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Full Length Article

Use of APSIM to Model Nitrogen Use Efficiency of Rain-fed Wheat

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Abstract

Nitrogen uptake and supply directly depends upon timing and method of application, soil physical conditions, climate and plant genetic features. Therefore, it varies with location and environment. Crop simulation models can be complementary decision support tools in field experiments to develop innovative crop management systems. APSIM (Agricultural Production Systems Simulator) is software which allows dynamic simulation of crop production, residue management, soil water and nutrient flow under different timing and methods of fertilizer application. In present studies, APSIM was calibrated and validated to predict nitrogen use efficiency of wheat under rain-fed conditions for Pothwar region of Pakistan. Field experiments were laid out using RCBD four factor factorial design replicated four times at PMAS-Arid Agriculture University, Rawalpindi Research area. Two wheat genotypes were planted during years (2010-11 and 2011-12) using different nitrogen rates [N_0 (No fertilizer), N_{50} (50kg ha^{-1}), N_{100} (100 kg ha^{-1}) and N_{150} (150 kg ha^{-1})] and application methods by keeping individual plot size of 4m x 6m and row spacing of 25cm. Maximum nitrogen use efficiency (108.49 kg kg^{-1}) was calculated for N_0 while minimum NUE (25.47 kg kg^{-1}) calculated for N_{150}. Split dose application method gave more NUE (58.95 kg kg^{-1}) than full dose nitrogen application method (53.77 kg kg^{-1}). Genotype NARC-2009 performed better and gave maximum NUE (60.55 kg kg^{-1}), while minimum NUE (52.17 kg kg^{-1}) was calculated for Chakwal-50. Similarly, during 2010-11, more NUE (60.19 kg kg^{-1}) was calculated than 2011-12 (50.52 kg kg^{-1}). Days to maturity, biomass nitrogen, grain yield and grain nitrogen were recorded from the field experiment as well as simulated by APSIM model. The simulated outcomes for all these parameters were strongly correlated. The simulation depicted a strong dependency of the mineral nitrogen concentration upon plant nitrogen uptake and growth. The validation skill scores like R^2 and RMSE confirmed the ability of APSIM to model nitrogen use efficiency in wheat under rain-fed conditions. Therefore, simulation modeling approaches should be adopted to recommend optimum fertilizer dose and timing to get maximum crop yield and eliminate nitrogen losses in the context of extreme climate variability.

Keywords: Crop simulation Models; APSIM; Wheat; Nitrogen Use Efficiency

Introduction

Agriculture, particularly in South Asia, is facing marvelous new challenges due to population growth and sluggishness in farm level efficiency in concentrated farming areas (Aggarwal *et al*., 2000). It is projected that by 2020, food grain requirement in South Asia would be almost 50% more than the current demand (Paroda and Kumar, 2000) which has to be met from same or even shrinking land due to increasing competition for land and other resources by non-agricultural sector. Increasing environmental threats in farming fields, in the form of diminishing soil fertility, dropping water tables, enhancing salinity, increasing resistance to pesticides, and deprivation of irrigation water quality, is additionally compounding the problem (Ladha *et al*., 2003). The intensifying temperature, CO_2 and erratic rainfall accompanying global climatic change may further impact food production (IPCC, 2001; Aggarwal, 2003). Such impacts are estimated to be severe in South Asia, especially in Pakistan due to its large population, predominance of agriculture in economy, and its limited resource endowments. Supplementary food production, particularly of rice and wheat in tropics, would require higher irrigation and fertilizer inputs, which may, however, result in increased methane and nitrous oxide emissions, which are the major agricultural sources of global warming (IPCC, 2001). Since food production is essential to meet the rising population requirement, strategies need to be established that can lead to greater food production while ensuring negligible greenhouse gas (GHG) emissions and maintaining soil. Traditional agronomic practices needs to be replaced with modern tools to feed billion of people. The tools like simulation modeling and proper nitrogen application methods and rates could be a better option to enhance crop productivity in limited resources.

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Nitrogen is the most demanding element by the crop and its deficiency can limit the crop yield. Major grain crops (wheat, paddy and maize) utilize 1 kg of nitrogen to produce 68,44 and 49 kg of paddy, wheat and maize grain, respectively (Witt *et al.*, 1999; Pathak *et al.*, 2003; Janssen *et al.*, 1990). At present a huge amount of N is being used by the world population, almost 83 million metric tons, which is almost a 100-fold increase over the last century. Approximately, 60% of the nitrogen fertilizer is used for production of three major cereals i.e. wheat, rice and maize worldwide. Nitrogen availability regulates numerous aspects of plant growth. The resource capturing tissues (meristematic activity and cell extension) are dependent upon N availability. It is estimated that by the end of 2050, 50-70% grains from cereal crops will be required to fulfill the food requirement of a huge population of 9.3 billion (Smil, 2005).

Nitrogen use efficiency (NUE) can be defined as dry matter accumulation per unit of nitrogen applied. NUE idea delivers a numerical measure of the usefulness of plants to absorb and transform available N into potential yield under different cropping systems. N fertilizer is among the central inputs for cereal production (Giller, 2004). Over the globe, NUE for grain crops is nearly 33% including wheat (Raun and Johnson, 1999). Suitable N application rates and timing are precarious for fulfilling plant requirements and enhancing NUE. Higher use of artificial fertilizer may result in soil and environmental pollution like eutrophication (Abril *et al*., 2007). Crop rotation, soil edaphic features, temperature, soil water, N fertilizer rates and crop types affect NUE (Halvorson *et al.*, 2002). Halitligil *et al.* (2000) and Thomas *et al.* (2007) specified that plant NUE affected by nitrogen fertilizers in semi-arid and variable rain-fed situations.

Availability of nitrogen during various growth and development phases of wheat is an important determinant of yield and quality of grain (Zende *et al*., 2005). Lopez-Bellido *et al*. (2005) recommended split N application to wheat at vegetative stages as a trick suggested from the viewpoint both of the climate and farmers profit. In earlier studies, it has been concluded that late season nitrogen addition as dry fertilizer material were most effective in attaining higher grain nitrogen concentration, yield and increased fertilizer recovery and efficiency (Kumari *et al.*, 2000; Michael *et al*., 2000; Anthony *et al.*, 2003; Melaj *et al.,* 2003; Fallahi *et al*., 2008).

Simulation modeling of natural phenomenon has been improved during the recent decades as a result of advancement in information technology. Crop growth, development and yield in relation to various climatic factors have been modeled. Crop productivity directly depends upon the interaction between plant, water, soil and environment. Simulation of plant growth stages and crop yield permits better planning and efficient management of crop production processes. Creating new plans and conclusion in crop production gradually makes implementation of numerous model-based decision support tools especially in the context of changing climatic issues. Simulation models which are used to simulate crop growth are generally mechanistic, i.e. these models not only try to explain relationship between simulated variables and parameters but also the appliance of the designated methods (Challinor *et al*., 2009). Although many crop growth simulation models are established and assessed at the field scale, and the only problem was there that they were not made to simulate huge areas, now a day it is a common practice to use these dynamic models in evaluation of agricultural impacts and alteration to climate changeability and change, from a field to the national level (Parry *et al*., 2005; Rosenberg, 2010). Duxbury *et al*. (2000) elaborated by eight long term experiments on wheat-rice based cropping system that higher N-use efficiency and N-recovery for wheat than rice. In south Asia and China several long-run experiments showed variations in response of wheat and rice to nitrogen. However, in all circumstances, nitrogen fertilization enhanced agronomic yields of both rice and wheat crops. Furthermore in high nitrogen application there wasn't any declining trend in yield, but only control treatments showed decline in yield (Dawe *et al*., 2000; Yadav *et al*., 2000).

