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Impact of environmental changes and land management practices on wheat production in India

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Dynamic C3 crop model in ISAM

There are six stages in the growth of C3 crop that are modeled in ISAM (Song et al. 2013). The concept of Growing Degree Days (GDD) is used to define wheat growth and divide the wheat-growing season into different phenological stages. Daily GDD is calculated as the difference between daily average air temperature and base temperature since the planting day. Each stage is governed by heat requirement range (fraction of maximum GDD) and switches to the next stage when the heat unit index (=accumulated GDD/maxGDD) exceeds the maximum limit for that stage. GDD is calculated daily and accumulated GDD is calculated as cumulative GDD that increases along the growing season.

During emergence, the seeds stay below the ground, increase in size and gain weight. The emergence of the shoot from the ground marks the beginning of the second stage, the initial vegetative stage. Maximum carbon assimilated is allocated to the shoot in this stage and leads to rapid increase in LAI and a small increase in length of the stem. The third stage, normal vegetative stage, is marked with a rapid increase in length of the stem and the roots to support vertical growth of the plant. The maximum LAI of the crop is reached by the end of the third stage. The fourth stage, initial reproductive stage, marks the onset of reproductive stage in the crop and development of storage organs. Allocation of assimilated carbon to storage organs begins and vegetative development of the plant stops. The fifth stage, post-reproductive stage, marks the solidification of grains and increased nutrient allocation to the grains while ensuring capable roots to support the plant. There are other factors like light availability, temperature stress and nitrogen availability that act as limiting factors to the crop growth and nutrient allocation is promoted in the crop in a way that the impact of these factors is minimized. For instance, there is a greater allocation of carbon to the roots when the crop experiences water stress to ensure more vertical development of roots to extract water from deeper soil levels. Finally, the crop is ready to be harvested when the heat requirement of the crop is fulfilled (GDD= maxGDD). Each growth stage is also marked with a maximum number of days that the plant can spend in each stage to ensure that wheat grown in all climatological regions enters each stage based on the defined conditions for each phenology stage.

Total carbon assimilation by vegetation is calculated at hourly intervals using the C3 photosynthesis (Song et al., 2013) after taking into account the water, nutrient and light availability. Maintenance respiration and growth respiration losses are considered as a part of carbon lost to the environment. Fractions of net carbon assimilated after accounting for respiratory losses are allocated to different plant pools (leaves, stem, coarse root, fine root, and grain) based on the growth stage.

Table S1: List of all variables/parameters and their values for the spring wheat model. The model equations for C3 crops are described in Song et al. 2013.

Symbol	Definition	Value	Source
V_{cmax25}	Maximum carboxylation rate at the reference temperature of $25^{o}C$	130 $\mu mol\ m^{-2}s^{-1}$	
T_{high}	$^{1}/_{2}$ point of high temperature inhibition function in carbon assimilation	308 K	Lokupitiya et al. 2009
T_{base}	Base atmospheric temperature for calculating daily GDD	278.15 K	Gill et al. 2014
$T_{soil_{critical}}$	Base soil temperature for crop planting	290.52 K	
GDD_{max}	Required total heat above base temperature	1800 [$_{o}$C]	
HUI_{day}	Heat Unit Index of the *i*th day	variable	
T_{avg}	Average daily air temperature	variable	
HUI_{v1}	Minimum heat unit index during the initial vegetative period	0.07	This study
HUI_{v2}	Minimum heat unit index during the normal vegetative period	0.27	This study
HUI_{r1}	Minimum heat unit index during the reproductive period	0.51	This study
HUI_{r2}	Minimum heat unit index during the post-reproductive period	0.70	This study
$D_{max_{emer}}$	Maximum number of days in emergence period	7	This study (calibrated)
$D_{max_{v1}}$	Maximum number of days in initial vegetative period	30	This study(calibrated)
$D_{max_{v2}}$	Maximum number of days in normal vegetative period	46	This study(calibrated)
$D_{max_{r1}}$	Maximum number of days in reproductive period	16	This study(calibrated)
$D_{max_{r2}}$	Maximum number of days in post-reproductive period	35	This study(calibrated)
$C_{storage\_ref}$	Initial carbon storage in seed as referenced seeding rate	15 gC	
R_{seed_ref}	Referenced seeding rate	1011715 seeds/acre	
$CN_{\boldsymbol{leaf}}$	C:N ratio of leaf	15	Drewniak et al. 2013
$CN_{\boldsymbol{stem}}$	C:N ratio of stem	50	Drewniak et al. 2013
$CN_{\boldsymbol{root}}$	C:N ratio of root	30	Drewniak et al. 2013
$CN_{\boldsymbol{grain}}$	C:N ratio of grain	40	Drewniak et al. 2013
$Ashoot_{\boldsymbol{e}}$	Allocation fraction for shoot during emergence period	0.60	This study(calibrated)
$Aroot_{\boldsymbol{e}}$	Allocation fraction for root during emergence period	0.40	This study(calibrated)
$Al_{\boldsymbol{v1}}$	Allocation fraction for leaves during initial vegetative period	0.45	This study(calibrated)
$As_{\boldsymbol{v1}}$	Allocation fraction for stem during initial vegetative period	0.35	This study(calibrated)

