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Invited Articles (Silver Jublee Publication)

Revisiting statistical spectral-agrometeorological wheat yield models for Punjab using MODIS EVI and NCMRWF re-analysis temperature data

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ABSTRACT

Use of space-based spectral information with weather inputs for wheat yield modeling by empirical and crop simulation models is reviewed and extended with enhanced spectral modeling approach for districts in central Punjab. The study uses multi-date and multi-year MODIS data at 250m resolution to both identify wheat crop and develop temporal spectral Enhanced Vegetation Index (EVI) profile for 2001-2019 period. Recently developed high resolution (12km) gridded temperature data from NCMRWF, namely India Monsoon Data Assimilation and Analysis (IMDAA) has been used for computing district-level average of daily (AV) and night-time (NT) temperatures. Multiple linear regression analysis with statistical tests on significance of coefficients for various inputs is used to investigate significance of various input parameters in yield models on multi-district data set. Results identify both area under spectral profile (AS-EVI) and mean peak value (PK-EVI) have significant control on yield. Individual district-level trend based yield (YT) is a significant coefficient in the multi-district models. Model performance is significantly improved by the inclusion of phase-specific temperatures and at specific post-flowering phases the night temperature figured in best models. Significance of the results in development of spatially resolved yields for applications like yield forecast, crop insurance and climate change studies is discussed.

Keywords: Spectral-agromet models; Wheat yield; MODIS EVI; Nighttime temperature.

Since the success of Large Area Crop Inventory Experiment (LACIE) conducted during 1974-77 (MacDonald and Hall, 1980), a large amount of literature is now available for the use of RS data for crop yield modelling (Basso and Liu, 2019, Milesi *et al*., 2010). Studies on RS-based wheat yield models in India were taken up after the initial success of wheat mapping with Landsat MSS of Karnal district in 1983-84 and correlation between NDVI and district wheat yields (Dadhwal, 1986). The use of RS and weather data for crop yield modeling in India was reviewed by Dadhwal and Ray (2000) and a wheat-specific review which covered use of RS data for crop biophysical parameters and integration with crop simulation models by Dadhwal *et al*., (2003). A large number of studies with different objectives, data sets and improvements in analysis are summarized in Table 1.

Studies cited in Table 1 indicate different types of approaches for district level yield models with the use of ratio and NDVI as vegetation index and with fixed date of profile-based parameters being used for empirical model development; temperature and rainfall data has mostly been used for model development. Wheat is sensitive to higher temperatures during grain filling which reduces the grain filling duration (Dadhwal *et al.*, 1986, Dadhwal, 1989). Temperature remains a critical model parameter in empirical yield models even when they are entirely meteorological yield models (Bhagia *et al*., 2005, Rao *et al.*, 2015). Empirical models with variable selection also include minimum temperature at specific stages. However, the role of nighttime temperature has received less attention and studies using simulation models (Lobell *et al.*, 2007) and district-level statistical models (Jaishanker *et al*., 2007) have supported the separate effect of nighttime temperatures.

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Table 1: Selected studies on use of spectral and weather data for wheat yield modeling

