Supplementary Material-1

**Table S1** Physical and chemical properties of the study area used in model evaluation and application

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Depth (cm) | LL  (cm3 cm-3) | DUL  (cm3 cm-3) | SAT  (cm3 cm-3) | SRGF | BD  (g cm-3) | SOC  (%) |
| 0-15 | 0.078 | 0.244 | 0.55 | 1.00 | 1.46 | 0.58 |
| 15-30 | 0.072 | 0.23 | 0.36 | 0.51 | 1.59 | 0.51 |
| 30-45 | 0.072 | 0.23 | 0.44 | 0.31 | 1.62 | 0.48 |
| 45-60 | 0.072 | 0.23 | 0.43 | 0.15 | 1.62 | 0.47 |
| 60-75 | 0.100 | 0.23 | 0.43 | 0.15 | 1.61 | 0.47 |
| 75-100 | 0.100 | 0.24 | 0.53 | 0.15 | 1.61 | 0.47 |
| 100-150 | 0.100 | 0.21 | 0.53 | 0.15 | 1.49 | 0.47 |

LL: lower limit of soil water; DUL: drained upper limit; SAT: saturation; SRGF: relative root distribution; BD: bulk density;

SOC: soil organic carbon.

**Table S2** Details of crops and data used for calibration and validation

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Crop | Cultivar | Calibration data  (years) | Validation data (years) | Source |
| Rice | Shatabdi | 2013, 2014 | 2015, 2016 | AICRPAM (2016) |
| Mustard | B-9 | 2010-11 | 2011-12 | AICRPAM (2012) |
| Lentil | WBL-77 (Moitree) | 2012-13 | 2013-14 | Maji (2017) |
| Potato | Jyoti | 2010-11, 2011-12 | 2012-13, 2013-14 | AICRPAM (2014) |
| Wheat | PBW-343 | 2013-14, 2014-15 | 2015-16 | Thentu (2016) |
| Maize | Rajkumar | 2012-13 | 2013-14 | Ray (2015) |
| Groundnut | TG-51 | 2007 | 2008 | Fangzauva (2011) |

**Table S3** Summary of 29 GCMs used in this study for climate change impact assessment (Ruane and McDermid, 2017)

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Symbol | GCM | Horizontal resolution | Symbol | GCM | Horizontal resolution |
| A | ACCESS1-0 | 1.25° x 1.875° | P | MIROC-ESM | ~ 2.8° x 2.8° |
| B | BCC-CSM 1-1 | ~ 2.8° x 2.8° | Q | MPI-ESM-LR | ~ 1.9° x 1.875° |
| C | BNU-ESM | ~ 2.8° x 2.8° | R | MPI-ESM-MR | ~ 1.9° x 1.875° |
| D | CanESM2 | ~ 2.8° x 2.8° | S | MRI-CGCM3 | ~ 1.1° x 1.125° |
| E | CCSM4 | ~ 0.9° x 1.25° | T | NorESM1-M | ~ 1.9° x 2.5° |
| F | CESM1-BGC | ~ 0.9° x 1.25° | U | FGOALS-g2 | ~ 2.8° x 2.8° |
| G | CSIRO-Mk3-6-0 | ~ 1.9° x 1.875° | V | CMCC-CM | ~0.75° x 0.75° |
| H | GFDL-ESM2G | ~ 2.0° x 2.5° | W | CMCC-CMS | ~ 1.875° x 1.875° |
| I | GFDL-ESM2M | ~ 2.0° x 2.5° | X | CNRM-CM5 | ~ 1.4° x 1.4° |
| J | HadGEM2-CC | 1.25° x 1.875° | Y | HadGEM2-AO | 1.25° x 1.875° |
| K | HadGEM2-ES | 1.25° x 1.875° | Z | IPSL-CM5B-LR | ~ 2.5° x 1.26° |
| L | INM-CM4.0 | 1.5° x 2.0° | 1 | GFDL-CM3 | 2° x 2.5° |
| M | IPSL-CM5A-LR | ~ 1.9° x 3.75° | 2 | GISS-E2-R | 2° x 2.5° |
| N | IPSL-CM5A-MR | ~ 1.3° x 2.5° | 3 | GISS-E2-H | 2° x 2.5° |
| O | MIROC5 | ~ 1.4° x 1.4° |  |  |  |