Ar_{v1}	Allocation fraction for roots during initial vegetative period	0.20	This study(calibrated)
Al_{v2}	Allocation fraction for leaves during normal vegetative period	0.58	This study(calibrated)
As_{v2}	Allocation fraction for stem during normal vegetative period	0.32	This study(calibrated)
Ar_{v2}	Allocation fraction for roots during normal vegetative period	0.10	This study(calibrated)
Al_{r1}	Allocation fraction for leaves during reproductive period	0.00	This study(calibrated)
As_{r1}	Allocation fraction for stem during reproductive period	0.05	This study(calibrated)
Ar_{r1}	Allocation fraction for roots during reproductive period	0.10	This study(calibrated)
$Ag_{r1_{max}}$	Maximum allocation fraction for grains during reproductive period	0.85	This study(calibrated)
Ag_{r1}	Allocation fraction for grains during reproductive period	variable	This study
Al_{r2}	Allocation fraction for leaves during post-reproductive period	0.00	This study(calibrated)
As_{r2}	Allocation fraction for stem during post-reproductive period	0.00	This study(calibrated)
Ar_{r2}	Allocation fraction for roots during post-reproductive period	0.05	This study(calibrated)
$Ag_{r2_{max}}$	Allocation fraction for grains during post-reproductive period	0.95	This study(calibrated)
Ag_{r2}	Allocation fraction for grains during post-reproductive period	variable	This study
T_{min}^{stress}	Minimum temperature for inducing heat stress in the crop	25$_o$C	Deryng et al. 2014
T_{max}^{stress}	Maximum temperature for wheat to have non-zero daily grain growth rate	35$_o$C	Deryng et al. 2014
Rt_{high}	Daily death rate of leaves from heat stress	variable	This study
SLA	Specific Leaf Area	45 m$_2$/kgC	This study
H_a	Maximum canopy height	0.95 m	Drewniak et al. 2013
$phen$	Phenology Stage	variable	
$T_{stress_{fact}}$	Daily heat stress factor due to high T_{avg}	variable	
day	Julian day	variable	
Rt_{max}	Maximum death rate of green leaves due to heat stress	variable	
LAI_{max}	Maximum LAI	7.0	Drewniak et al. 2013

Table S2: Climatology based planting day criteria for each grid cell. (*Average minimum temperature based on 1901-1950 climatology).

Minimum temperature* of region ($T_{air_{min}}, K$)	**Criteria**	**Notation**	**Spatial regions represented**
$T_{air_{min}} < 275.0$	- Julian day > 260 (September 17) - Average of last 7 day air temperature < 24.81oC	$day > 260$ $T_{air}(7\ days) < 297.96\ K$	- Northern parts of India - Indo-Gangetic Plains
$275.0 \leq T_{air_{min}} < 277.5$	- Julian day > 260 (September 17) - Average of last 7 day air temperature < 22.81oC - Average of last 30 days precipitation < 20 mm	$day > 260$ $T_{air}\ (7\ days) < 295.96\ K$ $Prec(30\ days) < 20\ mm$	- Parts of eastern India where rice is harvested a few months ahead of wheat plantation on the same land.
$T_{air_{min}} \geq 277.5$	- Julian day > 260 (September 17) - Average of last 7 day air temperature < 32.01oC - Average of last 30 days precipitation < 100 mm	$day > 260$ $T_{air}\ (7\ days) < 305.16\ K$ $Prec(30\ days) < 100\ mm$	- Central India and parts of southern India.

Table S3: List of equations for spring wheat specific processes and variables used in this study. The variables used here are defined in Table S4.