Pan *et al*. (2006) developed the dynamic model for N uptake and accretion of N in the grains and their simulation. Lower values of RMSE depicted that the performance of model was good for all the treatments. As a result it was clear that model can simulate seed nitrogen accumulation and protein production under varying growing environments. Crop simulation models are site and crop specific in nature and cannot be used in other areas until and unless validated under local conditions. APSIM model was parameterized under local conditions mainly on wheat crop being staple food and is cultivated under a wide range of climatic conditions. Nitrogen use efficiency has not yet been modeled in Pakistan, so keeping in view the above scenarios; the present study was undertaken with the objectives to investigate modeling dynamics and accumulation of inorganic N in the plant and the yield response to different N fertilizer rates under rain fed conditions.

Materials and Methods

The parameterization and evaluation of APSIM model for nitrogen use efficiency of two wheat genotypes was under taken through field experiments conducted at Research area of PMAS-Arid Agriculture University, Rawalpindi during 2010-11 and 2011-12. Chemical properties of the soil like pH was 7.5, EC (0.20-0.24 dS m^{-1}), nitrogen was 0.04% while available P was 3.64 mg kg^{-1}. Experiments were laid out in accordance with four ways factorial Randomized Complete Block Design (RCBD) with four replications. Treatments applied were four nitrogen rates [T_1 = Control (N_0), T_2 = 50 kg N (N_{50}), T_3 =100 kg N (N_{100}) and T_4 =150 kg N (N_{150})], two application methods (AM_1 = Full dose of nitrogen at sowing and AM_2 = Three equal doses (1/3rd of each treatment) of nitrogen at sowing, tillering and at flag leaf stage), two genotypes (G1 = NARC-2009 and G2 = Chakwal-50) and two environments (Y_1=2010-11, Y_2=2011-12).Phosphorous was applied @ 50 kg ha^{-1} in the form of single super phosphate (SSP). Individual plot size for each treatment was 4m x 6m for each genotype with row spacing of 25cm. Climatic conditions during 2010-11 and 2011-12 are presented in Fig. 1.

Nitrogen Estimation

Amount of Nitrogen was determined at Zadok's (Zadok *et al*., 1974) growth stages (Three leaf, Anthesis and at Maturity) from a randomly selected area of 0.25 m^2 from each plot. The samples were oven dried at 65°C for 48 h and grounded by using Wiley Mill and dried samples were kept in plastic bottles for the determination of nitrogen contents.

Digestion for Total Nitrogen

A ground and well dried 0.2 g plant sample was poured in digestion tubes, a digestion mixture of 4.4 mL having lithium sulphate, selenium powder and $H_2O_2$was mixed and digested for 2 h at 360ºC till solution became colorless, then and 50 mL of H_2O were added and dissolved perfectly. The solution was diluted up to 100 mL. After settling down, the clear solution was ready for additional study for N_T calorimetrically (Anderson and Ingram, 1993).

Colorimetric Determination of Total Nitrogen (%)

A solution of sodium nitroprusside was made of sodium tartrate, sodium citrate; 5 mL reagent having sodium salicylate and 0.1 mL each standard was added. It was mixed well and left for 15 min. Then 5 mL of reagent containing a solution of NaOH, water and sodium hypochlorite was added to each test tube and left for one h for full color development. Absorbance of samples was measured using spectrophotometer at 665 nm.

Plant N_T calculated by the following formula:

$$N_T \% = C/W \times 0.01$$

Where C is corrected concentration (µg /mL) and W is Weight of sample (g)

Nitrogen Uptake Efficiency (NUpE)

Nitrogen Uptake Efficiency was estimated according to Rahimizadeh *et al.* (2010).

$$(NUpE) = N_T/N_{supply}$$

Where N_T is total plant N uptake and N_{supply} is sum of soil N content at sowing and N fertilizer.

Nitrogen Utilization Efficiency (NUtE)

NUtE was determined according to Rahimizadeh *et al.* (2010).

$$(NUtE) = G_y/ N_T$$

Nitrogen Use Efficiency (NUE)

NUE was calculated according to Rahimizadeh *et al.* (2010)

$$NUE = G_y/N_{supply}$$

Where G_y is grain yield, N_{supply} is sum of soil N content at sowing and N fertilizer.

Model Calibration

Model calibration and validation against an independent data set is an essential step in model development. APSIM model was parameterized and evaluated for nitrogen dynamics in wheat. In the present study the APSIM model was evaluated for simulation of days after sowing, dry matter accumulation (biological yield), grain yield, biomass nitrogen, total nitrogen, grain total nitrogen as these were the major constituent of optimal crop productivity. Genotypic coefficients were incorporated into wheat in file of model until observed and simulated results were close to each other.

Model evaluation

The model was validated from the data collected from the field experiment during 2010-11 and 2011-12. The main focus of the current study was simulation of days to maturity, biomass, grain yield, grain nitrogen contents. For this, simulated data was compared with observed data. The performance of the APSIM model was validated through validation skill scores like root mean square error (RMSE), d-stat and coefficients of determination (R^2).

$$RMSE = [\sum_{i=1}^{n}(P_i - O_i)^2 / n]^{0.5}$$

Where, O_i and P_i are the observed and predicted (simulated) values for the variables under consideration and n is the number of observations. Model performance increases as RMSE proceed to zero while d-stat and R^2 approaches to unity (Table 1).

Results

Total Nitrogen

Nitrogen contents at three leaf stage were estimated to determine nitrogen uptake by wheat crop at particular stage. Total nitrogen differed significantly with application rates. Maximum (5.33 kg ha^{-1}) total nitrogen uptake was observed for treatment $N_{150,}$ while minimum (3.71 kg ha^{-1}) for treatment N_0 (Table 2) at three leaf stage (Z-13). Nitrogen application methods caused significant variation in nitrogen uptake at three leaf stage. Total nitrogen in plant biomass was higher (4.77 kg ha^{-1}) for split dose compared to that of full dose (4.36 kg ha^{-1}) of nitrogen application. A significant difference was observed for total nitrogen at three leaf stage between growing years (2010-11 and 2011-12). Higher total nitrogen (4.84 kg ha^{-1}) was taken up during 2010-11 while lower amount of nitrogen (4.26 kg ha^{-1}) during 2011-12.

Table 1: Genotypic coefficients used for APSIM model parameterization for both genotypes

	NARC-2009	Chakwal-50
Thermal Time for Grain Filling	662	634
Photothermal Sensitivity	3.37	3.31
Vernalization Sensitivity	0	0
Growing degree days to flower initiation	1300	1200

Table 2: Total nitrogen, nitrogen uptake efficiency and nitrogen use efficiency for varying nitrogen rates and application methods among for wheat genotypes during 2010-11 and 2011-12.