**Table S4** Crop management details used for sequence analysis in DSSAT

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Sequence | Crop | Planting date | Plant density (plant m-2) | Row space (cm) |
| R-Mu-G | Rice  Mustard  Groundnut | 7-Jul  31-Oct  15-Feb | 36  39  33 | 20  30  30 |
| R-L-G | Rice  Lentil  Groundnut | 7-Jul  31-Oct  27-Feb | 36  35  33 | 20  30  30 |
| R-P-G | Rice  Potato  Groundnut | 7-Jul  31-Oct  20-Feb | 36  13  33 | 20  50  30 |
| R-W-G | Rice  Wheat  Groundnut | 7-Jul  31-Oct  20-Mar | 36  250  33 | 20  25  30 |
| R-Mz-G | Rice  Maize  Groundnut | 7-Jul  31-Oct  27-Mar | 36  5.5  33 | 20  60  30 |
| R-Mu-Fl | Rice  Mustard  Fallow | 7-Jul  31-Oct | 36  39 | 20  30 |

*R-Mu-G: Rice-Mustard-Groundnut*

*R-L-G: Rice-Lentil-Groundnut*

*R-P-G: Rice-Potato-Groundnut*

*R-W-G: Rice-Wheat-Groundnut*

*R-Mz-G: Rice-Maize-Groundnut*

*R-Mu-Fl: Rice-Mustard-Fallow*

**Table S5** Time series prices of crops used in the study to estimate rice equivalent yield

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
|  | Price (Rs kg-1) | | | | | | |
| Year | Rice | Groundnut | Mustard | Lentil | Wheat | Maize | Potato |
| 1991 | 2.3 | 6.5 | 6.7 | 6.2 | 2.8 | 2.1 | 1.8 |
| 1992 | 2.7 | 7.5 | 7.6 | 6.7 | 3.3 | 2.5 | 2.1 |
| 1993 | 3.1 | 8.0 | 8.1 | 7.2 | 3.5 | 2.7 | 2.9 |
| 1994 | 3.4 | 8.6 | 8.3 | 7.7 | 3.6 | 2.9 | 3.2 |
| 1995 | 3.6 | 9.0 | 8.6 | 8.3 | 3.8 | 3.1 | 3.7 |
| 1996 | 3.8 | 9.2 | 8.9 | 9.0 | 4.8 | 3.2 | 5.1 |
| 1997 | 4.2 | 9.8 | 9.4 | 9.6 | 5.1 | 3.6 | 5.4 |
| 1998 | 4.4 | 10.4 | 10.0 | 10.4 | 5.5 | 3.9 | 6.9 |
| 1999 | 4.9 | 11.6 | 11.0 | 11.2 | 5.8 | 4.2 | 4.4 |
| 2000 | 5.1 | 12.2 | 12.0 | 12.0 | 6.1 | 4.5 | 3.7 |
| 2001 | 5.3 | 13.4 | 13.0 | 13.0 | 6.2 | 4.9 | 6.1 |
| 2002 | 5.3 | 13.6 | 13.3 | 13.2 | 6.2 | 4.9 | 5.9 |
| 2003 | 5.5 | 14.0 | 16.0 | 15.0 | 6.3 | 5.1 | 4.1 |
| 2004 | 5.6 | 15.0 | 17.0 | 15.3 | 6.4 | 5.3 | 5.7 |
| 2005 | 5.7 | 15.2 | 17.2 | 15.4 | 6.5 | 5.4 | 6.3 |
| 2006 | 5.8 | 15.2 | 17.2 | 15.5 | 8.5 | 5.4 | 6.9 |
| 2007 | 7.5 | 15.5 | 18.0 | 17.0 | 10.0 | 6.2 | 7.7 |
| 2008 | 9.0 | 21.0 | 18.3 | 18.7 | 10.8 | 8.4 | 5.6 |
| 2009 | 10.5 | 21.0 | 18.3 | 18.7 | 11.0 | 8.4 | 12.0 |
| 2010 | 10.0 | 23.0 | 18.5 | 22.5 | 11.7 | 8.8 | 6.7 |
| 2011 | 10.8 | 27.0 | 25.0 | 28.0 | 12.9 | 9.8 | 7.1 |
| 2012 | 12.5 | 37.0 | 30.0 | 29.0 | 13.5 | 11.8 | 9.9 |
| 2013 | 13.1 | 40.0 | 30.5 | 29.5 | 14.0 | 13.1 | 7.8 |
| 2014 | 13.6 | 40.0 | 31.0 | 30.8 | 14.5 | 13.1 | 12.9 |
| 2015 | 14.1 | 40.3 | 33.5 | 34.0 | 15.3 | 13.3 | 6.3 |
| 2016 | 14.7 | 42.2 | 37.0 | 39.5 | 16.3 | 13.7 | 13.7 |
| 2017 | 15.5 | 44.5 | 40.0 | 42.5 | 17.4 | 14.3 | 5.1 |
| 2018 | 17.5 | 48.9 | 42.0 | 44.8 | 18.4 | 17.0 | 9.3 |
| 2019 | 18.2 | 50.9 | 44.3 | 48.0 | 19.3 | 17.6 | 9.6 |
| 2020 | 18.7 | 52.8 | 46.5 | 51.0 | 19.8 | 18.5 | 18.5 |