Sr. No.	Model Type	Sensor@	RS Input$	Weather%	Yield	Trend	Study Area	Use	Source
1	Statistical	AVHRR	M; NDVI;	-	Dist.	-	Punjab/PUN	Model	Dubey *et al*., (1991)
2	Statistical	MSS, LISS	S; NIR/R	-	Dist.	-	Haryana/HAR	Forecast	Sharma *et al*., (1993)
3	Statistical	MSS, LISS	S; NDVI	-	Dist.	Yes	PUN	Forecast	Medhavy *et al*., (1995)
4	Statistical	LISS	S; NIR/R	-	Dist.	-	MP	Model	Dadhwal et al., (1997)
5	Statistical	AVHRR	S; NDVI	Obs; R	Dist.	-	Rajasthan	Forecast	Manjunath *et al*., (2002)
6	Statistical	AVHRR	M; NDVI	Obs; T	Dist.	-	HAR, PUN	Forecast	Kalubarme *et al*., (2003)
7	Statistical	LISS	S; NDVI	Obs; T, R	Dist.	Yes	HAR	Forecast	Verma *et al*., (2003)
8	Statistical	LISS	S; NDVI	Obs; T,R,S, PET	Dist.	Yes	PUN	Model	Bazgeer *et al*., (2006)
9	Statistical	WiFS	M; fAPAR	Obs; TRS	Dist.	-	HAR	Model	Patel *et al*., (2006)
10	Statistical	SPOT-VGT	M; NDVI	Obs; T	Dist.	-	Rajasthan	Model	Jaishanker *et al*., (2007)
11	Statistical	AVHRR	M; NDVI	G; T,SM Obs; R	State		India	Model	Prasad *et al*., (2007)
12	Statistical	AVHRR, MODIS	M; NDVI	Sat; LST, S, AET	Dist	-	Gujarat	Model	Bhattacharya *et al*., (2007)
13	Statistical	TM,Skysat	M;GCVI				Bihar	Yield Gap	Jain *et al*., (2016)
14	CERES-Wheat	-	-	Obs; T,R	Dist	Yes	India & UP		Nain *et al*., (2002, 2003)
15	WTGROWS	WiFS	M; NDVI	Int; T,R,S	Dist	-	Haryana		Nain *et al*., (2004)
16	WTGROWS	LISS	S; NDVI	Int; T,R,S	Field	-	Delhi		Sehgal *et al*., 2005
17	WTGROWS	-	-	Obs.; T, R	State	Yes	India	Forecast	Kalra *et al*., (2006)
18	WOFOST	WiFS	M; NDVI	Int; T,R,S	State	-	India	Forecast	Chaudhary *et al*., (2010)
19	WOFOST	SV,IW	M; NDVI	Int; T,R,S	Dist	-	Punjab		Tripathy *et al*., (2013)
20	APSIM	LT,MD	M;GCVI, LST	G;Sat;LST	S,M	-	IG-Plains	Yield Gap	Jain *et al*., (2017)
21	CERES-Wheat	-	-	G	Dist.	-	UP	Model	Mishra *et al*., (2021)
22	InfoCrop	TM,MSI	M;LAI	G	Field	-	Haryana	Field Scale	Dhakar *et al*., (2022)

@: AVHRR(NOAA), MSS/TM(Landsat), LISS/WiFS(IRS), MODIS(Terra),SK-SkySat ,MSI(Sentinel-2); $: S-Single Date, M-Multi-date, P-Profile; RS Parameter; LST, LAI or Vegetation Indices; **%**: Obs-Observatory, I-Interpolated, G-Gridded, Sat-Satellite; Parameters: T-Temperature, R-Rainfall, S-Sunshine/Solar Radiation, SM-Soil Moisture, ET-Evapotranspiration, AET-Actual ET, PET-Potential ET

Studies on the use of crop simulation models with remote sensing data assimilation (Table 1) have explored many models such as APSIM (Jain *et al*., 2017), CERES-Wheat (Nain *et al*., 2004, Mishra *et al.,* 2021), InfoCrop (Dhakar *et al*., 2022), WOFOST (Chaudhary *et al*., 2010, Tripathy *et al*., 2013) and WTGROWS (Sehgal *et al*., 2002, 2005) with most common use of RS inputs in phenology and leaf area index inputs. Use of field-level yield is limited (Sehgal *et al.,* 2005, Jain *et al.,* 2013, Dhakar *et al.,* 2022) due to logistical difficulties of yield collection. Studies by Patel *et al.,* (2006) and Bhattacharya *et al.,* (2011), process multi-date RS data for estimating agrometeorological parameters of fAPAR and AET before using empirical approach to relate them to district-level yields.

In spectral-agromet studies in India, while spectral predictors are with spatial coverage, the agrometeorological predictors are station-based observations. In this study a new gridded dataset created by NCMRWF under the Indian Monsoon Data Assimilation and Analysis (IMDAA) project was used. It has a 12km resolution and is available for satellite era (since 1979) and has been created by 4-D Var assimilation. Since it uses a large number of hitherto unused Indian observations, it is a credible alternative to routinely used ERA or MERRA reanalysis (Rani *et al*., 2021).

This study revisits the empirical statistical model with the use of MODIS sensor allowing for longer time series from the same RS mission and adopts the use of an alternate vegetation index, namely Enhanced Vegetation Index (EVI).

MATERIALS AND METHODS

Study districts

The study was conducted over 5 contiguous districts of Punjab, namely, Barnala (GA-1410 sq km), Faridkot (GA-1469 sq km), Fatehgarh Sahib (GA-1180 sq km), Ludhiana (GA-3767 sq km) and Moga (GA-2216 sq km) (Fig.1).