Treatments	TN Z-13	TN Z-60	TN Z-92	NUtE	NUE
Nitrogen Rate (NR)					
N_0	3.71d	14.77d	18.94d	203.19a	108.49a
N_{50}	4.18c	28.15c	36.07c	121.65b	51.35b
N_{100}	5.03b	52.83b	67.73b	80.52c	40.12c
N_{150}	5.33a	55.55a	71.20a	66.76d	25.47d
LSD	0.2660	0.6538	0.8348	10.146	4.6791
Application Methods (AM)					
Split	4.36b	40.39a	51.78a	120.63NS	58.95a
Full	4.77a	35.25b	45.19b	115.43NS	53.77b
LSD	0.1881	0.4623	0.5903	NS	3.3087
Years (Y)					
Y1	4.84a	39.06a	50.07a	125.56a	60.55a
Y2	4.29b	36.58b	46.90b	110.5b	52.17b
LSD	0.1881	0.4623	0.5903	7.1740	3.3087
Genotypes (G)					
NARC-2009	4.79a	39.39a	50.49a	125.13a	62.19a
Chakwal-50	4.34b	36.26b	46.49b	110.93b	50.52b
LSD	0.1881	0.4623	0.5903	7.1740	3.3087

TN Z-13= Total Nitrogen at Three leaf, TN Z-60=Total Nitrogen at Anthesis, TN Z-92= Total Nitrogen at Maturity, NUtE=Nitrogen uptake efficiency, NUE= Nitrogen Use Efficiency

Table 3: Validation skill scores for DAS, Biological yield, Biomass TN, Grain yield and Grain Nitrogen at different Zadok's stages for split application of Nitrogen

Parameters	Zadok's Stage	RMSE	d-Stat
DAS	Z13	6.11	0.9999
	Z60	11.37	0.9997
	Z92	7.37	0.9999
Biological Yield	Z13	4.00	0.999
	Z60	894.88	0.996
	Z92	1484.11	0.996
Biomass Total Nitrogen	Z13	0.62	1.000
	Z60	1.84	1.000
	Z92	2.30	1.000
Grain Yield	Z92	375.11	0.9977
Grain Nitrogen	Z92	1.25	0.9996

There was significant difference between genotypes for nitrogen uptake. Genotype NARC-2009 took up more nitrogen (4.79 kg/ha) than Chakwal-50 (4.34 kg/ha) at three leaf stage.

Total nitrogen at anthesis stage (Z-60) differed significantly at different nitrogen rates. Treatment N_0 accumulated minimum nitrogen (14.76 kg ha^{-1}) while N_{150} accrued maximum nitrogen (55.55 kg ha^{-1}). In split doses, higher total nitrogen uptake (40.39 kg ha^{-1}) was measured than that in full dose nitrogen application method (35.25 kg ha^{-1}). Significant difference for total nitrogen was observed among years at anthesis stage. During 2010-11, maximum nitrogen (39.06 kg ha^{-1}) was estimated, whereas the minimum total nitrogen (36.58 kg ha^{-1}) in plant biomass was observed during 2011-12. Genotype NARC-2009 harvested maximum nitrogen (39.39 kg ha^{-1}) than Chakwal-50 (36.26 kg ha^{-1}).

Treatment N_0 accumulated minimum nitrogen (18.94 kg ha^{-1}), while N_{150} accrued maximum nitrogen (71.2 kg ha^{-1}) at maturity stage (Z-92). In split doses, higher nitrogen (51.78 kg ha^{-1}) was measured as compared to full dose nitrogen application method (45.19 kg $ha^{-})^{1}$. Significant difference for total nitrogen at maturity stage was observed during both years. During 2010-11, higher total nitrogen (50.07 kg ha^{-1}) was calculated, whereas, minimum total nitrogen (46.90 kg ha^{-1}) was calculated during 2011-12. Similarly, for genotype NARC-2009, harvested total nitrogen (50.49 kg ha^{-1}) was higher as compared to Chakwal-50 (46.49 kg ha^{-1}).

Nitrogen Uptake Efficiency (NUpE)

Nitrogen rates and application methods caused significant variation for nitrogen uptake efficiency in the two genotypes during both years of experimentation. Maximum nitrogen uptake efficiency (0.53) was recorded for N_0 as compared to N_{150} (0.38) (Table 2). Regarding nitrogen application methods, higher NUpE was recorded for split doses (0.49) as compared to full doses (0.43). Similarly, between years the higher nitrogen uptake efficiency was observed during 2010-11 (0.46) as compared to (0.45) during 2011-12. Genotypes also differed significantly for nitrogen uptake efficiency. Maximum nitrogen uptake efficiency (0.48) was calculated for genotype NARC-2009 compared to that of Chakwal-50 (0.44).

Nitrogen Use Efficiency (NUE)

Nitrogen rates differed significantly for showing nitrogen use efficiency. Maximum NUE (108.49 kg kg^{-1}) was calculated for N_0 while minimum nitrogen use efficiency (25.47 kg kg^{-1}) calculated for N_{150} (Table 2). Similarly, nitrogen application methods varied significantly for NUE. Split nitrogen doses gave higher nitrogen use efficiency (58.95 kg kg^{-1}) compared with 53.77 kg kg^{-1} for full dose nitrogen application method. Likewise, nitrogen use efficiency differed considerably for both the years. Maximum nitrogen use efficiency (60.55 kg kg^{-1}) was calculated during 2010-11, whereas the minimum NUE (52.17 kg kg^{-1}) was found during 2011-12. Both genotypes differed significantly for nitrogen use efficiency. Genotype NARC-2009 showed maximum nitrogen use efficiency (62.19 kg kg^{-1}) compared with Chakwal-50 which had minimum NUE (50.52 kg kg^{-1}).

