water-stressed conditions (Munjal & Dhanda 2005), and wheat stem water-soluble carbohydrates determined at anthesis in a water-limited environment (Xue *et al*. 2009). However, for breeding purposes, these approaches are expensive and time-consuming methods for yield screening, especially if thousands of genotypes have to be evaluated in several locations and environments. Even though we identified only a limited association of NWI-3 and CT with grain yield from international locations, both parameters continue to offer great advantages (inexpensive and non-time consuming) for yield evaluation in north-west Mexico (Babar *et al*. 2006; Gutierrez *et al*. 2010*a*) and to predict yield performance in a few testing sites in central and west Asia, and north Africa.

The conclusion from the present work is that NWI-3 and CT measurements from north-west Mexico were only marginally effective in identifying advanced lines with broad adaptation across many international testing sites for the three international yield trials. The NWI-3 and CT from north-west Mexico measured in three environments (well irrigated, water-stressed and high-temperature) showed few consistent significant associations with the grain yield of nurseries located in diverse worldwide regions where the three yield trials were evaluated. Apparently, the lack of association could be due to other weather factors (drought) that affected the yield performance, and/or that few advanced lines were well adapted to local growing conditions at each testing site. Even though these two indirect selection parameters were basically ineffective in predicting yield performance at international sites, they have demonstrated their ability to serve as an indirect selection tool for high yield in spring and winter wheat at a single location.

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