District level wheat statistics

The data on annual fully revised estimates of wheat acreage and yield for the period 2001-2019 were obtained from Directorate of Economics and Statistics online database (http://aps.dac.gov.in/APY/Index.htm)

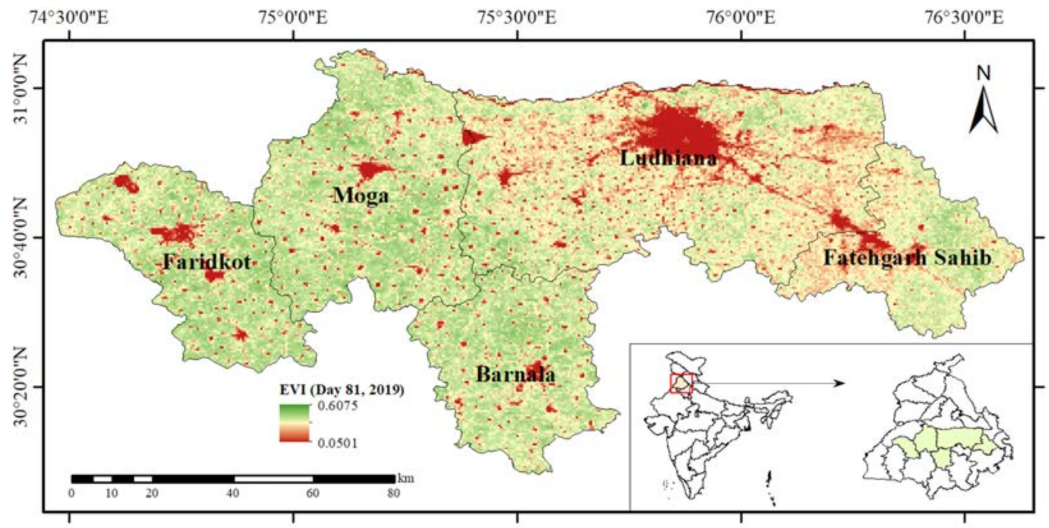

Fig. 1: Study districts map illustrated with MODIS EVI of the study districts (2019, Day of year = 81)

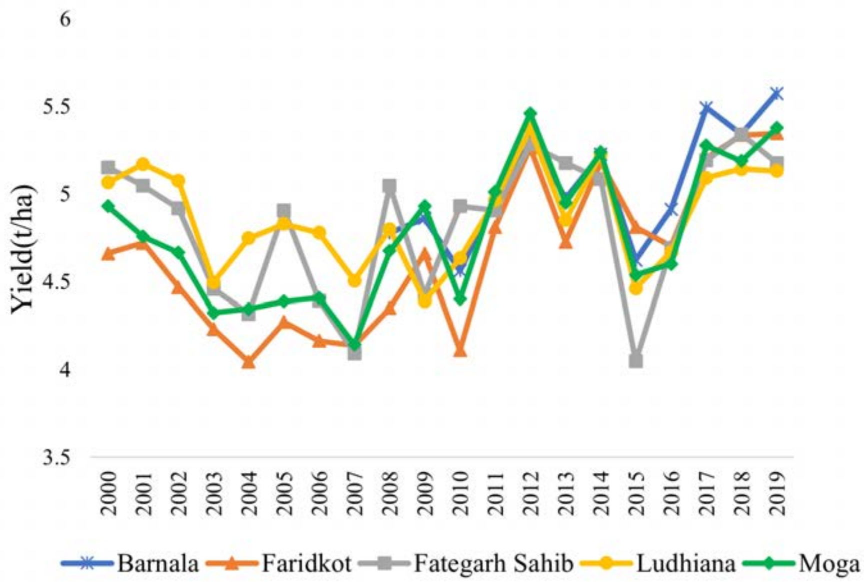

Fig. 2: Wheat yields in 5 study districts across the period (X-axis =Year of harvest)

Remote sensing data and pre-processing

Processed and filtered MODIS EVI data from Terra satellite filtered at 10-day interval was obtained from University of Natural Sciences and Resources (BOKU, Vienna) website (https://ivfl-info.boku.ac.at). It hosts an on-demand data service platform for distributing processed and filtered MODIS data. The processing and filtering details are provided by Vouluni *et al.*, (2012).