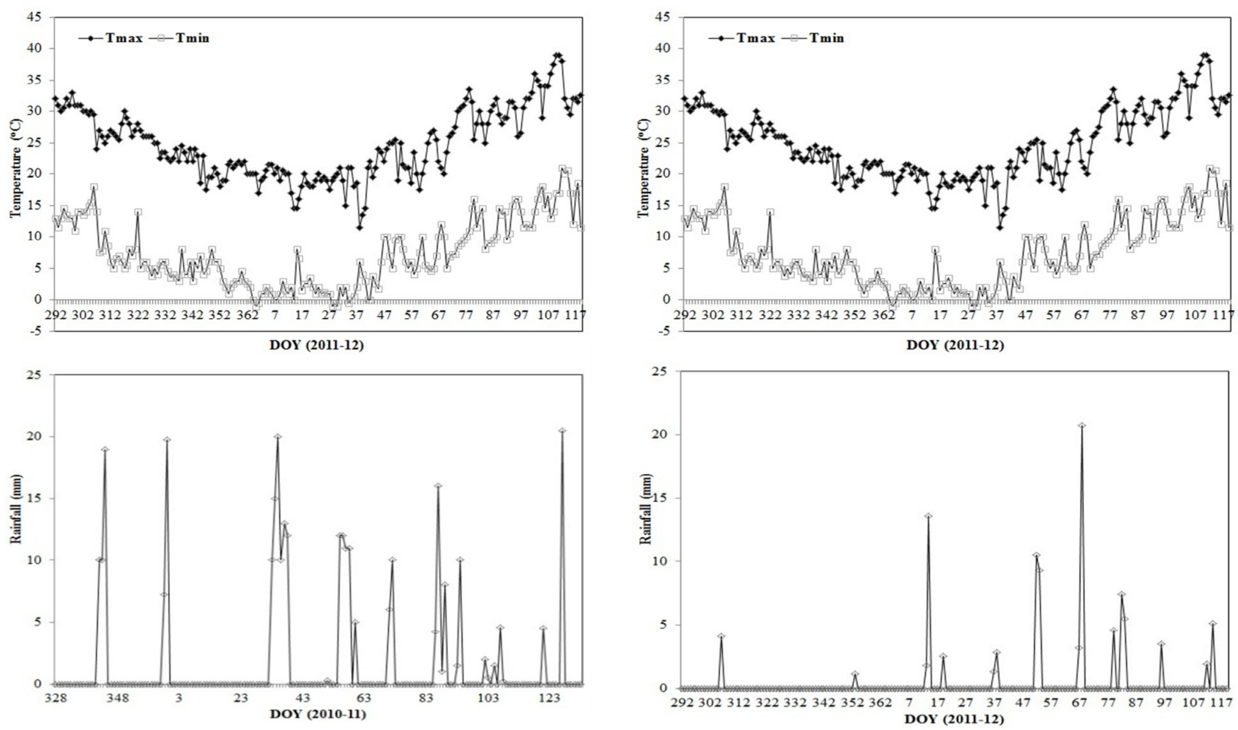

Fig 1: Climatic conditions during the growing the wheat crop growing season of 2010-11 and 2011-12

Days After Sowing

APSIM model was parameterized (Thermal Time for Grain Filling 662 and 634, photo thermal sensitivity 3.37 and 3.31, growing degree days to flower initiation 1300 and 1200, and vernalization sensitivity was 0 for cv NARC-2009 and Chakwal-50) to simulate days after sowing under different nitrogen regime and application methods during 2010-11 and 2011-12 for two wheat genotypes. There was a close association between observed and simulated days after sowing for Zadok's scale (Three leaf, Anthesis and Maturity). Maximum observed days after sowing (171) were calculated when nitrogen was applied @ 100 kg ha^{-1} whereas, simulated DAS (169) were close to observed with the 100 kg N ha^{-1} application. Nitrogen application methods also differed significantly for the calculation of days after sowing. Days after sowing were higher for split dose nitrogen application method i.e., observed (165.2) and simulated (164) than full dose nitrogen application method i.e. observed (158.67) and simulated (160). During the two environments viz. Y1 = 2010-11 and Y2 = 2011-12 considerable change in days after sowing were calculated. During the first year, more days after sowing were observed (167) than the preceding year (153). The simulated days after sowing were higher during 2010-11 (166) than 2011-12 (158). The simulated days after sowing were close to observed values. Nitrogen rates and application methods influenced days after sowing significantly. The simulated days after sowing by APSIM model at three leaf stage were extraordinarily close to observed days after sowing. At three leaf stage same observed (34.3) and simulated days after sowing (34.4) were calculated. Fig. 2 represents observed and simulated days after sowing of two wheat genotypes at different nitrogen rates and application methods for both years. Maximum observed days after sowing ranged from 147-180 while simulated DAS were 156-178.

Biomass Total Nitrogen

APSIM model was parameterized to simulate biomass total nitrogen contents under different nitrogen regime and application methods during 2010-11 and 2011-12 for two wheat genotypes at three phenological stages (Three leaf, Anthesis and Physical Maturity). Observed and simulated biomass total nitrogen contents were very close to each other at three leaf, anthesis and maturity stages. Fig. 3 represents observed and simulated biomass total nitrogen by APSIM model for two years. Modeled biomass total nitrogen contents differed significantly for varying nitrogen rates and application methods for two wheat genotypes during both the years. At three leaf stage observed (1.45 g/m^2) and simulated (1.46 g/m^2) biomass total nitrogen were similar. Whereas, nitrogen application method behaved differently. Observed biomass total nitrogen was higher when nitrogen was applied as full dose (1.51 g/m^2) at the time of sowing than split dose (1.42 g/m^2) nitrogen application method. Simulated biomass total nitrogen was also higher for full dose nitrogen at the time of sowing (1.54 g/m^2) than splitting (1.43 g/m^2) at different phenological stages. While at anthesis higher biomass total nitrogen

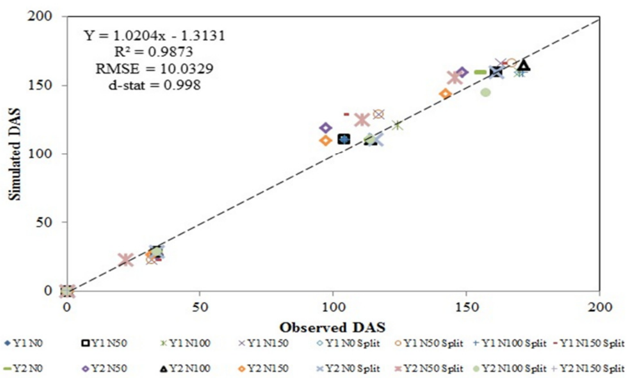

Fig. 2: Comparison of observed and simulated DAS for different nitrogen application rates and methods during both years

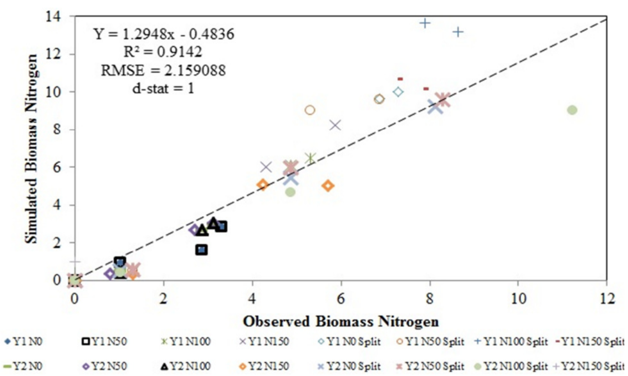

Fig. 3: Comparison of observed and simulated biomass total nitrogen for different nitrogen application rates and methods during both years

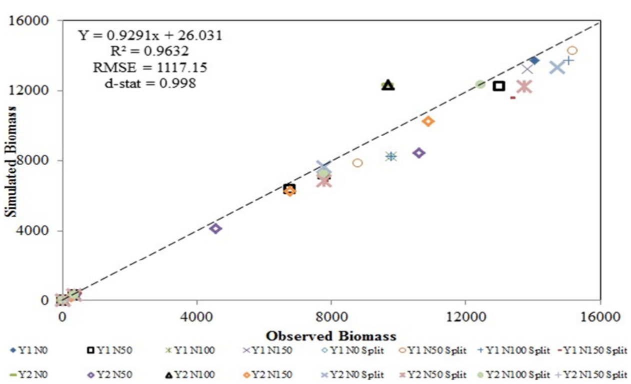

Fig. 4: Comparison of observed and simulated biomass for different nitrogen application rates and methods during both years

recorded for split dose nitrogen application method (5.3 g/m^2) than full dose application method (4.6 g/m^2). Higher biomass total nitrogen simulated for split dose application method (5.8 g/m^2) than full dose application method (5.1 g/m^2) at anthesis stage. At maturity stage maximum biomass total nitrogen observed (12.5 g/m^2) and modeled (13.1 g/m^2) for higher nitrogen rates whereas, minimum biomass total nitrogen recorded (9.3 g/m^2) and modeled (9.8 g/m2) for control nitrogen rates (data not shown). Higher biomass total nitrogen was observed (1.47, 5.1, and 12.6 g/m^2) and simulated (1.47, 5.3, and 12.8 g/m^2) during 2010-11 than 2011-12 at all the phenological stages i.e. three leaf, anthesis and maturity respectively.

