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Customization of DNDC Model: Simulation of Yield and Nitrogen Balance in Rice (*Oryza sativa* L.) in Relation to Climate Change, Soil and Management Interventions

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A field study was conducted at two different locations at research farms of Department of Soil Science, Punjab Agricultural University, Ludhiana, Punjab, on sandy loam soils during *kharif* 2015 and 2016 to evaluate the DNDC (Denitrification-Decomposition) model. Simulation were made to assess the impact of climate change scenario, soil and management interventions on past (1986-2016) and future (2020-2050) yield, nitrogen (N) balance and use efficiency of rice, and to made projections for future yield, N balance and use efficiency of rice for different texture soils and different locations of central Punjab. Results indicate that simulated rice grain yield, N uptake, volatilization and leaching increases but agronomic and recovery efficiency decreases at higher N levels. Simulated rice grain yield, N uptake, volatilization, agronomic and recovery efficiency would decrease in future time slices but leaching would increase. Per cent reduction in yield would be more in end part of mid century, lower at higher N levels (150-180 kg N ha^{-1}) and in fine textured soils (silt loam). During time slice-4 (TS-4) (2040-2050) highest reduction in yield is expected at Patiala (54.7%) followed by Ludhiana (50.7%) then Amritsar (43.5%) but under higher N treatments (150 and 180 kg ha^{-1}) yield reduction trend would be in the order of Ludhiana> Patiala> Amritsar. Trend for per cent increase in leaching during TS-4 would be Patiala> Amritsar> Ludhiana but volatilization would be Ludhiana> Patiala> Amritsar. The study suggests that higher N levels could be good option to compensate yield reduction in future however higher N levels would lead to higher N leaching and volatilization.

Key words: DNDC (Denitrification-Decomposition) model, N uptake, volatilization, leaching, agronomic efficiency, recovery efficiency

Rice-wheat is a dominant cropping system in Indo-Gangetic plains of India. The average yield of rice is 5.5 t ha^{-1}, which is lower than the potential yield (6.0-8.4 t ha^{-1}) and is influenced by climatic factors (including rainfall, solar radiation and temperature) and management interventions like irrigation regime, cultivar and applied fertilizers. The yields of rice and wheat are likely to reduce in future due to climate change in future (Jalota *et al.* 2013, 2014). At present, nitrogen (N) fertilizer is applied in excess in the quest for higher yields ignoring economic water and N productivities and environmental pollution (by runoff, leaching and ammonia volatilization). Excess of N applied to the rice crop not only enhances losses through various mechanisms, but results in imbalance of several ecosystem function and services (Zhang *et al.* 2012; Meena *et al.* 2014) and is of increasing concern worldwide as it induces a greenhouse effect, acid rain, nitrate pollution in groundwater, and eutrophication of surface water (Galloway *et al.* 2004; Yan *et al.* 2011). In the climate change scenarios change in temperature, precipitation and CO_2 concentration in the atmosphere may change the soil N dynamics and amount of fertilizer in the rice (Jeppesen *et al.* 2011; Patil *et al.* 2012). It is expected that N leaching can increase with rise in precipitation events (Patil *et al.* 2012; Olesen 2014). Gaseous loss and uptake can decrease, but leaching can increase with increase in temperature (Jalota *et al.* 2013).

To mitigate yield loss and manage N efficiently at present and in future, it is of prime importance to quantify the N balance components and identify the magnitude of the component not contributing to yield. Nitrogen balance have been quantified by simulation models like Crop Syst model by Jalota *et al.* (2013, 2014); DNDC (Denitrification-Decomposition) by Pathak *et al.* (2006) and Katayangi *et al.* (2013);

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Table 1. Physicochemical properties of soil at two locations

Depth (cm)	pH	EC (dS m^{-1})	OC (%)	NH$_4^+$-N (ppm)	NO$_3^-$-N (ppm)	P (kg ha^{-1})	K (kg ha^{-1})	Bulk density (Mg m^{-3})	Hydraulic conductivity (m h^{-1})	Sand	Silt (%)	Clay	Texture
Location 1 (30º93' N, 75º75' E)													
0-15	7.3	0.330	0.49	11.4	23.1	46.0	98.2	1.39	1.26	78.4	12.9	8.7	Sandy loam
15-30	7.4	0.087	0.16	11.2	21.1	33.3	74.4	1.48	1.30	77.3	12.4	10.3	Sandy loam
30-60	6.9	0.214	0.17	6.1	19.3	30.2	86.4	1.45	1.64	74.9	14.0	11.1	Sandy loam
60-90	7.5	0.174	0.14	7.3	14.6	18.2	60.0	1.49	1.78	74.1	15.3	11.6	Sandy loam
90-120	7.7	0.212	0.11	6.9	10.8	10.4	70.4	1.60	1.86	70.2	15.2	14.6	Sandy loam
120-150	8.00	0.130	0.09	4.0	7.6	8.8	44.6	1.50	1.66	68.8	16.2	16.0	Sandy loam
150-180	8.03	0.168	0.08	8.3	13.0	6.4	33.4	1.63	1.42	66.6	16.2	18.2	Sandy loam
Location 2 (30º58' N, 75º50' E)													
0-15	6.8	0.222	0.26	12.84	25.67	34.0	102.6	1.32	1.12	85.8	8.9	6.3	Sandy loam
15-30	6.79	0.102	0.17	12.84	16.34	30.3	82.4	1.68	1.06	82.5	10.4	8.1	Sandy loam
30-60	7.10	0.144	0.08	14.00	16.34	25.4	79.4	1.51	1.73	79.6	12.0	8.4	Sandy loam
60-90	7.05	0.166	0.08	11.67	14.00	18.8	74.0	1.42	1.78	77.5	12.9	9.6	Sandy loam
90-120	7.60	0.190	0.06	8.17	12.84	16.9	52.2	1.32	1.30	75.4	13.1	11.5	Sandy loam
120-150	7.84	0.142	0.03	9.34	12.84	12.8	55.6	1.43	1.42	73.7	13.0	13.3	Sandy loam
150-180	7.92	0.108	0.04	7.00	10.50	8.4	57.4	1.59	1.08	71.4	14.1	14.5	Sandy loam

Hydrus-1D model by Li *et al.* (2015) and under field conditions (Bijay-Singh *et al.* 2001; Shi *et al.* 2012). Under field conditions, the estimation of N balance components is difficult. Alternatively, simulation technique with a suitable crop models for N balance is a powerful tool. For this purpose, DNDC model is one of the models available in the literature and selected for its ability to capture the major effects of N on rice (Pathak *et al.* 2006). No doubt, lot of information on N management and dynamics is available for the present time (Li *et al.* 1994a, 1994b; Pathak *et al.* 2006; Katayangi *et al.* 2013), but little is known for future in the changing climate change scenario in relation to soil, climatic and management conditions. Keeping this in view, field and simulation studies were undertaken to understand the effects of N levels and climate change scenario on rice grain yield and N balance components.