Dataset/Process/Variable	Equation
Heat Stress	$Ag_{r1/r2}(phen) = \begin{cases} Ag_{r1/r2_{max}}(phen), & if\ T_{avg} < T_{min}^{stress} \\ Ag_{r1/r2_{max}}(phen) * \frac{(35 - T_{avg})}{10}, & T_{min}^{stress} \leq T_{avg} \leq T_{max}^{stress} \\ 0, & if\ T_{avg} > T_{max}^{stress} \end{cases}$ ..Eq. S1 $T_{stress_{fact}}(day) = \begin{cases} 1, & if\ T_{avg} < T_{min}^{stress} \\ \frac{(35 - T_{avg})}{10}, & T_{min}^{stress} \leq T_{avg} \leq T_{max}^{stress} \\ 0, & if\ T_{avg} > T_{max}^{stress} \end{cases}$ ..Eq. S2 $Rt_{high}(day) = Rt_{max} * (1 - T_{stress_{fact}}(day))^3$ ..Eq. S3
Annual nitrogen fertilizer data (0.5_o X 0.5_o) from 1900 to 2005	$frac_i = \frac{fert_{wheat_i}(2000)}{fert_{total_i}(2000)}$ ..Eq. S4 $fert_{wheat_i}(yr) = frac_i * fert_{total_i}(yr)$ ..Eq. S5
Annual wheat area data (0.5_o X 0.5_o) from 1997 to 2014	$Area_{wheat_{state}}(yr) = \sum_{k=1}^{all\ districts} Area_{wheat_k}(yr)$ ..Eq. S6 $fr_{state_{yr}} = \frac{Area_{wheat_{state}}(yr)}{Area_{wheat_{state}}(2000)}$ ..Eq. S7 $TWA_i(yr) = fr_{state_{yr}} * TWA_i(2000), \forall\ i\ \in state$ ..Eq. S8
Annual area equipped for irrigation (0.5_o X 0.5_o) from 1997 to 2014	$AEI_{avg_i}(yr) = \begin{cases} (AEI_{HYDE_{FINAL_i}}^{IR}(yr) + AEI_{HYDE_{FINAL_i}}^{CP}(yr) + AEI_{EARTHSTAT_i}^{IR}(yr) + AEI_{EARTHSTAT_i}^{CP}(yr))/4, & if\ 1997 \leq yr \leq 2005 \\ fr_{IRRI\_AR_{yr}} = \frac{Area_{IRRI\_AR}(yr)}{Area_{wheat_{state}}(2005)}, \quad AEI_{avg_i}(yr) = AEI_{avg_i}(2005) * fr_{IRRI\_AR_{yr}} & if\ yr > 2005 \end{cases}$ ..Eq. S9
Annual actual wheat production	$Prod_{act}(yr) = \frac{\sum_{i=1}^{all\ grids}\{[Prod_{S_{CON}}(yr)_i * AEI_{avg}(yr)_i] + [Prod_{S_{IRRI}}(yr)_i * [TWA(yr)_i - AEI_{avg}(yr)_i]]\}}{\sum_{i=1}^{all\ grids} TWA(yr)_i}$ ..Eq. S10
Impact of each factor on wheat production	$Impact_{factor}(yr) = Prod(S_{CON}(yr)) - Prod(S_{<factor>}(yr))$ ..Eq. S11

Table S4: Definition of all variables and parameters used in the equations presented in Table S3.

Symbol	Definition	Source
yr	Year	
i	Variable representing number of grids in study area	
k	Variable representing number of districts in a state	
$Prod_{act}$	Actual annual wheat production of India	
S_{CON}	Control run with all input forcings (atmospheric CO_2, temperature, nitrogen fertilizer, irrigation) varying with time	
$S_{<factor>}$	Simulations with all but one input forcing (*factor*) varying with time	
$Prod_{S_{CON}}$	Wheat production from S_{CON} case (irrigated case)	
$Prod_{S_{<factor>}}$	Wheat production from $S_{<factor>}$ case	
$Area_{wheat_k}(yr)$	Annual wheat harvested area at district (*k*) level	MAFW, India
$Area_{wheat_{state}}$	Annual wheat harvested area at state level evaluated by summing up data from all districts in a state	
$fr_{state_{yr}}$	Fraction of annual wheat harvested area at state-level for year *yr* with that of year 2000.	
TWA_i	Total wheat harvested area in ith grid	This study
$AEI^{IR}_{HYDE_{FINAL_i}}$	Gridded Area Equipped for Irrigation (AEI) with HYDE 3.1 Final as dataset used for downscaling and maximizing consistency with AEI_IR	Siebert et al. 2015
$AEI^{CP}_{HYDE_{FINAL_i}}$	Gridded Area Equipped for Irrigation (AEI) with HYDE 3.1 Final as dataset used for downscaling and maximizing consistency with AEI_CP	Siebert et al. 2015
$AEI^{IR}_{EARTHSTAT_i}$	Gridded Area Equipped for Irrigation (AEI) with EARTHSTAT as dataset used for downscaling and maximizing consistency with AEI_IR	Siebert et al. 2015
$AEI^{CP}_{EARTHSTAT_i}$	Gridded Area Equipped for Irrigation (AEI) with EARTHSTAT as dataset used for downscaling and maximizing consistency with AEI_CP	Siebert et al. 2015
AEI_{avg}	Average AEI for each grid cell	
$frac_i$	Fraction of wheat to total fertilizer amount for ith grid	
$fert_{wheat_i}(yr)$	Fertilizer amount added to wheat for ith grid for the year yr	
$fert_{total_i}(yr)$	Total fertilizer amount added in ith grid for the year yr	
$Impact_{factor}$	Difference between production from S_{CON} and $S_{<factor>}$	

Table S4: Temporal variations of different input forcings and their impacts on annual wheat production in SWE1 during the study period (1980-2016).