Biological Yield

APSIM model was parameterized (Thermal Time for Grain Filling 662 and 634, Photothermal sensitivity 3.37 and 3.31, Growing degree days to flower initiation 1300 and 1200, and vernalization sensitivity was 0 for *cv.* NARC-2009 and Chakwal-50) to simulate biological yield (dry matter) under different nitrogen regime and application methods during 2010-11 and 2011-12 for two wheat genotypes. Some of the observed and simulated values remained close to 1:1 while in most cases model under predicted dry matter accumulation at different phenological stages of wheat. The greater dispersion recorded at maturity where dry matter values become higher while at early stages simulated and observed values have close agreement. The trend of simulated dry matter at early growth stage i.e. three leaf stage, showed good association with observed while significant dispersion recorded at anthesis stage. However, regression line stability showed that model simulated dry matter with good precision (Fig. 4) for all the nitrogen application rates, methods and genotypes during two years.

Observed and simulated biological yield were close to each other. A direct relation with nitrogen fertilizing rates calculated in simulating biological yield by APSIM model. At higher nitrogen fertilizer levels (N_{100} and N_{150}) maximum dry matter simulated (14560 kg ha^{-1}) whereas, minimum dry matter simulated (11650 kg ha^{-1}) for control nitrogen rate (N_0) at maturity stage. Similarly, variation for biological yield simulation was yield during 2011-12 (11470) kg ha^{-1}) than 2010-11 (13457 kg ha^{-1}) was due the less moisture availability during 2011-12.

Grain Yield

Simulated grain yield under different nitrogen regime and application methods during 2010-11 and 2011-12 for two wheat genotypes. Fig. 5 represents observed and simulated grain yield of two wheat genotypes at different nitrogen rates and application methods for both years. Observed and simulated grain yield were very close to each other. Nitrogen application rates and methods varied potentially for simulating grain yield of wheat crop. A direct relation with nitrogen fertilizing rates calculated in simulating grain yield by APSIM model. At higher nitrogen fertilizer levels (N_{100} and N_{150}) maximum grain yield simulated whereas, minimum grain yield simulated for control nitrogen rate (N_0). Similarly, variation in grain yield simulation during 2011-12 than 2010-11 was observed/recorded.

Grain Total Nitrogen

There was a close association among observed and simulated grain total nitrogen. The simulated grain total nitrogen was very close to observed values. Nitrogen rates, application methods and wheat genotypes influenced grain total nitrogen during both years. Fig. 6 represents observed and simulated grain total nitrogen of two wheat genotypes at different nitrogen rates and application methods for both years. Maximum grain nitrogen was accumulated with higher nitrogen application rates (6.7 g/m^2) and simulated grain total nitrogen (6.56 g/m^2) was also in accordance with observed values while minimum observed (2.23 g/m^2) and simulated grain total nitrogen (2.26 g/m^2) was recorded from control nitrogen treatments. Similarly, higher grain nitrogen observed (4.56 g/m^2) and simulated (5 g/m^2) for split dose nitrogen application method than full dose nitrogen application method. Meanwhile, higher grain nitrogen was accumulated by genotype NARC-2009 (5.54 g/m^2) than Chakwal-50 (4.32 g/m^2) also the simulated grain nitrogen was very close to observed values viz. simulated grain was 5.45 and 4.51 g/m^2 for NARC-2009 and Chakwal-50, respectively. Likewise, similar to observed grain nitrogen contents minimum grain total nitrogen was simulated (4.1 g/m^2) by APSIM during 2011-12 while maximum for 2010-11 (4.8 g/m^2).

Discussion

Nitrogen uptake efficiency (NUpE) measures the amount of nitrogen taken up by crop/plant. NUpE is the most important factor which determines the NUE particularly, under N stress conditions (Wang *et al*., 2011) and genetic variation forNUE under different N levels has been observed (Gaju *et al*., 2011). It was suggested that NUE can be increased by increasing nitrogen uptake (Dalal *et al.,* 2013). The results of present study depicted that nitrogen application rates and methods significantly affected NUpE in two wheat genotypes. The highest nitrogen uptake efficiency (0.53) was calculated for control and split doses (0.49), while the lowest NUpE (0.38) was found for N_{150}. This indicated that NUpE is positively correlated with nitrogen use efficiency. The N uptake by crop root after anthesis resulted to 5-50% grain N in wheat (Kichey *et al*., 2007) therefore split application methods of N particularly at anthesis could contribute to maximum NUpE provided environmental conditions remained normal as was in 2010-11 (Fig. 1). Rahimizadeh *et al.* (2010) depicted a decrease in NUpE with increasing nitrogen rates in wheat. Split banding method could be considered as best method to maximize NUpE as our study depicted higher NUpE for split doses (0.49) as compared to full doses (0.43).

Nitrogen use efficiency is the measure of grain yield produced by applying one unit of nitrogen. In present study, N fertilizer rates and application methods affected Nitrogen use efficiency of wheat. The nitrogen use efficiency for split

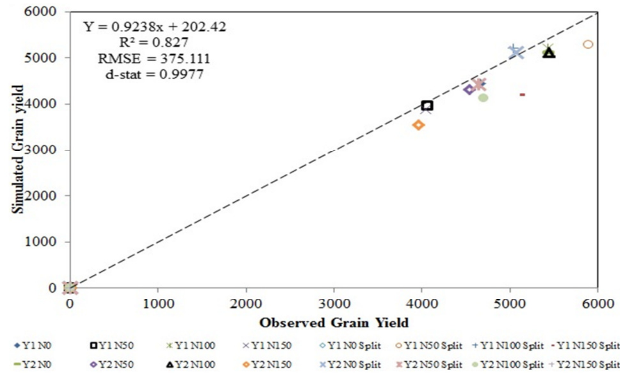

Fig. 5: Comparison of observed and simulated grain yield (kg/ha) for different nitrogen application rates and methods during both years

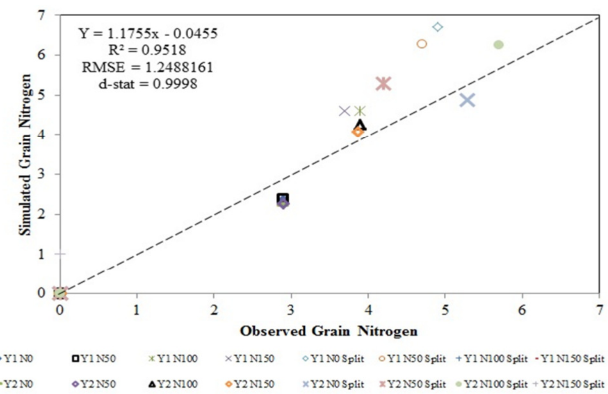

Fig. 6: Comparison of observed and simulated grain total nitrogen for different nitrogen application rates and methods during both years

dose application was higher than full dose which decreased with increasing nitrogen rates. Reduction of NUE during 2011-12 compared with 2010-11 might be due to lower grain yield, which was because of less moisture due to limited rainfall at early crop establishment and at anthesis stage. Poorly established plants were incapable of utilizing the available resources, hence resulted lower yield. Nitrogen use efficiency is the yield harvested per unit nitrogen applied. In the control treatment, no nitrogen was applied in the field and grain yield was the product of nitrogen present in the soil profile, so maximum nitrogen use efficiency was found for control treatment. We found significant genetic variation for NUE; the higher NUE was recorded for NARC-2009 (62.19) while in Chakwal-50 it remained 50.52. The difference might be due to accumulation and distribution of N at early developmental stages as it was concluded that 50-95% N in grain comes from stored N in shoots and roots taken up by crop before anthesis (Kichey *et al*., 2007). Similarly, difference in genotype canopy architecture (leaves, stem and root) could also resulted to variation for NUE as leaves and stems are biggest source of grain N while contribution by roots and chaffs are about 10-15% respectively (Critchley, 2001). Genotypic variation for NUE has also been previously recorded due to differences in the absorption of nitrate and N remobilization (Xiao-li *et al.*, 2011). The dependence of N accumulation and availability on genotype can be evaluated by applying different nitrogen regimes. NUE decreased with increase in N, therefore, optimum rate and timing of N application need to be determined to obtain maximum profit (Timsina *et al.*, 2001).