Materials and Methods

Site and climate data

The study area is characterized by sub-tropical and semi-arid type of climate with hot and dry summer from April to June followed by hot and humid period during July to September and cold winters from November to January. Past 30 years (1985–2016) weather data on maximum temperature (Tmax), minimum temperature (Tmin) and rainfall (RF) recorded at meteorological observatories of Amritsar (31°31′56″N, 74°52′25″ E), Ludhiana (30°75′48″ N, 75°48′30″ E) and Patiala (30°19′38″ N, 76°24′00″ E) was collected from School of Climate Change and Agro-meteorology, PAU, Ludhiana. The base weather of Tmax, Tmin and rainfall at Amritsar, Ludhiana and Patiala is 30.3 °C, 15.4 °C and 720 mm; 29.8 °C, 16.6 °C and 745 mm; and 30.2 °C, 17.4 °C and 774 mm, respectively. The future data (2021-2050) of Tmax, Tmin and RF for Amritsar, Ludhiana and Patiala under A1B scenario was derived from regional climate model PRECIS and bias was minimized (Jalota *et al.* 2014). The data was analyzed for present time slice from 1986 to 2016 (TS-1) and mid century for time slices of 2021-2030 (TS-2), 2031-2040 (TS-3) and 2041-2050 (TS-4).

Field experimentation

The field experiments were conducted during *kharif* seasons of 2015 and 2016 on sandy loam (Typic Ustochrept) soils at two different locations at research farm of Department of Soil Science, Punjab Agricultural University, Ludhiana (247 m above mean sea level). The physicochemical properties of the two locations are presented in table 1. At location 1, thirty-days-old seedlings of variety PR 124 were transplanted on June 27, 2015 and June 25, 2016 in plot size of 17×6 m^2 while at location 2 on June 29, 2015 and July 8, 2016 in plot size of 14×4.3 m^2 after the wheat crop. Treatment includes two irrigation regimes (based on two days drainage period *i.e.* alternate wetting and drying (I_1) and irrigation based on soil water suction of 16 kPa (I_2)), and four levels of N (0, 60, 120 and 180 kg N ha^{-1}). The amount of irrigation water applied from transplanting to maturity was about 1400 mm in I_1 and 1200 mm in I_2. These treatments were replicated thrice in split-plot design with irrigation as main and fertilizer level as sub-plots. The biometric observations (periodic plant height, dry matter accumulation, number of tillers m^{-2}), yield attributing characters (thousand grain weight, grain and straw yield, plant N uptake) and soil samples (for N and soil organic C) were taken from both the experiments.

The N use efficiency in terms of recovery efficiency (RE) and agronomic efficiency (AE) were calculated as equation 1 and 2, respectively.

$$\text{RE (\%)} = \frac{\begin{matrix}\text{N uptake in} \\ \text{fertilized treatment}\end{matrix} - \begin{matrix}\text{N uptake in zero} \\ \text{N treatment}\end{matrix}}{\text{Quantity of N applied in N fertilized treatment}} \times 100 \quad \ldots(1)$$

$$\text{AE (kg kg}^{-1}\text{)} = \frac{\begin{matrix}\text{Grain yield in N} \\ \text{fertilized treatment}\end{matrix} - \begin{matrix}\text{Grain yield in zero} \\ \text{N treatment}\end{matrix}}{\text{Quantity of N applied in N fertilized treatment}} \quad \ldots(2)$$

Model simulations

Model description

The model used was Denitrification–Decomposition (DNDC), which is a process-oriented simulation model of soil C and N biogeochemistry. The DNDC consists of 4 interacting submodels: soil climate, crop growth, decomposition, and denitrification (Fig. 1). First, a soil climate sub-model calculates hourly soil moisture and temperature dynamics. Second, crop growth sub-model, calculates water and N uptake by vegetation, root respiration and plant growth, and partitioning of biomass into grain, stalk, and roots. Third, a decomposition sub-model, following the basic structure of NCSOIL (nitrogen and carbon transformations in soil) calculates daily rates of residue-C, humas-C (less active carbon) and microbial biomass decomposition. In addition, this sub-model calculates net N mineralization, nitrification, ammonification, ammonia (NH_3) volatilization, and ammonium (NH_4^+) adsorption. Fourth, a denitrification sub-model, based on the aggregate-level model is activated when a rain event occurs.

Model calibration and validation

The DNDC model was calibrated with the data (baseline data of weather, soil, management, location, and other inputs) obtained from the field experimentations during 2015 and 2016 at Ludhiana. Model parameters were derived through experimental observations, literature and some were kept as default