Gridded hourly temperature (2m) reanalysis data

High resolution gridded reanalysis data of hourly temperature (2m) was obtained from https://rds.ncmrwf.gov.in. Hourly data in universal time, netcdf format and Kelvin units, were overlaid with district boundaries and district averages of each hour (IST) were computed using R packages. The predictors for yield modelling were daily average temperature (°C) for 20 days, starting from 61, 81 and 101 days of the year (AVT61, AVT81 and AVT101). Hourly temperatures from 1900h to 0600h of the next day were used for computing the night temperature (NT) for three 20-day periods starting on day 61, 81 and 101 of the year (NT61, NT81, NT101).

Statistical analysis

The statistical analysis was carried out using open-source R package as implemented in the JASP (JASP Team, 2022) software.

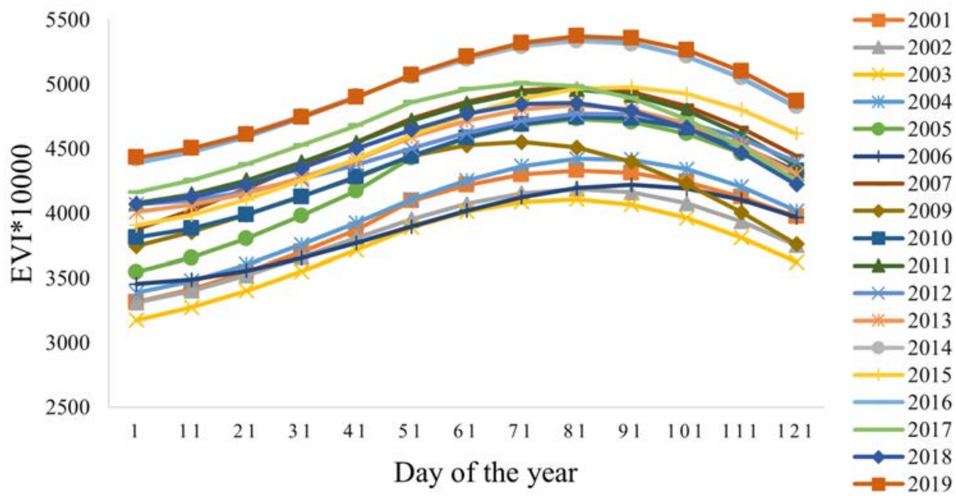

Fig. 3: Filtered EVI profile of wheat pixels in Faridkot district 2001-2019

RESULTS AND DISCUSSION

Trend in yield

Yields of study districts during the analysis period ranged between 4.04-5.57 t ha^{-1}. Differences in mean yield in t ha^{-1} and the coefficient of variation (in parentheses) for study districts were 5.05 (6.6%) for Barnala, 4.66 (9.3%) for Faridkot, 4.83 (8.3%) for Fategarh Sahib, 4.87 (5.9%) for Ludhiana and 4.78 (8.2%) for Moga and 4.82 (8.0%) for the pooled data. Annual wheat yields indicating the year-to-year variability and differences amongst the districts in wheat yields are presented in Fig. 2. Reported yields were regressed on year of harvest to detect the presence of any linear trend: while in case of Faridkot, Fatehgarh Sahib and Ludhiana, linear trends were not significant, for Barnala (0.061 t ha^{-1} yr^{-1}, t-value 2.733, $P< 0.021$) and Moga (0.037 t ha^{-1} yr^{-1}, t-value 2.855, $P<0.011$), the trends were significant. The low value of trend indicates that wheat yields are reaching plateau and decrease in growth rates of wheat productivity has been observed by many authors.

Spectral wheat yield models

The EVI temporal profile after wheat pixel identification and smoothing to derive filtered EVI at fixed 10-day interval showed typical behavior of greening, peak and senescence consistent with the rabi season growth. Variation across the years on timing and value of peak EVI were apparent for all the districts. As a representative case, the EVI temporal plots for Faridkot district are shown in Fig. 3.

Averaged across the years and districts the mean EVI and coefficient of variation (CV%, in parenthesis) the 10-day filtered EVI for day1 to day 111 of the year were 0.411(8.0), 0.418(8.4), 0.424(8.4), 0.434(8.4), 0.449(7.2), 0.461(7.1), 0.471(6.9), 0.476(6.8), 0.477(6.9), 0.471(7.1), 0.461(7.3), 0.443(7.6). The variability of EVI is higher in early and late season and the average peak across districts and years is much flatter. EVI was used in yield models as two derived parameters, namely sum of area under EVI curve for 100-day period (-10 to 91 of day of year of harvest) and average of top 3 EVI values. AS-EVI ranged between 36.96 and 50.18 with CV of 7.2% while range in PK-EVI and CV were 0.409-0.535 and 9.9%.