The validation skill score like RMSE, d-stat and R^2 confirmed the efficiency of model for simulation of days after sowing (Table 3). The higher value of d-stat (0.998) and regression coefficient (R^2=0.98) confirmed the better performance of APSIM model in the rain-fed ecosystem of Pakistan under different nitrogen regime. The lower value of RMSE (10.09) at maturity stage also lead to the conclusion that APSIM model can simulate days after sowing accurately under different nitrogen regime. Days to maturity depends upon the climatic conditions as well as the nutrient availability. During second year of the current study the temperature was higher than the previous year so crop fulfilled its growing degree day's requirement in short period of time which resulted in less DAS. Yield simulation might be improved if models can simulate more accurate phenological stages like days after sowing in response to different nutrients regimes (Zhang *et al.*, 2008). The accurate simulation of DAS by APSIM showed that model can work with good accuracy and can be used to make decisions about crop managements like right amount of fertilizer at right time, right method and right combination. Similarly, understanding the impact of climate change and management practices on crop phenology is of importance to have appropriate adaptation strategies. Since the APSIM model was used to quantify the changes in wheat phenology in terms of vernalization and photoperiod sensitivity as well as the changes in thermal time of pre- and post-flowering stage among wheat varieties. Therefore, APSIM could capture phenological changes of spring wheat caused by different N rate and application methods with good accuracy. The validation skill score like RMSE, d-stat and R^2 confirmed the efficiency of model for simulation of biomass total nitrogen (Table 3). The higher value of regression coefficient (R^2=0.91) and d-stat (1) confirmed the better performance of APSIM model in the rain-fed ecosystem of Pakistan under different nitrogen regime. Similarly, lower value of RMSE (2.159) confirmed the adaptability of APSIM model in Pakistani climate. Among genotypes, modeled biomass total nitrogen was close to observed biomass total nitrogen at maturity for NARC-2009. Chen *et al.* (2010) simulated biomass total nitrogen with APSIM-wheat module and concluded that the model explained more than 90% variation in crop biomass. Farmers typically apply low N to wheat crop in low rainfall cropping systems which resulted to less biomass total nitrogen. However, farmers could get benefit by using higher fertilizer rates and adjusting N fertilizer application time using knowledge of crop simulation, probability theory, profit function and finance techniques (Monjardino *et al.*, 2013).

The validation skill score like RMSE, d-stat and R^2 confirmed the efficiency of model for simulation of biological yield (Table 3). The results depicted that simulated model was close to observed values with stable regression line (R^2=0.87). The root mean square error for observed and simulated biomass accumulation at maturity was 1171 kg ha^{-1}. The low value of RMSE depicted that performance of APSIM model was good in simulation of biological yield. Observed biological yield and modeled biological yield differed significantly for varying nitrogen rates and application methods for both wheat genotypes during both years. Maximum biological yield was modeled by APSIM for genotype NARC-2009 for nitrogen rate N_{100} when it was applied as split dose during 2010-11. The minimum biological yield was simulated for Chakwal-50 with highest nitrogen application rate (N_{150}). The dry matter accumulation was enhanced at post anthesis stages. Addition of nitrogen at late growth stages like anthesis resulted increased dry matter accumulation (Jun-Hua *et al.*, 2010) like in our results where drymatter accumulation remained maximum for N_{150} split dose during 2010-11. Dry matter translocation efficiency (12.15–28.25%) was not affected by N treatments, but it was affected by the cultivars and the growing period. The dry matter translocation efficiency in our study were higher than the values concluded previously (Dordas and Sioulas, 2009). The difference in dry matter production was due to variation in soil moisture status. During the first year (2010-11), timely rains favored better crop establishment, there by resulting higher production. On the contrary, due to prevailing drought spell during 2011-12, crop was unable to get benefits from resources. During 2011-12, temperature was also higher than the previous growing year which resulted to lesser dry matter. Variability in crop dry matter as a result of prevailing environmental conditions has also been concluded by White and Wilson (2006), while Marino *et al.* (2011) stated that nitrogen had principal role in dry matter accumulation and enhancing grain yield in wheat crop. Similarly, Khayatnezhad and Gholamin (2012) concluded highest dry matter production for wheat crop due to increased nitrogen levels.

Different validation skill scores were used to check the performance of APSIM model (Table 3). The results depicted that model simulated close to observed values with stable regression line (R^2=0.83) and d-stat close to unity (0.998). The root mean square error for observed and simulated biomass accumulation at maturity was 375. The low value of RMSE depicted that APSIM model simulated grain yield reliably. Meinke (1996) stated that model simulation is dependent upon climate, soil and plant genetic factors. Similarly, observed grain yield and modeled grain yield differed greatly for varying nitrogen rates and application methods for the two wheat genotypes during both years. Maximum grain yield was modelled by APSIM for genotype NARC-2009 during 2010-11 for the split dose nitrogen rate N_{100}, whereas minimum grain yield was simulated for Chakwal-50 with highest nitrogen application rate (N_{150}). Martre *et al.* (2006) simulated grain yield with varying nitrogen rates and found direct relation between grain yield and applied nitrogen. Results of Saeed *et al.* (2013) concluded that application of N in split doses at different critical stages resulted higher grain yield. Introduction of high yielding and more input responsive varieties have potential to uptake maximum nitrogen and exhibit a positive correlation with added Nitrogen in soil (Ali *et al*., 2005). Hussain *et al.* (2010) suggested using high yielding drought tolerant varieties for optimum yield. Tadayon (2007) elaborated that genotypes vary for grain yield production due to their genetic behavior under different nitrogen regime.

APSIM model simulated higher grain nitrogen than observed grain nitrogen. APSIM was tested by different skill scores like R^2, d-stat and RMSE. The value of R^2, d-stat and RMSE were 0.95, 0.99 and 1.25, respectively, which confirmed the reliability of APSIM model in the rain-fed conditions of Pakistan. Several crop models have reliably simulated the accumulation of grain dry mass and grain total nitrogen (Jamieson and Semenov, 2000; Asseng *et al*., 2002). Nitrogen is the key component of many compounds. In present study, grain nitrogen was affected by nitrogen rates (Garrido-Lestache *et al*., 2005). Variability in grain N contents among different wheat genotypes for different N rates have been concluded by Nakano and Morita (2009).