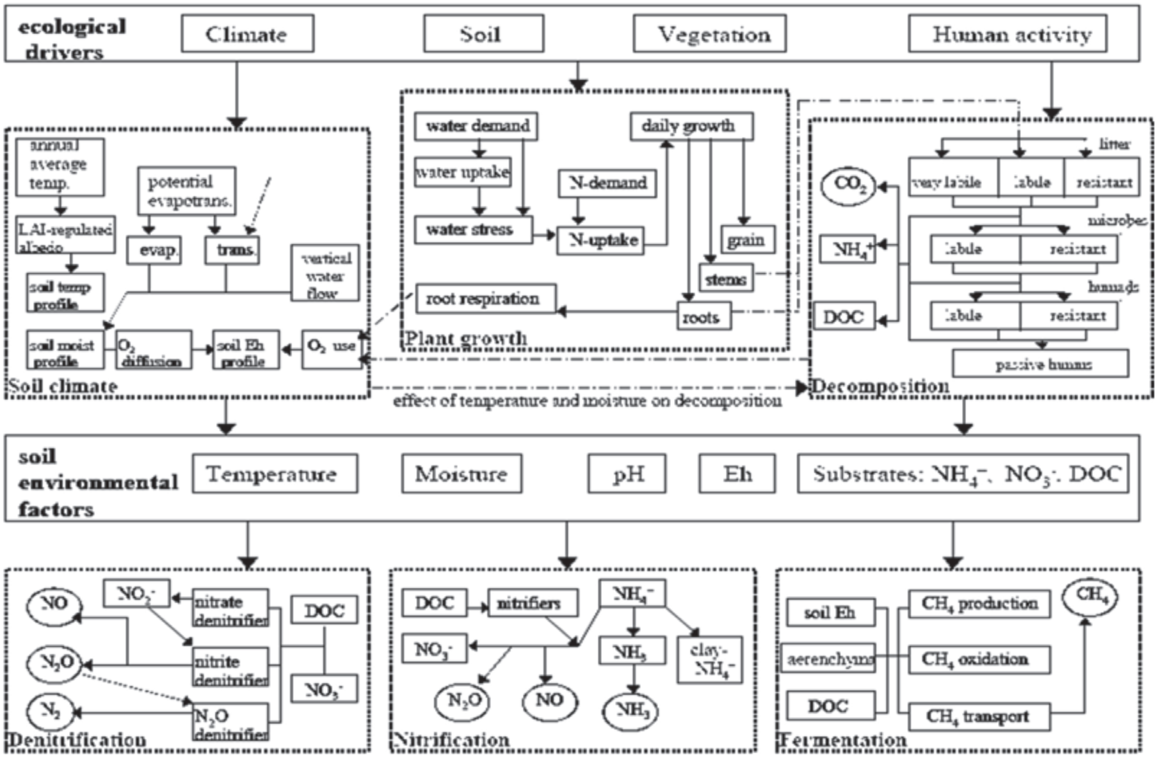

Fig. 1. Schematic flow diagram of DNDC model

Table 2. Input parameters for DNDC model

Input parameter	Value and units	Source
Max potential yield	6000-8400 kg ha^{-1}	Jalota *et al.* (2011)
Climate data (rainfall, max and min temperature)	Daily variations in (mm and ^{0}C)	A1B scenario
Organic carbon	0.025- 0.045 kg C kg^{-1}	Lab experimentation
Amnonical and nitrate N	Variable accordingly	Lab experimentation
Micobial index	1	default
Clay content	0.6-0.18	Lab experimentation
Hydraulic conductivity	0.0112-0.0126 m ha^{-1}	Lab experimentation
Soil pH	1.3-1.7 Mg m^{-3}	Lab experimentation
Bulk density	7.2-7.9	Lab experimentation
Planting and harvesting dates	Variable accordingly	Field experimentation
Biomass fraction (grain, leaf, stem and root)	0.34, 0.18, 0.19 and 0.29	default
C/N ratio (grain, leaf, stem and root)	40, 45, 45 and 45	default
Thermal degree days for maturity	2000	default
Water demand	508	default
N fixation index	0.05	default
Optimum temperature	25	default
Tillage (date and depth)	Variable accordingly	Field experimentation
Fertilization (date, dose and form of application)	Variable accordingly in urea form	Field experimentation
Irrigation (date, depth and method)	Variable accordingly	Field experimentation

(Table 2). The model performance was validated on independent data sets of yield and N uptake from three different locations *i.e.* Ludhiana 30°75′48″N, 75°48′30″E, semi arid), Sri Muktsar Sahib (30°26.749′ N 74°30.638′ E, semi arid) and Gurdaspur (32°02′01.35″ N, 75°24′26.73″ E, hot subhumid (dry)) in different agro-climatic regions of the Punjab state.

Model prediction capability

Prediction capability of the model was tested by the following indicators:

1. Nash–Sutcliffe modeling efficiency, ME (Nash and Sutcliffe 1970)

$$ME = 1 - \frac{\left[\sum_{i=1}^{n}\left(o_i - p_i\right)^2\right]}{\left[\sum_{i=1}^{n}\left(o_i - \bar{O}\right)^2\right]} \qquad \ldots(3)$$

where, o_i is the observed value corresponding to p_i (predicted value), and $\bar{o}$ is the observed mean.

2. Root mean square error (RMSE)

$$RMSE = \left\{\sum_{i=1}^{N}\frac{1}{n}\left(p_i - o_i\right)^2\right\}^{0.5} \qquad \ldots(4)$$

where, n is the number of cases, p_i is the predicted value, and o_i is the corresponding observed value. The RMSE is an index of actual error produced by the model.

3. Index of agreement (d) (Willmott 1981)

$$d = 1 - \frac{\sum_{i=1}^{n}\left(p_i - o_i\right)^2}{\sum_{i=1}^{n}\left(\left|p_i'\right| + \left|o_i'\right|\right)^2} \qquad \ldots(5)$$

where, $o'_i = o_i - o$ and $p'_i = p_i - p$.

p and o are the predicted and observed means, respectively.

Nash–Sutcliffe modeling efficiencies can range from $-\infty$ to 1. The simulation results are considered to be good if $ME \geq 0.75$ and satisfactory if $0.36 \leq ME \leq 0.75$ (Popov 1979). An efficiency of 1 (ME = 1) corresponds to a perfect match between modeled values and observed data. An efficiency of 0 (ME = 0) indicates that the model predictions are as accurate as the mean of the observed data, whereas an efficiency less than zero ($-\infty < ME < 0$) occurs when the observed mean is a better predictor than the model. The index of agreement (d) is a measure of the degree to which the predicted variation precisely estimates the observed variation where d = 1 corresponds to perfect agreement.

Simulation of soil texture effect

After calibration and validation, DNDC model was run for past (1986-2016) and future (2021-2050) time scenario for yield and N balance components for dominant soil textures of Punjab. Physicochemical characteristics of dominant soil textures are presented in table 3.

