Supplement of

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

Shilpa Gahlot et al.

Correspondence to: Somnath Baidya Roy (drsbr@iitd.ac.in)

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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                        |
|-----------------|---------------------------------------------------------------------------|---------------------|-------------------------------|
| $V_{\text{cmax25}}$ | Maximum carboxylation rate at the reference temperature of 25°C             | 130 $\mu$mol m$^{-2}$s$^{-1}$ |                               |
| $T_{\text{high}}$ | $\frac{1}{2}$ point of high temperature inhibition function in carbon assimilation | 308 K               | Lokupitiya et al. 2009       |
| $T_{\text{base}}$ | Base atmospheric temperature for calculating daily GDD                     | 278.15 K            | Gill et al. 2014             |
| $T_{\text{soil cricital}}$ | Base soil temperature for crop planting                                    | 290.52 K            |                               |
| $GDD_{\text{max}}$ | Required total heat above base temperature                               | 1800 [°C]           |                               |
| $HUI_{\text{day}}$ | Heat Unit Index of the $i$th day                                           | variable            |                               |
| $T_{\text{avg}}$ | 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                    |
| $D_{\text{max emer}}$ | Maximum number of days in emergence period                           | 7                   | This study (calibrated)       |
| $D_{\text{max v1}}$ | Maximum number of days in initial vegetative period                      | 30                  | This study(calibrated)        |
| $D_{\text{max v2}}$ | Maximum number of days in normal vegetative period                      | 46                  | This study(calibrated)        |
| $D_{\text{max r1}}$ | Maximum number of days in reproductive period                           | 16                  | This study(calibrated)        |
| $D_{\text{max r2}}$ | Maximum number of days in post-reproductive period                     | 35                  | This study(calibrated)        |
| $C_{\text{storage ref}}$ | Initial carbon storage in seed as referenced seeding rate              | 15 gC               |                               |
| $R_{\text{seed ref}}$ | Referenced seeding rate                                                | 1011715 seeds/acre  |                               |
| $CN_{\text{leaf}}$ | C:N ratio of leaf                                                       | 15                  | Drewniak et al. 2013          |
| $CN_{\text{stem}}$ | C:N ratio of stem                                                      | 50                  | Drewniak et al. 2013          |
| $CN_{\text{root}}$ | C:N ratio of root                                                       | 30                  | Drewniak et al. 2013          |
| $CN_{\text{grain}}$ | C:N ratio of grain                                                      | 40                  | Drewniak et al. 2013          |
| $A_{\text{shoot e}}$ | Allocation fraction for shoot during emergence period                   | 0.60                | This study(calibrated)        |
| $A_{\text{root e}}$ | Allocation fraction for root during emergence period                    | 0.40                | This study(calibrated)        |
| $A_{l1}$       | Allocation fraction for leaves during initial vegetative period         | 0.45                | This study(calibrated)        |
| $A_{s1}$       | Allocation fraction for stem during initial vegetative period           | 0.35                | This study(calibrated)        |
| Symbol     | Description                                                   | Value  | Source                  |
|------------|---------------------------------------------------------------|--------|-------------------------|
| $Ar_{v1}$  | 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             |
| $T_{min}$  | Minimum temperature for inducing heat stress in the crop      | 25°C   | Deryng et al. 2014     |
| $T_{max}$  | Maximum temperature for wheat to have non-zero daily grain growth rate | 35°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 |                   |