In conclusion, a better performance of genotype NARC-2009 under varying nitrogen regime proved its superiority thus recommended to farmers with N application of 100 kg ha^{-1}. Splitting of nitrogen fertilizers could be more beneficial than full dose nitrogen at the time of sowing imparting higher yield. The analysis of the modeling results indicated the strong dependency of the mineral nitrogen content upon plant nitrogen uptake and growth. The validation skill score R^2, d-stat and RMSE confirmed the ability of APSIM to model nitrogen use efficiency in wheat under rain-fed conditions. The APSIM model results for NUE under rain-fed conditions indicated that it could be used as decision support tool under different scenarios to have good management options.

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References

Abril, A., D. Baleani, N. Casado–Murillo and L. Noe, 2007.Effect of wheat crop fertilization on nitrogen dynamics and balance in the Humid Pampas, Argentina. *Agric. Ecosys. Environ.,* 119: 171–176

Aggarwal, P.K., 2003. Impact of climate change on Indian agriculture. *Plant Biol*. 30: 189–198

Aggarwal, P.K., S.K. Bandyopadhyay, H. Pathak, N. Kalra, S. Chander and S.K. Sujith, 2000. Analyses of yield trends of the rice–wheat system in north–western India. *Outlook Agric*., 29: 259–268

Ali, H., S. Ahmad, H. Ali and M. Yousaf, 2005. Impact of nitrogen application on growth and productivity of wheat (*Triticum aestivum* L.). *J. Agric. Soc. Sci*., 1: 1813–2235

Anderson, J.M. and J.S.I. Ingram, 1993. *Tropical soil biology and fertility: a handbook of methods.* CAB International, Wallingford, UK

Anthony, G., B. Woodard and J. Hoard, 2003. Foliar N application timing influence on grain yield and protein concentration of hard red winter and spring wheat. *Argon. J*., 95: 335–338

Asseng, S., A. Bar–Tal, J.W. Bowden, B.A. Keating, A. Van Herwaarden, J.A. Palta, N.I. Huth and M.E. Probert, 2002. Simulation of grain protein content with APSIM–N wheat. *Eur. J. Agron*., 16: 25–42

Challinor, A.J., F. Ewert, S. Arnold, E. Simelton and E. Fraser, 2009. Crops and climate change: progress, trends, and challenges in simulating impacts and informing adaptation. *J. Exp. Bot*., 60: 2775–2789

Chen, C., E. Wang and Q. Yu, 2010. Modelling the effects of climate variability and water management on crop water productivity and water balance in the North China plain. *Agric. Water Manage*., 97: 1175–1184

Critchley, C.S., 2001. A physiological explanation for the canopy nitrogen require–ment of winter wheat. *PhD Thesis,* University of Nottingham, UK, pp: 257

Dalal, R.C., W.M. Strong, J.E. Cooper and A.J. King, 2013. Relationship between water use and nitrogen use efficiency discerned by 13C discrimination and 15N isotope ratio in bread wheat grown under no–till. *Soil. Till. Res*., 128: 110–118

Dawe, D., A. Dobermann, P. Moya, S. Abdulrahmann, B. Singh, P. Lal, S.Y. Lil, B. Lin, G. Panaullah, O. Sarim, Y. Singh, A. Swarup, P.S. Tan and Q. Zhen, 2000. How widespread yields are decline in long–term rice experiments in Asia? *Field Crops Res*., 66: 175–193

Dordas, C.A and C. Sioulas, 2009. Dry matter and nitrogen accumulation, partitioning, and retranslocation in safflower (*Carthamus tinctorius* L.) as affected by nitrogen fertilization. *Field Crops Res*., 110: 35–43

Duxbury, J.M., I.P. Abrol, R.K. Gupta and K.F. Bronson, 2000. Analysis of long–term soil fertility experiments with rice–wheat rotations in south Asia. *In: Long–term soil fertility experiments in rice–wheat cropping systems. Rice-wheat consortium paper series 6. rice–wheat consortium for the Indo–Genetic plains.* pp: VII–XXII. I.P., Abrol, Bronson, K.F., Duxbury, J.M., Gupta, R.K. (eds.). New Delhi, India.

Fallahi, H.A., A. Nasseri and A. Siadat, 2008. Wheat yield components are positively influenced by nitrogen application under moisture deficit environments. *Int. J. Agri. Biol*., 10: 673–676

Gaju, O., V. Allard, P. Martre, J.W. Snape, E. Heumez, J. LeGouis, D. Moreau, M. Bogard, S. Griffiths, S. Orford, S. Hubbart and M. J. Foulkes, 2011. Identification of traits to improve the nitrogen–use efficiency of wheat genotypes. *Field Crops Res.,* 123: 139–152

Garrido-Lestache, E., R.J. Lopez–Bellido and F.J. Lopez–Bellido, 2005. Durum wheat quality under Mediterranean conditions as affected by N rate, timing and splitting, N form and S fertilization. *Eur. J. Agron*., 23: 265–278

Giller, K.E. 2004. Emerging technologies to increase the efficiency of the use of fertilizer nitrogen. *In: Agriculture and nitrogen cycle*. pp: 35–51. A.R. Moiser, J.K. Syers and J.R. Frency (eds.). Island Press Washington DC, USA

Halitligil, M.B., A. Akin, N. Bilgin, Y. Deniz, K. Ogretir, B. Altmel and Y. Isik, 2000. Effect of nitrogen fertilization on yield and nitrogen and water use efficiencies of winter wheat (durum and bread) varieties grown under conditions found in Central Anatolia. *Biol. Fert. Soils,* 31: 175–182

Halvorson, A.D., B.J. Wienhold and A.L. Black, 2002. Tillage, nitrogen, and cropping system effects on soil carbon sequestration. *Soil Sci. Soc. Amer. J*., 66: 906–912

Hussain, M., L.H. Akhtar, M. Rafiq, M.A. Aslam, A.H. Tariq, M. Aslam, M. Arshad and S. Ahmad, 2010. Mairaj–08: new wheat (*Triticum aestivum*) variety released for general cultivation under normal and late planting in Punjab Province (Pakistan). *Int. J. Agric. Biol*., 12: 341–347

IPCC, 2001. Climate change 2001: impacts, adaptation and vulnerability. *Inter–governmental panel on climate change.report of the working group II.* pp: 967. Cambridge, UK

Jamieson, P.D and M.A. Semenov, 2000. Modelling nitrogen uptake and redistribution in wheat. *Field Crop. Res*., 68: 21–29

Janssen, B.H., F.C.T. Guiking, D. van der, E.M.A. EijkSmaling, J. Wolf and H. van Reuler, 1990. A system for quantitative evaluation of the fertility of tropical soils (QUEFTS). *Geoderma,* 46: 299–318

Jun-Hua, Z., L. Jian–Li, Z. Jia–Bao, Z. Fu–Tao, C. Ya–Nan and W. Wei–Peng, 2010. Effects of nitrogen application rates on translocation of dry matter and nitrogen utilization in rice and wheat. *Acta Agron. Sin*., 36: 1736–1742

Khayatnezhad, M. and R. Gholamin, 2012. Effect of nitrogen fertilizer levels on different planting remobilization of dry matter of durum wheat varieties Seimareh. *Afr. J. Microbiol. Res*., 6: 1534–1539