Table 3. Physical and chemical characteristics of dominant soil series in Ludhiana district of Central Punjab

Soil depth (cm)	Sand (%)	Silt (%)	Clay (%)	CEC [cmol(p^+)kg^{-1}]	pH	OC (%)	NO^-_3–N (kg ha^{-1})	NH_4^+–N (kg ha^{-1})
Loamy sand								
0-17	90.9	4.0	5.6	3.4	8.3	0.09	9.2	7.8
17-35	83.2	8.8	8.1	5.0	8.4	0.26	10.6	11.5
35-50	69.7	17.3	13.0	6.7	8.4	0.21	7.1	7.0
50-81	63.6	23.1	13.3	8.6	8.4	0.24	14.4	13.4
81-116	57.0	26.4	16.7	9.8	8.5	0.20	12.7	12.2
116-138	47.1	29.9	23.6	13.2	8.6	0.16	6.7	5.4
138-160	82.6	8.6	9.4	5.8	8.6	0.06	7.4	5.9
160-180	82.6	8.6	9.4	5.8	8.6	0.06	7.4	5.9
Sandy loam								
0-17	76.2	13.9	9.9	7.0	8.4	0.49	21.1	11.4
17-39	71.6	16.4	12.1	7.4	8.2	0.16	21.1	11.2
39-55	67.6	18.0	14.0	8.0	8.3	0.17	19.3	6.1
55-70	65.2	20.0	14.6	8.4	8.2	0.14	14.6	7.3
70-88	71.3	15.1	13.6	7.0	8.3	0.11	10.8	6.9
88-104	72.0	13.5	14.6	9.4	8.2	0.09	7.6	4.0
104-150	72.1	13.5	14.5	9.2	8.1	0.08	13.0	8.3
150-180	72.1	13.5	14.5	9.2	8.1	0.08	13.0	8.3
Loam								
0-13	54.5	28.6	17.0	11.7	8.5	0.53	19.8	15.7
13-32	39.7	41.5	18.9	15.2	8.7	0.23	13.0	12.2
32-60	28.2	48.9	22.9	16.4	8.6	0.19	23.1	19.9
60-87	28.2	47.6	24.3	17.2	8.6	0.17	10.3	7.9
87-109	25.2	53.6	21.3	17.0	8.6	0.14	12.2	8.2
109-130	33.2	40.8	26.1	17.2	8.6	0.10	10.1	6.9
130-160	33.1	40.6	26.3	17.3	8.6	0.09	9.2	7.4
160-180	33.1	40.6	26.3	17.3	8.6	0.09	9.2	7.4
Silt loam								
0-26	25.0	56.8	18.2	11.0	8.3	0.76	45.2	31.4
26-44	16.6	64.4	19.0	11.7	8.5	0.19	13.1	8.4
44-63	73.5	20.1	6.4	4.1	8.6	0.09	5.9	7.1
63-77	28.5	62.5	9.0	5.9	8.5	0.09	4.1	3.3
77-87	82.0	11.2	6.8	4.5	8.6	0.06	3.3	1.3
87-150	94.8	0.8	4.4	2.9	8.7	0.03	10.7	8.6
150-180	94.8	0.8	4.4	2.9	8.7	0.03	10.7	8.6

Simulation of climatic change in different agro climatic zones

The effect of climate change at Amritsar, Ludhiana and Patiala representing the semi–humid, semi–tropical and semi–arid zones was simulated using climate and soil data generated by Jalota *et al.* (2014).

Results and Discussion

Climate change

From 1985 to 2050 the annual change in T_{max}, T_{min} and RF showed increasing trends at all the stations. T_{max}, T_{min} increased at rate of 0.084 and 0.105 °C yr^{-1} at Amritsar; 0.081 and 0.084 °C yr^{-1} at Ludhiana, and 0.075 and 0.079 °C yr^{-1} at Patiala, respectively. The corresponding increase in rainfall was 4.1, 5.9 and 8.7 mm yr^{-1}. It shows that rate of increase of T_{max} and T_{min} was more at Amritsar than Ludhiana than Patiala while that rainfall was more at Patiala than Ludhiana than Amritsar. In actual increase varied in different time slices of mid century compared to present time slice (PTS). Annual averaged T_{max} in TS-1 is 30.3 °C at Amritsar, 33.4 °C at Ludhiana and 30.3 °C at Patiala, which would increase by 1.8, 1.7 and 1.4 °C in TS-2, 2.0, 2.0 and 1.6 °C in TS-3; and 3.7, 3.7 and 3.3 °C in TS-4, respectively. T_{min} in TS-1 is 15.2 °C at Amritsar, 19.1 °C at Ludhiana and 17.5 °C at Patiala, which would increase by 2.9, 2.9 and 2.2 °C in TS-2, 3.2, 3.5 and 2.5 °C in TS-3; and 4.2, 4.4 and 3.4°C in TS-4, respectively (Fig. 2). Temperature change indicates