**Table S6** Scale of relative importance for analytic hierarchy process (Saaty, 1980)

|  |  |  |
| --- | --- | --- |
| Intensity of  Importance | Definition | Explanation |
| 1 | Equal importance | Two elements contribute equally to the property |
| 3 | Moderate importance of one over another | Experience and judgment slightly favour one over the other |
| 5 | Essential or strong importance | Experience and judgment strongly favour one over another |
| 7 | Very strong importance | An element is strongly favoured and its dominance is demonstrated in practice |
| 9 | Extreme importance | The evidence favouring one element over another is one of the highest possible order of affirmation |
| 2,4,6,8 | Intermediate values between two adjacent  judgments | Comprise is needed between two judgments |
| Reciprocals | When activity *j* compared to *k* is assigned one of the above numbers, the activity *k* compared to *j* is assigned its reciprocal | |

**Table S7** Priority matrix created for estimation of weights for TOPSIS analysis

|  |  |  |  |
| --- | --- | --- | --- |
|  | Yield | Nitrogen fixed | ETa |
| Yield | 1 | 9 | 5 |
| Nitrogen fixed | 0.11 | 1 | 0.25 |
| ETa | 0.20 | 4 | 1 |

**Table S8** Calibrated genetic coefficients for rice cultivar Shatabdi

|  |  |  |
| --- | --- | --- |
| Parameter | Description of genetic coefficient | Calibrated value |
| P1 | Time period (in degree days) during basic vegetative phase of the crop | 800.4 |
| P2R | Extent to which phasic development leading to panicle initiation is delayed (expressed as GDD in degree days) for each hour increase in photoperiod above P2O | 60 |
| P5 | Time period in GDD (degree days) from beginning of grain filling (3 to 4 days after flowering) to physiological maturity with a base temperature of 9 °C | 300.8 |
| P2O | Critical photoperiod or the longest day length (in hours) at which the development occurs at a maximum rate. | 13.5 |
| G1 | Potential spikelet number coefficient as estimated from the number of spikelets per g of main culm dry weight at anthesis | 59 |
| G2 | Single grain weight (g) under ideal growing conditions | 0.03 |
| G3 | Tillering coefficient (scaler value) relative to IR64 cultivar under ideal growing conditions | 1 |
| G4 | Temperature tolerance coefficient | 0.8 |

Table S9 Calibrated genetic coefficients for lentil cultivar Moitree

| Parameter | Description of genetic coefficient | Calibrated value |
| --- | --- | --- |
| CSDL | Critical Short Day Length below which reproductive development progresses with daylength effect (hour) | 11.4 |
| PPSEN | Slope of the relative response of development to photoperiod with time | -0.143 |
| EM-FL | Time between plant emergence and flower appearance (R1) | 40 |
| FL-SH | Time between first flower and first pod (R3) (photothermal days) | 6.5 |
| FL-SD | Time between first flower and first seed (R5) (photothermal days) | 15.5 |
| SD-PM | Time between first seed (R5) and physiological maturity (R7) | 33.5 |
| FL-LF | Time between first flower (R1) and end of leaf expansion | 40 |
| LFMAX | Maximum leaf photosynthesis rate at 30 C, 350 vpm CO2, and high light (mg CO2/m2-s) | 1 |
| SLAVR | Specific leaf area of cultivar under standard growth conditions (cm2/g) | 220 |
| SIZLF | Maximum size of full leaf (three leaflets) (cm2) | 10 |
| XFRT | Maximum fraction of daily growth that is partitioned to seed + shell | 0.96 |
| WTPSD | Maximum weight per seed (g) | 0.18 |
| SFDUR | Seed filling duration for pod cohort at standard growth conditions | 26 |
| SDPDV | Average seed per pod under standard growing conditions (#/pod) | 1 |
| PODUR | Time required for cultivar to reach final pod load under optimal conditions | 23 |
| THRSH | The maximum ratio of (seed/(seed + shell)) at maturity | 78 |