Spectral yield models with two commonly adopted predictors, average of three 10-day filtered EVI, centered on peak EVI (PK-EVI) and sum of daily EVI for a fixed 100-day period (AS-EVI) were developed for pooled data. Models were developed for each predictor and usefulness of predicted trend yield (YT) in the pooled model for 5 districts was observed. Results indicated AS-EVI marginally outperforms peak EVI as evaluated by R-square and RMSE which were as follows

$$Y= 2.150 + 5.574 \text{ PK-EVI} \quad (R^2 = 0.208, \text{RMSE} = 356) \quad \ldots [1]$$

$$Y = 1.865 + 0.066 \text{ AS-EVI} \quad (R^2= 0.282, \text{RMSE} = 0.340) \quad \ldots [2]$$

The spectral parameter could not fully explain the yield variation amongst districts, as inclusion of yield trend (YT), improved the model for both peak EVI and AS-EVI and slight edge of AS persisted in models with YT also as follows

$$Y = 1.136 + 3.378 \text{ PK-EVI} + 0.431 \text{ YT} \quad (R^2 = 0.281, \text{RMSE} = 0.342) \quad \ldots [3]$$

$$Y = 1.012 + 0.048 \text{ AS-EVI} + 0.342 \text{ YT} \quad (R^2 = 0.330, \text{RMSE} = 0.330) \quad \ldots [4]$$

These two spectral predictors have some complementary information as combined use of both spectral predictors was the best spectral model with both spectral parameters having significant t-value as follows:

$$Y = 2.274 + 0.174 \text{ AS-EVI} - 10.946 \text{ PK-EVI}$$

Table 2: Multiple linear regression and agromet -spectral models for wheat yield prediction in Punjab

Model-I	Spectral and average temperature as predictor variable for selection							
Variable	Intercept	YT	AS-EVI	PK-EVI	AV81	AV101		
Coefficient	2.761	0.276	0.113	-8.091	0.096	-0.105		
Std. Error	1.117	0.134	0.044	4.182	0.042	0.034		
t-value (P)	2.471*	2.046*	2.558*	-1.935#	2.288*	-3.129**		
Model-II	Spectral, average and night temperatures as predictors variable for selection							
Variable	Intercept	YT	AS-EVI	PK-EVI	NT61	NT81	NT101	AV61
Coefficient	5.338	0.235	0.123	-7.248	-0.169	0.120	-0.249	0.115
Std. Error	0.868	0.103	0.032	3.156	0.028	0.035	0.036	0.026
t-value(P)	6.149***	2.288**	3.782***	-2.296*	-5.986***	3.463***	-6.970***	4.442***