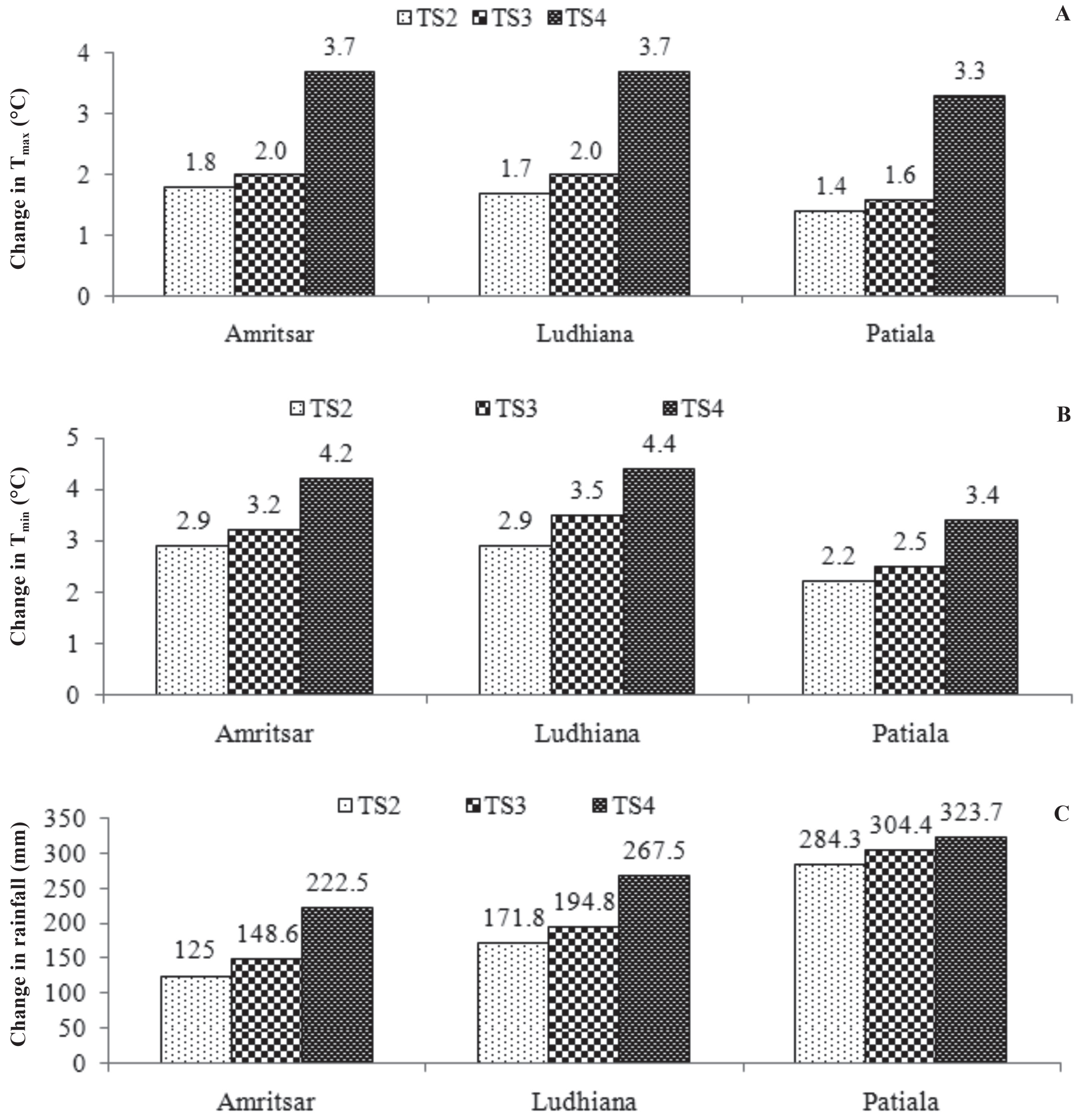

Fig. 2. Change in maximum temperature (A), minimum temperature (B) and rainfall (C) in different slices of mid-century compared to present time slice (1985-2016) (TS-1 – 1986-2016; TS-2 – 2021-2030; TS-3 – 2031-2040)

that increase in T_{max} and T_{min} is less in Patiala than Amritsar and Ludhiana. Rainfall (RF) in TS-1 is 713.7 mm at Amritsar,782.6 mm at Ludhiana and 783.7 at Patiala, which would increase 125.1, 171.8 and 284.3 mm in TS-2, 148.6, 194.8 and 304.4 mm in TS-3; and 222.5, 267.5 and 323.7 in TS-4, respectively compared to PTS (Fig. 2).

Model calibration and validation

The simulated data on yield and N uptake matched closely to the observed data (Fig. 3). Values of RMSE, ME, d and coefficient of determination (R^2) were 4.25, 0.84, 0.96 and 0.61 for grain yield and 8.04, 0.89, 0.95 and 0.84 for total N uptake during calibration (2015-16) in different agro-climatic regions of the Punjab state on independent data sets of yield and N uptake computed as prediction capability indices (given in Table 4) indicates that model can successfully simulate yield and N uptake in rice.

Simulated rice yield

Averaged simulated rice yield in TS-1 under different N treatments 0, 60, 120 and 180 kg ha^{-1} was

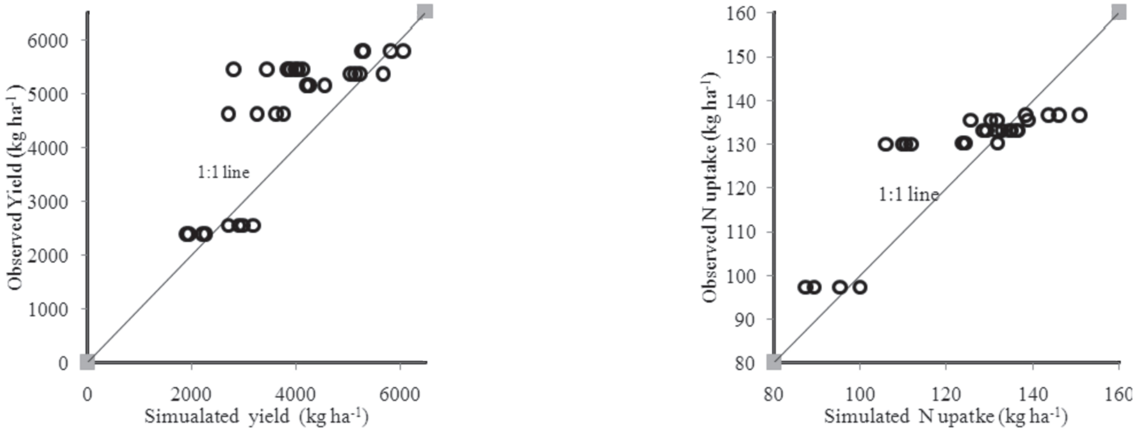

Fig. 3. Observed and simulated yield and N uptake in rice

Table 4. Customization of DNDC model

Statistical indicator	Calibration (experimental sites data)		Validation (mean of different location)	
	Yield	N uptake	Yield	N uptake
Root mean square error (*RMSE*)	4.25	8.04	7.71	8.56
Nash-Sutcliffe modeling efficiency (*ME*)	0.84	0.89	0.83	0.95
Index of agreement (*d*)	0.96	0.95	0.95	0.94
Coefficient of determination (R^2)	0.90	0.89	0.81	0.95

Table 5. Simulated and observed rice grain yield and N uptake under different nitrogen levels (mean values at both locations)

N levels (kg N ha^{-1})	Observed yield (t ha^{-1})			Predicted yield (t ha^{-1})	Observed N uptake (kg N ha^{-1})	Predicted N uptake (kg N ha^{-1})
	2015	2016	Mean			
0	2.70	3.00	2.85	2.47	74.8	65.7
60	4.20	4.22	4.21	4.60	110.8	123.0
120	5.07	5.67	5.37	5.61	129.1	133.4
180	5.28	5.83	5.56	5.77	148.6	136.5

2.47, 4.61, 5.62 and 5.78 t ha^{-1}, respectively. These results are closer to the observed yield in research trials (Table 5).

Averaged simulated rice yield in TS-1 under different N treatments 0, 100, 120, 150 and 180 kg N ha^{-1} were 2.17, 5.31, 5.62, 5.63 and 5.78 t ha^{-1}, respectively (Table 6). With changed climate in future, the rice yield would decline, but rate of reduction in yield would variable under different levels of N and time slice. For example, yield decline during TS-2, TS-3 and TS-4 were 37, 43 and 51 per cent at 120 kg N ha^{-1}, which gets lowered by 36, 44 and 60 per cent with 100 kg N ha^{-1}; 26, 34 and 49 per cent with 180 kg N ha^{-1}. Thus, application of higher rates of N in future can be of help to compensate yield loss in future. Raj *et al.* (2016) also reported application of 125% N can prevent the yield loss by 6 per cent as compared to 100% recommended N treatment.