Kichey, T., B. Hirel, E. Heumez, F. Dubois and J. Le Gouis, 2007. In winter wheat (*Triticum aestivum* L.), post–anthesis nitrogen uptake and remobilization to the grain correlate with agronomic traits and nitrogen physiological markers. *Field Crop Res*.102: 22–32

Kumari, K., M. Sharma, R.K. Sharma and S.S. Balloli, 2000. Effect of late application of nitrogen on yield and protein content of wheat. *Ann. Agric. Res*., 21: 288–291

Ladha, J.K., J.E. Hill, J.M Duxbury, R.K. Gupta, L.W. Harrington, 2003. Improving the Productivity and Substantiality of Rice–Wheat Systems: Issues and Impacts. ASA Special Publication No. 65. *Amer. Soc. Agron*., p: 231

Lopez-Bellido, L., R.J. Lopez–Bellido and R. Redondo, 2005. Nitrogen efficiency in wheat under rain-fed Mediterranean conditions as affected by split nitrogen application. *Field Crops Res*., 94: 86–97

Marino, S., R. Tognetti and A. Alvino, 2011.Effects of varying nitrogen fertilization on crop yield and grain quality of emmer grown in a typical Mediterranean environment in central Italy. *Europ. J. Agron*., 34: 172–180

Martre, P., P.D. Jamieson, M.A. Semenov, R.F. Zyskowski, J.R. Porter and E. Triboi, 2006. Modelling protein content and composition in relation to crop nitrogen dynamics for wheat. *Europ. J. Agron.,* 25: 138–154

Meinke, K., 1996. Topological methods for algebraic specification. *Theor. Compt. Sci*., 166: 263–290

Melaj, M.A., H.N. Echeverria, S.C. Lopez, G. Studdert, F. Andrade and N.O. Barbaro, 2003. Timing of nitrogen fertilization in wheat under conventional and no–tillage system. *Agron. J*., 95: 1525–1531

Michael, J., T. Ottman, A. Doerge, C. Edward and E. Martin, 2000. Durum grain quality as affected by N–fertilizer near anthesis and irrigation during grain fills. *Agron. J*., 92: 1035–1041

Monjardino, M., T.M. McBeath, L. Brennan and R.S. Llewellyn, 2013. Are farmers in low–rainfall cropping regions under–fertilising with nitrogen?A risk analysis. *Agric. Sys.,* 116: 37–51

Nakano, H. and S. Morita, 2009. Effects of seeding rate and nitrogen application rate on grain yield and protein content of the bread wheat cultivar 'Minamino kaori' in Southwestern Japan. *Plant Prod. Sci*., 12: 109–115

Pan, J., Y. Zhu, D. Jiang, T. Dai, Y. Li and W. Cao. 2006. Modeling plant nitrogen uptake and grain nitrogen accumulation in wheat. *Field Crops Res*., 97: 322–336

Paroda, R.S and P. Kumar, 2000. Food production and demand in South Asia. *Agric. Econ. Res. Rev*. 13: 1–24

Parry, M., C. Rosenzweig and M. Livermore, 2005. Climate change, global food supply and risk of hunger. *Philos. Trans. Royal Soc. B. Biol. Sci*, 360: 2125–2138

Pathak, H., P.K. Aggarwal, R. Roetter, N. Kalra, S.K. Bandyopadhaya, S. Prasad and H. Van Keulen, 2003. Modeling the quantitative evaluation of soil nutrient supply, nutrient use efficiency, and fertilizer requirements of wheat in India. *Nutr. Cycl. Agroecosyst*., 65: 105–113

Rahimizadeh, M., A. Kashani, A.Z. Feizabadi, A.R. kooocheki and M.N. Mahallati, 2010. Nitrogen use efficiency of wheat as affected by preceding crop, application rate of nitrogen and crop residues. *Aus. J. Crop Sci*., 4: 363–368

Raun, W.R. and G.V. Johnson, 1999. Improving nitrogen use efficiency for cereal production. *Agron. J*., 91: 357–363

Rosenberg, N.J., 2010. Climate change, agriculture, water resources: what do we tell those that need to know? *Clim. Change*, 100: 113–117

Saeed, B., A.Z. Khan, S.K. Khalil, H.U. Rahman, F. Ullah, H. Gul and H. Akbar, 2013. Response of soil and foliar applied nitrogen and sulfur towards yield and yield attributes of wheat cultivars. *Pak. J. Bot*., 45: 435–442

Smil, V., 2005. Do we need higher farm yields during the first half of the 21st century? *In: Yields of farmed species*. pp. 1–14. R. Sylvester–Bradley, J. Wiseman (Eds.). Nottingham University Press, Nottingham, UK

Tadayon, M.R., 2007. Effects of supplemental irrigation and N fertilization increase of two wheat cultivars under dryland conditions. *Ph.D. Thesis*. Shiraz University, Shiraz, Iran

Thomas, G.A., R.C. Dalal, E.J. Weston, C.J. Holmes, A.J. King, D.N. Orange and K.J. Lehane, 2007. Zero tillage and nitrogen fertilizer application in wheat and barley on a vertosol in a marginal cropping area of south–west Queensland. *Aus. J. Exp. Agric*., 47: 965–975

Timsina, J., U. Singh, M. Badaruddin, C. Meisner and M.R. Amin, 2001. Cultivar, nitrogen, and water effects on productivity and nitrogen–use efficiency and balance for rice–wheat sequences of Bangladesh. *Field Crops Res*., 72: 143–161

Wang, S., J. Xing, C. Jang, Y. Zhu, J.S. Fu and J. Hao, 2011. Impact assessment of ammonia emissions on inorganic aerosols in east china using response surface modeling technique. *Environ. Sci. Technol.,* 45: 9293–9300

White, E.M. and F.E.A. Wilson, 2006. Responses of grain yield, biomass and harvest index and their rates of genetic progress to nitrogen availability in ten winter wheat varieties. *Irish J. Agric. Food Res*., 45: 85–101

Witt, C., A. Dobermann, S. Abdulrahman, H.C. Gines, W. Guanghuo, R. Nagarajan, S. Satawatananont, T. Thuc Son, P. Sy Tan, L. Van Tiem, G.C. Simbahan and D.C. Olk, 1999. Internal nutrient efficiencies of irrigated lowland rice in tropical and subtropical Asia. *Field Crops Res.,* 63: 113–138

Xiao-li, W., S. Yu–hua, W. Su–hua, D. Yan and F. Ke, 2011. Physiological Responses of Two Wheat Cultivars to Nitrogen Starvation. *Agric. Sci. China*., 10: 1577–1585

Yadav, R.L., B.S. Dwivedi, K. Prasad, O.K. Tomar, N.J. Shurpali and P.S. Pandey, 2000. Yield trends, and changes in soil organic–C and available NPK in a long–term rice–wheat system under integrated use of manures and fertilizers. *Field Crops Res*., 68: 219–246

Zadok, J. C., T.T. Chang and B.F. Konzak, 1974. A decimal code for growth stages of cereals. *Weed Res*., 14: 415–421

Zende, N.B., H.N. Sethi, A.P. Karunakar and D.J. Jiotode, 2005. Effect of sowing time and fertility levels on yield and quality of durum wheat genotypes. *Res. Crops*, 6: 194–196

Zhang, X., S. Chen, H. Sun, D. Pei and Y. Wang, 2008. Dry matter, harvest index, grain yield and water use efficiency as affected by water supply in winter wheat. *Irrig. Sci*., 27: 1–10

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