| $T_{stress,act}$ | 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 < 24.81°C | $day > 260$  
$T_{air (7 days)} < 297.96 K$ | - 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 < 22.81°C  
- Average of last 30 days precipitation < 20 mm | $day > 260$  
$T_{air (7 days)} < 295.96 K$  
$Prec(30 days) < 20 \text{ mm}$ | - 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 < 32.01°C  
- Average of last 30 days precipitation < 100 mm | $day > 260$  
$T_{air (7 days)} < 305.16 K$  
$Prec(30 days) < 100 \text{ mm}$ | - 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              | \( Ag_{r1/r2} = \begin{cases} Ag_{r1/r2_{max}}(\text{phen}), & \text{if } T_{avg} < T_{\text{stress min}} \\ Ag_{r1/r2_{max}}(\text{phen}) \times \frac{10}{(35 - T_{avg})}, & T_{\text{stress min}} \leq T_{avg} < T_{\text{stress max}} \\ 0, & \text{if } T_{avg} > T_{\text{stress max}} \end{cases} \)  
\text{..Eq. S1} \ |
|                         | \( T_{\text{stress fact (day)}} = \begin{cases} 1, & \text{if } T_{avg} < T_{\text{stress min}} \\ \frac{10}{(35 - T_{avg})}, & T_{\text{stress min}} \leq T_{avg} < T_{\text{stress max}} \\ 0, & \text{if } T_{avg} > T_{\text{stress max}} \end{cases} \)  
\text{..Eq. S2}  |
|                         | \( R_{t_{\text{high (day)}}} = R_{t_{\text{max}}} \times (1 - T_{\text{stress fact (day)}})^3 \)  
\text{..Eq. S3}  |
| Annual nitrogen fertilizer data (0.5° X 0.5°) from 1990 to 2005 | \( \text{frac}_i = \frac{f_{\text{ert wheat (2000)}}}{f_{\text{ert total (2000)}}} \)  
\text{..Eq. S4}  |
|                         | \( f_{\text{ert wheat (yr)}} = \text{frac}_i \times f_{\text{ert total (yr)}} \)  
\text{..Eq. S5}  |
| Annual wheat area data (0.5° X 0.5°) from 1997 to 2014 | \( \text{Area}_{\text{wheat state (yr)}} = \sum_{k=1}^{\text{all districts}} \text{Area}_{\text{wheat k (yr)}} \)  
\text{..Eq. S6}  |
|                         | \( f_{\text{r state yr}} = \frac{\text{Area}_{\text{wheat state (yr)}}}{\text{Area}_{\text{wheat state (2000)}}} \)  
\text{..Eq. S7}  |
|                         | \( TWA_{i (yr)} = f_{\text{r state yr}} \times TWA_{i (2000)}, \forall i \in \text{state} \)  
\text{..Eq. S8}  |
| Annual area equipped for irrigation (0.5° X 0.5°) from 1997 to 2014 | \( AEI_{\text{avg} i (yr)} = \begin{cases} (AEI_{\text{avg} i (yr)}) + \frac{AEI_{\text{avg} i (yr)}}{\text{Area}_{\text{wheat state (yr)}}} / 4, & \text{if } 1997 \leq yr \leq 2005 \\ \frac{f_{\text{r IRRI AR yr}}}{\text{Area}_{\text{wheat state (2005)}}}, & \text{if } yr > 2005 \end{cases} \)  
\text{..Eq. S9}  |
| Annual actual wheat production | \( \text{Prod}_{\text{act (yr)}} = \sum_{i=1}^{\text{all grids}} [\text{Prod}_{\text{CON (yr)}} \times \text{AEI}_{\text{avg} i (yr)}] + \frac{\text{Prod}_{\text{IRRI (yr)}}}{\sum_{i=1}^{\text{all grids}} TWA_{i (yr)}]} \)  
\text{..Eq. S10}  |
| Impact of each factor on wheat production | \( \text{Impact}_{\text{factor (yr)}} = \text{Prod}(S_{\text{CON (yr)}}) - \text{Prod}(S_{\text{<factor> (yr)}}) \)  
\text{..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<sub>act</sub>   | Actual annual wheat production of India                                    |                             |
| S<sub>CON</sub>      | Control run with all input forcings (atmospheric CO₂, temperature, nitrogen fertilizer, irrigation) varying with time |                             |
| S<sub>&lt;factor&gt;</sub> | Simulations with all but one input forcing (<i>factor</i>) varying with time |                             |
| Prod<sub>(S<sub>&lt;factor&gt;</sub>)</sub> | Wheat production from S<sub>CON</sub> case (irrigated case) |                             |
| Prod<sub>(S<sub>&lt;factor&gt;</sub>)</sub> | Wheat production from S<sub>&lt;factor&gt;</sub> case |                             |
| Area<sub>wheat</sub>&lt;k,(yr)&gt; | Annual wheat harvested area at district (<i>k</i>) level | MAFW, India                |
| Area<sub>state</sub> | Annual wheat harvested area at state level evaluated by summing up data from all districts in a state |                             |
| f<sub>state, yr</sub> | Fraction of annual wheat harvested area at state-level for year yr with that of year 2000. |                             |