Table 6. Simulated grain yield under different nitrogen levels and time slices of Ludhiana

N levels	Time slice			
	TS-1	TS-2	TS-3	TS-4
	Rice yield (t ha^{-1})			
0	2.47	1.39 (44)	1.24 (50)	1.20 (51)
100	5.31	3.41 (36)	2.98 (44)	2.11 (60)
120	5.62	3.52 (37)	3.21 (43)	2.77 (51)
150	5.63	3.80 (32)	3.59 (36)	3.04 (46)
180	5.78	4.30 (26)	3.82 (34)	3.46 (40)

Value in parenthesis is per cent reduction in yield; TS 1 – 1986-2016; TS-2 – 2021-2030; TS-3 – 2031-2040; TS-4 – 2041-2050

Simulated N balance components, agronomic and recovery efficiency

Averaged simulated N balance components under different N treatments are given in table 7. Plant uptake at 0, 100, 120, 150 and 180 kg N ha^{-1} was 65.7, 130.1, 133.4, 135.6 and 136.5 kg N ha^{-1}, respectively during 1986-2016 (TS-1). With changed

Table 7. Simulated nitrogen balance components at experimental sites (Ludhiana) under different nitrogen levels and time scenario

Component	N levels (kg N ha^{-1})	Plant uptake (kg N ha^{-1})	Leaching (kg N ha^{-1})	Volatilization (kg N ha^{-1})	Nitrogen use efficiency	
					Agronomic (kg kg^{-1})	Recovery (%)
TS-1	0	65.7	10.9	8	-	-
(1986-2016)	100	130.1	14.5	28	28.3 (0)	64.4 (0)
	120	133.4	15.5	32.7	26.3 (7)	50.4 (22)
	150	135.6	19.8	47.1	21.0 (26)	46.6 (28)
	180	136.5	20.2	53.6	18.4 (35)	39.3 (39)
TS-2	0	63.1 (-4)	11.2 (+3)	7.0 (-13)	-	-
(2021-2030)	100	105.0 (-19)	15.2 (+5)	28.0 (-0)	20.1 (29)	41.9 (35)
	120	107.7 (-19)	16.1 (+4)	31.7 (-3)	17.8 (37)	37.1 (42)
	150	120.3 (-11)	20.8 (+5)	46.2 (-2)	16.9 (40)	38.1 (41)
	180	125.3 (-8)	22.9 (+13)	49.5 (-8)	16.1 (43)	34.5 (46)
TS-3	0	61.4 (-5.6)	12.5 (+15)	6.5 (-19)	-	-
(2031-2040)	100	102.5 (-21)	16.9 (+17)	27.5 (-2)	17.4 (39)	41.1 (36)
	120	108.3 (-19)	18.2 (+17)	31.1 (-5)	16.5 (-42)	39.1 (39)
	150	114.1 (-16)	23.4 (+18)	44.3 (-6)	15.7 (45)	33.1 (49)
	180	123.4 (-10)	25.8 (+28)	46.8 (-13)	14.3 (50)	34.4 (46)
TS-4	0	59.2 (-10)	13.8 (+27)	5.0 (-38)	-	-
(2041-2050)	100	99.2 (-24)	19.1 (+32)	28.9 (+3)	9.1 (68)	40.0 (38)
	120	100.1 (-25)	20.0 (+29)	32.2 (-2)	13.1 (54)	34.1 (47)
	150	108.9 (-20)	23.1 (+17)	43.7 (-7)	12.0 (58)	33.2 (48)
	180	112.4 (-18)	29.6 (+47)	46.7 (-13)	13.6 (52)	29.6 (54)

Value in parenthesis is per cent reduction (+) and increase (-)

climate in future, the plant uptake during TS-2, TS-3 and TS-4 would be reduced by 19, 19 and 25 per cent at 120 kg N ha^{-1}; 8, 10 and 18 per cent at 180 kg N ha^{-1}, respectively. Leaching during TS-1 is 10.9, 14.5, 15.5, 19.8 and 20.2 kg N ha^{-1} with N levels of 0, 100, 120, 150 and 180 kg N ha^{-1}, respectively. It would increase in future because of more rainfall and less uptake. During TS-4, leaching N levels of 0, 100, 120, 150 and 180 kg N ha^{-1} would be increased by 27, 32, 29, 17 and 47 per cent, respectively. Volatilization is 8, 28, 32.7, 47.1 and 53.6 kg N ha^{-1} at 0, 100, 120, 150 and 180 kg N ha^{-1} levels, respectively in TS-1, which would reduce by 38, -3, 2, 7 and 13 per cent, respectively during TS-4, might be due to less availability of N to be volatilizable in the total N pool. Thus, application of higher rates of N can be used to compensate decrease in uptake in future but higher leaching and volatilization would also occur.

Simulated N use efficiency in terms of agronomic and recovery efficiency of model for TS-1 under different N levels is close to the field investigations and decreases with rise in N levels (Jalota *et al.* 2011; Ahmed *et al.* 2017), agronomic efficiency of 28.3 kg kg^{-1} at 100 kg N ha^{-1} treatment was reduced by 35 per cent at 180 kg N ha^{-1} during TS-1. At each N level agronomic efficiency decreased from TS-1 to TS-4, and the decrease was more at higher N level. Similar results were obtained for recovery efficiency which varies from 64.4 to 39.0 per cent in TS-1 and would reduce in future. However, rate of reduction would be higher at higher levels of N.

Up-scaling of the model

Calibrated and validated DNDC model was up-scaled for whole Ludhiana district, where yield and N balance components were simulated for different textured soil such as loamy sand, sandy loam, loam and silt loam. Future up-scaling was done for Amritsar and Patiala, two districts of central Punjab. The dominant soil profiles of these districts were studied for yield and N balance.