Significance test (Probability of error) <10%;#; <5%:*; <1%:**; <0.1% ***

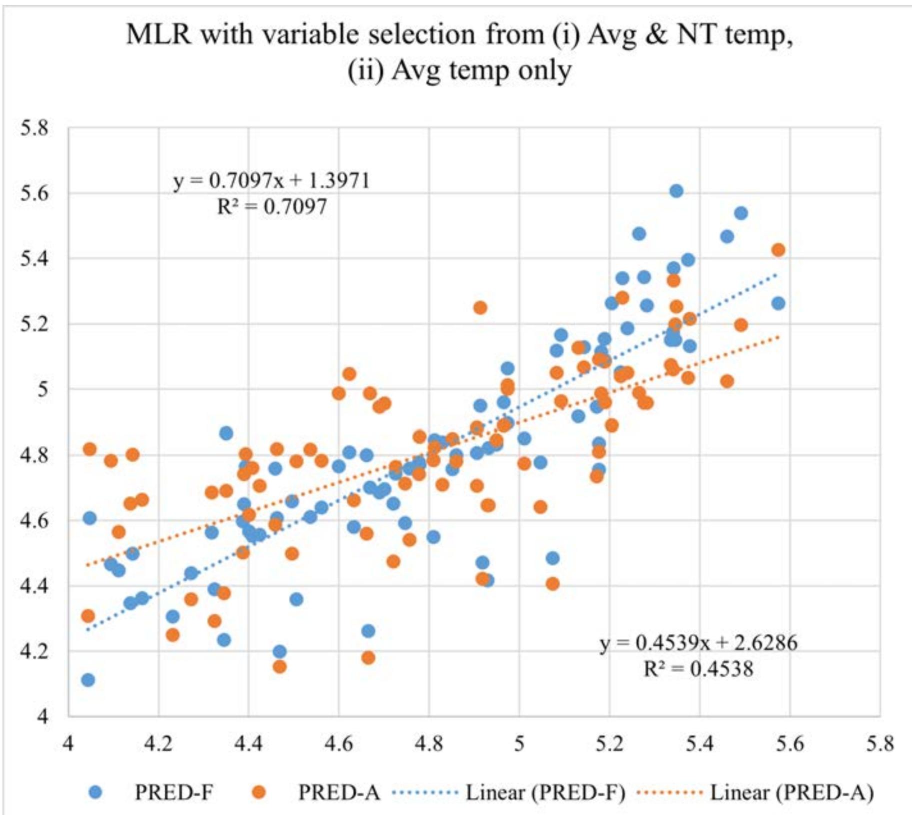

Fig. 4: Scatterplot of MLR predicted wheat yield with observed yields for Model-I (Pred-A) and Model-II (Pred-F).

$(R^2 = 0.333, RMSE = 0.329)$ … [5]

Additional improvement in the two-parameter spectral model were evaluated. In the combined spectral model also, use of yield trend (YT) as proxy for inter-district differences adjusted for year of harvest produced the best predictor of this analysis

$$Y = 1.393 + 0.160\ AS\text{-}EVI - 11.560\ PK\text{-}EVI + 0.362\ YT$$
$(R^2 = 0.383, RMSE = 0.318)$ …[6]

Multiple linear agromet-spectral models & importance of night temperatures

Multiple linear regression model with spectral (PK-EVI, AS-EVI), yield trend (YT) and temperature during specific 20-day periods were developed with variable selection by backward elimination procedure. The two models investigated were Model-I where only average temperatures were used and included six predictors (Model-I: PK-EVI, AS-EVI, YT, AV61, AV81 and AV 101) and Model-II which included both average and nighttime average temperature and thus had nine predictors (Model-II: PK-EVI, AS-EVI, YT, AV61, AV81, AV101, NT61, NT81, NT101) for elimination. Yields predicted by Model-I and Model-II were compared with observed yields (Fig 4). Model-II was the best model with R^2 of 0.710 and RMSE of 0.224 and included night temperature terms for all the three periods and average temperature for 61-80 day of year (March). In comparison, the Model-I with use of average temperatures as predictors had R^2 of 0.454 and RMSE of 0.303. Stronger association of yield variability to night temperature than average temperature is suggested by these results. Model-II performance in terms of RMSE indicates this to be only 4.65 percent of pooled yield, which indicates its possible use for yield prediction.

This study revisited the empirical agrometeorological-spectral wheat yield models with current RS and yield data. Since the early attempts of 1990s where major RS data was either Landsat MSS/TM or IRS LISS-I/II for limited date analysis or NOAA-AVHRR for full spectral profile models, here MODIS data with improved spectral characteristics and frequent observations was used. With present availability of Indian AWIFS and SoumiNPP, this data of similar nature would continue to be available. Current constellations like Planet have capability to deliver even daily coverage of cloud free areas with under 5m resolution which would allow field-scale model development.

New spectral channels and new VI are providing another opportunity to develop new category of models. Here EVI has been used, and recent comparison of NDVI and EVI have given promising results for use of EVI for yield modeling (Kouadio *et al.*, 2014, Son *et al.*, 2014). New high-resolution data from reanalysis by NCMRWF is used. This data has higher spatial resolution and it would allow easily to explore additional agrometeorological variables as input. The study covered a compact group of districts and only a pooled model was developed. This approach contrasts with studies that develop separate models for each district, which reduces the observation data set. Pooled models can only be developed for districts which have similar agroclimate, cropping pattern and grouping should be based on objective analysis as demonstrated by Nain *et al*., (2003) for Uttar Pradesh where use of agglomerative clustering of inter-annual deviations from trend was used to divide state of Uttar Pradesh into homogenous groups for purpose of wheat yield prediction.

In addition to re-establishing the requirement of combining spectral and agrometeorological inputs, the study clearly brings about improvement in models by inclusion of night temperature as predictors. NT had significant coefficients even in the presence of average daily temperature. Such models can be used for yield projections under future climate. The approach adopted here can be modified to smaller areal units (villages or gridded) and facilitate objective comparison of empirical and CSM based yield assessment. In addition, with larger number of input parameters, this approach would allow data-driven new models using AI/ML techniques (Paudel *et al.*, 2021).

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