| TWA<sub>i</sub>      | Total wheat harvested area in <i>i</i>th grid                            | This study                  |
| AEI<sub>HYDEFINAL</sub>&lt;<sub>i</sub>&gt; | 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<sub>HYDEFINAL</sub>&lt;<sub>i</sub>&gt; | 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<sub>IR</sub>&lt;<sub>EARTHSTAT</sub>&lt;<sub>i</sub>&gt; | Gridded Area Equipped for Irrigation (AEI) with EARTHSTAT as dataset used for downscaling and maximizing consistency with AEI_IR | Siebert et al. 2015          |
| AEI<sub>CP</sub>&lt;<sub>EARTHSTAT</sub>&lt;<sub>i</sub>&gt; | Gridded Area Equipped for Irrigation (AEI) with EARTHSTAT as dataset used for downscaling and maximizing consistency with AEI_CP | Siebert et al. 2015          |
| AEI<sub>avg</sub>    | Average AEI for each grid cell                                            |                             |
| frac<sub>i</sub>     | Fraction of wheat to total fertilizer amount for <i>i</i>th grid          |                             |
| fert<sub>wheat</sub>&lt;,(yr)&gt; | Fertilizer amount added to wheat for <i>i</i>th grid for the year yr |                             |
| fert<sub>total</sub>&lt;,(yr)&gt; | Total fertilizer amount added in <i>i</i>th grid for the year yr          |                             |
| Impact<sub>factor</sub> | Difference between production from S<sub>CON</sub> and S<sub>&lt;factor&gt;</sub> |                             |
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 CO₂ level    | 1.82 a ppm/yr                       | 0.46 a Mt/yr                              | 0.26 a Mt/ppmCO₂                                     |
| Average growing season temperature* | 0.03 oC/yr                        | -0.18 a Mt/yr                             | -3.52 a Mt/oC                                        |
| Average water demand              | 356.27 mm/yr                        | 0.17 a Mt/yr                              | 0.35 a 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 CO₂ level    | 1.82 a ppm/yr                       | 0.03 a Mt/yr                              | 0.02 a Mt/ppmCO₂                                     |
| Average growing season temperature* | 0.04 oC/yr                        | 0 Mt/yr                                  | -0.03 Mt/oC                                         |
| Average water demand              | 18.22 mm/yr                         | 0 Mt/yr                                  | 0.04 a Mt/1000 mm                                   |
| Average nitrogen fertilizer per unit area | 3.09 a kgN/ha/yr                   | 0.02 a Mt/yr                              | 0.01 a 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 CO₂ level    | 1.82 a ppm/yr                       | 0.02 a Mt/yr                              | 0.01 a Mt/ppmCO₂                                     |
| Average growing season temperature* | 0.03 oC/yr                        | -0.01 Mt/yr                              | -0.12 Mt/oC                                         |
| 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 CO₂ level    | 1.82 a ppm/yr                       | 0.02 a Mt/yr                              | 0.01 a Mt/ppmCO₂                                     |
| Average growing season temperature* | 0.03 oC/yr                        | -0.01 Mt/yr                              | -0.12 Mt/oC                                         |
| 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%
| 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 ppm/yr                         | 0.03 Mt/yr                               | 0.02 Mt/ppmCO$_2$                                   |
| Average growing season temperature* | 0.02°C/yr                           | -0.06 Mt/yr                              | -0.36 Mt/°C                                         |
| Average water demand              | 2.87 mm/yr                          | 0 Mt/yr                                  | 0.07 Mt/1000 mm                                     |
| Average nitrogen fertilizer per unit area | 2.54 kgN/ha/yr                      | 0 Mt/yr                                  | 0 Mt/kgN/ha                                         |

*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).**
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