Simulated rice yield and nitrogen balance components in soils of different textures

Rice yield and N balance components varied under different textured soils and time slices (Table 8). In TS-1, rice yield increases with fineness of texture and N level. The yield was highest in silt loam soil in all levels of N treatment. There would be continuous decrease in yield during future time slices for all texture soils. Per cent reduction in yield would

Table 8. Yield and nitrogen balance under different textured soils of Ludhiana district and per cent change in different time slices

Nitrogen	TS-1 (1986-2016)				TS-2 (2021-2030)				TS-3 (2031-2040)				TS-4 (2041-2050)			
(kg N ha^{-1})	ls	sl	L	sil	ls	sl	l	sil	ls	sl	l	sil	ls	sl	l	sil
	Yield (t ha^{-1})				Per cent change in yield											
120	4.87	5.62	5.43	5.94	50.5	37.3	41.9	35.3	47.3	42.8	49.8	40.5	56.6	48.9	67.1	47.9
150	5.31	5.63	5.68	5.95	52.2	32.5	34.6	30.7	46.8	36.2	42.1	34.2	43.4	46.5	49.7	43.5
180	5.58	5.78	5.71	6.11	41.8	25.6	33.0	24.3	45.2	33.9	40.5	32.1	46.4	39.3	42.9	38.0
	Plant uptake (kg N ha^{-1})				Per cent change in plant N uptake											
120	127.3	133.4	130.2	150.7	25.1	19.3	16.4	17.1	18.0	18.8	15.1	16.7	23.6	23.1	35.7	22.1
150	132.3	135.6	135.2	152.9	26.4	11.3	17.0	10.0	18.7	15.9	15.8	14.1	21.9	19.5	28.3	17.5
180	133.3	136.5	137.4	153.8	20.2	8.2	17.2	7.3	17.1	9.6	16.0	8.5	17.7	18.2	28.9	15.7
	Leaching (kg N ha^{-1})				Per cent change in N leaching											
120	64.5	15.5	10.9	13.2	-12.2	-3.9	-97.2	-80.3	-14.0	-17.4	-102.8	-84.8	-16.3	-83.5	-80.3	-97.7
150	68.8	19.8	11.8	14.1	-12.4	-5.1	-100.8	-84.4	-16.4	-18.2	-90.7	-75.9	-22.4	-95.8	-70.9	-87.2
180	69.3	20.2	13.8	16.1	-16.2	-13.4	-91.3	-78.3	-24.8	-27.7	-68.8	-59.0	-28.7	-114.5	-55.3	-69.6
	Volatilization (kg N ha^{-1})				Per cent change in volatilization											
120	42.3	32.7	15.9	30.7	2.4	3.1	10.1	3.3	3.8	4.9	23.3	5.2	1.2	-102.5	63.8	1.6
150	56.7	47.1	24.3	45.1	1.6	1.9	9.1	2.0	4.9	5.9	19.8	6.2	6.0	-79.8	59.4	7.5
180	63.2	53.6	28.5	51.6	6.5	7.6	11.2	7.9	10.8	12.7	22.8	13.2	10.9	-63.9	60.9	13.4
	Agronomic efficiency (kg kg^{-1})				Per cent change in agronomic efficiency											
120	24.8	26.2	25.1	27.0	6.5	17.8	10.9	18.6	9.1	16.5	10.5	17.3	7.4	13.1	5.9	13.9
150	22.8	21.0	21.8	21.7	6.0	16.0	12.5	16.7	8.9	15.7	12.2	16.4	11.9	12.3	11.6	12.9
180	20.5	18.4	18.3	18.9	9.0	16.1	11.0	16.7	8.7	14.3	10.7	14.9	9.8	12.6	12.4	13.1
	Recovery efficiency (%)				Per cent change in recovery efficiency											
120	53.3	54.6	33.1	58.3	28.4	37.1	22.0	38.8	38.5	39.1	25.7	40.8	33.5	34.1	13.4	35.7
150	46.0	46.6	29.8	48.1	24.1	38.1	19.8	39.4	32.9	35.1	22.8	36.4	30.9	33.2	19.2	34.5
180	38.9	39.3	26.1	40.6	25.1	34.5	17.4	35.6	29.1	34.4	19.8	35.6	29.3	29.6	15.9	30.7

ls - loamy sand; sl - sandy loam; l – loam; sil- silt loam be more in end part of mid century, lower at higher N levels and fine texture soils. During TS-4, per cent reduction would be 56.6, 43.4 and 46.4 per cent in loamy sand, 47.9, 43.5 and 38 per cent for silt loam in 120, 150 and 180 kg N ha^{-1}, respectively.

Like yield plant uptake was more at higher N level and in silt loam soil in TS-1, which decreased in TS-2, TS-3 and TS-4. For example, during TS-1 plant uptake of 127.3 and 150.7 kg N ha^{-1} at N level of 120 and 180 kg N ha^{-1} in loamy sand; and 150.7 and 153.8 kg N ha^{-1} in silt loam soil were reduced by 23.6 and 17.7 per cent in loamy sand and 22.1 and 15.7 per cent in silt loam soil, respectively. Leaching was less in silt loam soil than loamy sand. Leaching increased during TS-2, TS-3 and TS-4 than TS-1. For example, during TS-1 leaching loss of 64.5 and 69.3 kg N ha^{-1} at N level of 120 and 180 kg N ha^{-1} in loamy sand; and 13.2 and 16.1 kg N ha^{-1} in silt loam soil were reduced by 16.3 and 28.7 per cent in loamy sand, and 97.7 and 69.6 per cent in silt loam soil, respectively. Volatilization was more in increased N level and decreased with fineness of the soil. It decreased during TS-2, TS-3 and TS-4 than TS-1. For example, during TS-1 volatilization loss of 42.3 and 63.2 kg N ha^{-1} at 120 and 180 kg N ha^{-1} in loamy sand; and 30.7 and 51.6 kg N ha^{-1} in silt loam soil were reduced by 1.2 and 10.9 per cent in loamy sand and 1.6 and 63.4 per cent in silt loam soil, respectively. Agronomic and recovery efficiency also varied in different textured soils. Higher agronomic and recovery efficiency was reported in lower levels of N (120 kg N ha^{-1}) and silt loam soil series. The trend would remain similar for all time slices but there would be reduction in agronomic efficiency and recovery efficiency in future. Similar results were reported by Jalota *et al.* (2013, 2014).