Input Forcing (*i*)	Rate of change of *i* in study period	Rate of change in annual wheat production	Change in annual wheat production per unit change in *i*
Elevated atmospheric CO_2 level	1.82[a] ppm/yr	0.46[a] Mt/yr	0.26[a] Mt/ppmCO_2
Average growing season temperature*	0.03[a] °C/yr	-0.18[a] Mt/yr	-3.52[b] Mt/°C
Average water demand	356.27[a] mm/yr	0.17[a] Mt/yr	0.35[b] Mt/1000 mm
Average nitrogen fertilizer per unit area	3.34[a] kgN/ha/yr	0.24[a] Mt/yr	0.07[a] Mt/kgN/ha

[a] Values are significant at 99%
[b] Values are significant at 90%

Table S5: Temporal variations of different input forcings and their impacts on annual wheat production in SWE2 during the study period (1980-2016).

Input Forcing (*i*)	Rate of change of *i* in study period	Rate of change in annual wheat production	Change in annual wheat production per unit change in *i*
Elevated atmospheric CO_2 level	1.82[a] ppm/yr	0.03[a] Mt/yr	0.02[a] Mt/ppmCO_2
Average growing season temperature*	0.04[a] °C/yr	0 Mt/yr	-0.03 Mt/°C
Average water demand	18.22[b] mm/yr	0 Mt/yr	0.04[b] Mt/1000 mm
Average nitrogen fertilizer per unit area	3.09[a] kgN/ha/yr	0.02[a] Mt/yr	0.01 Mt/kgN/ha

[a] Values are significant at 99%
[b] Values are significant at 90%

Table S6: Temporal variations of different input forcings and their impacts on annual wheat production in SWE3 during the study period (1980-2016).

Input Forcing (*i*)	Rate of change of *i* in study period	Rate of change in annual wheat production	Change in annual wheat production per unit change in *i*
Elevated atmospheric CO_2 level	1.82[a] ppm/yr	0.02[a] Mt/yr	0.01[a] Mt/ppmCO_2
Average growing season temperature*	0.03[a] °C/yr	-0.01 Mt/yr	-0.12 Mt/°C
Average water demand	-10.95 mm/yr	0.01 Mt/yr	0.61[a] Mt/1000 mm
Average nitrogen fertilizer per unit area	3.03[a] kgN/ha/yr	0 Mt/yr	0 Mt/kgN/ha

[a] Values are significant at 99%
[b] Values are significant at 90%

Table S7: Temporal variations of different input forcings and their impacts on annual wheat production in SWE4 during the study period (1980-2016).

Input Forcing (*i*)	Rate of change of *i* in study period	Rate of change in annual wheat production	Change in annual wheat production per unit change in *i*

Elevated atmospheric CO_2 level	1.82[a] ppm/yr	0.03[a] Mt/yr	0.02[a] Mt/ppmCO_2
Average growing season temperature*	0.02[a] ^{0}C/yr	-0.06[a] Mt/yr	-0.36 Mt/^{0}C
Average water demand	2.87 mm/yr	0 Mt/yr	0.07 Mt/1000 mm
Average nitrogen fertilizer per unit area	2.54[a] kgN/ha/yr	0 Mt/yr	0 Mt/kgN/ha

[a] Values are significant at 99%
[b] Values are significant at 90%

Table S8: Temporal variations of different input forcings and their impacts on annual wheat production in SWE5 during the study period (1980-2016).

Input Forcing (*i*)	Rate of change of *i* in study period	Rate of change in annual wheat production	Change in annual wheat production per unit change in *i*
Elevated atmospheric CO_2 level	1.82[a] ppm/yr	0.12[a] Mt/yr	0.07[a] Mt/ppmCO_2
Average growing season temperature*	0.02[a] ^{0}C/yr	-0.14[a] Mt/yr	-1.36 Mt/^{0}C
Average water demand	72.77[a] mm/yr	0.05[b] Mt/yr	0.41 Mt/1000 mm
Average nitrogen fertilizer per unit area	2.84[a] kgN/ha/yr	0.05[a] Mt/yr	0.01[b] Mt/kgN/ha

[a] Values are significant at 99%
[b] Values are significant at 90%

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