Rice yield and nitrogen balance components at different locations

Rice yield and N balance varied under N levels and time slices when simulated for dominant soil series (sandy loam for Ludhiana, silt loam for Amritsar and loam for Patiala) at three locations of Punjab (Table 9). In TS-1, rice yield increases with

Table 9. Yield and nitrogen balance under different locations and time scenario

	N levels (kg N ha^{-1})	Amritsar				Ludhiana				Patiala			
		TS 1	TS 2	TS 3	TS 4	TS 1	TS 2	TS 3	TS 4	TS 1	TS 2	TS 3	TS 4
Yield (t ha^{-1})	120	5.62	3.52	3.21	2.77	4.93	3.08	2.94	2.78	4.53	2.46	2.34	2.05
	150	5.63	3.80	3.59	3.04	5.80	4.04	3.97	3.76	5.06	3.32	3.20	3.08
	180	5.78	4.30	3.82	3.46	5.91	4.67	4.67	4.38	5.12	3.94	3.89	3.70
Plant uptake (kg N ha^{-1})	120	133.4	107.7	108.3	100.1	130.3	119.4	119.0	113.2	128.5	102.3	101.0	99.4
	150	135.6	120.3	114.1	108.9	136.8	130.1	125.1	120.5	129.2	118.3	113.7	110.9
	180	136.5	125.3	123.4	112.4	148.6	139.9	132.0	126.8	135.4	128.1	120.7	117.2
Leaching (kg N ha^{-1})	120	15.5	16.1	18.2	20	4.2	5.1	5.4	5.9	11.5	16.3	16.5	17.4
	150	19.8	20.8	23.4	23.1	5.6	6.6	7.9	7.2	12.1	17.9	18.5	21.2
	180	20.2	22.9	25.8	29.6	9.7	10.1	11.5	13.4	15.2	21.4	22.1	27.4
Volatilization (kg N ha^{-1})	120	32.7	31.7	31.1	32.2	26.8	23.6	24.5	24.9	30.0	26.2	27.8	28.5
	150	47.1	46.2	44.3	43.7	36.7	31.5	33.0	36.1	42.4	36.0	38.0	38.4
	180	53.6	49.5	46.8	46.7	49.0	41.9	43.7	48.1	52.2	46.4	48.7	50.4
Agronomic efficiency (kg kg^{-1})	120	26.2	17.8	16.5	13.1	19.2	12.8	12.9	11.9	18.2	10.0	10.3	8.2
	150	21.0	16.0	15.7	12.3	21.2	16.7	17.2	16.0	18.1	13.7	13.9	13.4
	180	18.4	16.1	14.3	12.6	18.3	17.4	18.2	16.8	15.4	14.9	15.5	14.6
Recovery efficiency (%)	120	56.8	47.8	47.7	45.1	56.4	37.2	39.1	34.1	57.0	35.3	34.3	35.3
	150	49.1	45.4	42.2	40.9	46.6	38.1	34.0	30.5	46.1	38.9	35.9	35.9
	180	47.5	43.3	39.0	37.6	39.3	34.6	33.5	27.4	41.8	37.8	33.8	33.4

ls - loamy sand; sl - sandy loam; l – loam; sil - silt loam; TS-1 – 1986-2016; TS-2 – 2021-2030; TS-3 – 2031-2040; TS-4 – 2041-2050

N level, was highest at Amritsar (4.93, 5.80 and 5.91 t ha^{-1}) followed by Ludhiana (5.62, 5.63 and 5.78 t ha^{-1}) then Patiala (4.53, 5.06 and 5.12 t ha^{-1}) in 120, 150 and 180 kg N ha^{-1} treatments, respectively. There would be decrease in yield in future time slices, continuously at all locations. Per cent reduction in yield would be more in end part of mid century, lower at higher N levels and variable at different locations. For example, during TS-4 per cent reduction for recommended N level would be more at Patiala (54.7%) followed by Ludhiana (50.7%) then Amritsar (43.5%) but under higher N treatments (150 and 180 kg ha^{-1}) yield reduction trend would be Ludhiana> Patiala> Amritsar.

Plant uptake during TS-1 reported higher at Amritsar 130.3, 136.8, 148.6 kg N ha^{-1} at 120, 150 and 180 kg N ha^{-1}, respectively followed by Ludhiana (133.4, 135.6 and 136.5 kg N ha^{-1}) then Patiala (128.5, 129.2 and 135.5 kg N ha^{-1}). With change in climate there would be reduction in N uptake. For example, during TS-4 uptake would reduce by 25, 19.7 and 17.7 per cent at Ludhiana; 22.6, 14.2 and 13.4 per cent at Patiala and 13.1, 11.9 and 14.7 per cent at Ludhiana at 120, 150 and 180 kg N ha^{-1}, respectively.

Unlikely to yield leaching would increases linearly in future time slices. During TS-1, leaching was reported highest at Ludhiana> Patiala> Amritsar and trend would remain constant during TS-2, 3 and 4. However, trend for per cent increase in leaching during TS-4 would be Patiala> Amritsar> Ludhiana. Highest per cent increase in at Patiala might be due higher rainfall increment (8.75 mm yr^{-1}) than Ludhiana and Amritsar.

Volatilization would give decreasing trend during TS-2, 3 and 4 that might be due to reduction in amount of volatilizable N from N pool due to higher per cent increment in leaching. During TS-1, volatilization was higher at Ludhiana> Patiala> Amritsar for all N levels and would changes differently at different location during future time slices.

Agronomic and recovery efficiency also varied at different locations. In TS-1, Higher Agronomic and recovery efficiency was reported at Ludhiana district (26.2 kg kg^{-1}) as compared to Amritsar (19.2 kg kg^{-1}) and Patiala (18.2 kg kg^{-1}). The recovery and agronomic efficiency would decreases in future.

Conclusions

In present time slice, TS-1 (1986-2016) at Ludhiana, the observed T_{max}, T_{min} and RF were 35.5 °C, 25.2 °C and 576.3 mm, respectively. The projected T_{max} will increase by 2.4, 3.3 and 4.5 °C; T_{min} by 1.7, 2.2 and 3.0 °C; and RF by 67, 243 and 294 mm in TS-2 (2021-2030), TS 3 (2031-2040) and TS-4 (2041-2050), respectively compared to TS-1. Simulated rice grain yield, N uptake, volatilization, leaching increases but agronomic and recovery efficiency decreases at higher N levels. Simulated rice grain yield, N uptake, volatilization, agronomic and recovery efficiency would decrease in future time slices but leaching would increase. Per cent reduction in yield would be more in end part of mid century, lower at higher nitrogen levels and fine texture soils. During TS-4 (2040-2050) highest reduction in yield reported at Patiala followed by Ludhiana then Amritsar but under higher N treatments (150 and 180 kg ha^{-1}) yield reduction trend would be Ludhiana> Patiala> Amritsar. Trend for per cent increase in leaching during TS-4 would be Patiala> Amritsar> Ludhiana but volatilization would be Ludhiana> Patiala> Amritsar. The study suggests that higher N levels could be an option to compensate yield reduction in future however higher nitrogen levels would lead to higher losses.

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