Table S10 Calibrated genetic coefficients for potato cultivar Jyoti

|  |  |  |
| --- | --- | --- |
| Parameter | Description of genetic coefficient | Calibrated value |
| G2 | Leaf area expansion rate after tuber initiation (cm2/m2 d) | 2000 |
| G3 | Potential tuber growth rate (g/m2 d) | 22 |
| PD | Index that supresses tuber growth during the period that immediately follows tuber induction | 0.8 |
| P2 | Tuber initiation sensitivity to long photoperiods | 0.6 |
| TC | Upper critical temperature for tuber initiation (°C) | 17 |

Table S11 Calibrated genetic coefficients for wheat cultivar PBW-343

|  |  |  |
| --- | --- | --- |
| Parameter | Description of genetic coefficient | Calibrated value |
| P1V | Days, optimum vernalizing temperature, required for vernalization | 12.67 |
| P1D | Photoperiod response (% reduction in rate/10 h drop in pp) | 58.16 |
| P5 | Grain filling (excluding lag) phase duration (°C.d) | 930 |
| G1 | Kernel number per unit canopy weight at anthesis (#/g) | 30 |
| G2 | Standard kernel size under optimum conditions (mg) | 35 |
| G3 | Standard, non-stressed mature tiller wt (incl grain) (g dwt) | 1 |
| PHINT | Interval between successive leaf tip appearances (°C.d) | 97 |

**Table S12** Calibrated genetic coefficients for *rabi* maize cultivar Rajkumar

|  |  |  |
| --- | --- | --- |
| Parameter | Description of genetic coefficient | Calibrated value |
| P1 | Thermal time from seedling emergence to the end of the juvenile phase | 440 |
| P2 | Extent to which development (expressed as days) is delayed for each hour increase in photoperiod above the longest photoperiod at which development proceeds at a maximum rate | 0.8 |
| P5 | Thermal time from silking to physiological maturity | 740 |
| G2 | Maximum possible number of kernels per plant | 907 |
| G3 | Kernel filling rate during the linear grain filling stage and under optimum conditions (mg/day) | 15 |
| PHINT | Phylochron interval | 38 |

**Table S13** Calibrated genetic coefficients for mustard cultivar B-9

|  |  |  |
| --- | --- | --- |
| Parameter | Description of genetic coefficient | Calibrated value |
| CSDL | Critical Short Day Length below which reproductive development progresses with no daylength effect (hour) | 20 |
| PPSEN | Slope of the relative response of development to photoperiod with time | -0.008 |
| EM-FL | Time between plant emergence and flower appearance (R1) | 28.5 |
| FL-SH | Time between first flower and first pod (R3) (photothermal days) | 10 |
| FL-SD | Time between first flower and first seed (R5) (photothermal days) | 16.5 |
| SD-PM | Time between first seed (R5) and physiological maturity (R7) | 23.5 |
| FL-LF | Time between first flower (R1) and end of leaf expansion | 3 |
| LFMAX | Maximum leaf photosynthesis rate at 30 C, 350 vpm CO2, and high light (mg CO2/m2-s) | 1.28 |
| SLAVR | Specific leaf area of cultivar under standard growth conditions (cm2/g) | 330 |
| SIZLF | Maximum size of full leaf (three leaflets) (cm2) | 100 |
| XFRT | Maximum fraction of daily growth that is partitioned to seed + shell | 1 |
| WTPSD | Maximum weight per seed (g) | 0.007 |
| SFDUR | Seed filling duration for pod cohort at standard growth conditions | 20 |
| SDPDV | Average seed per pod under standard growing conditions (#/pod) | 22 |
| PODUR | Time required for cultivar to reach final pod load under optimal conditions (photothermal days) | 10 |

**Table S14** Calibrated genetic coefficients for groundnut cultivar TG-51

|  |  |  |
| --- | --- | --- |
| **Parameter** | **Description of genetic coefficient** | **Calibrated value** |
| CSDL | Critical Short Day Length below which reproductive development progresses with no daylength effect (for shortday plants) (hour) | 11.84 |
| EM-FL | Time between plant emergence and flower appearance (Photothermal days) | 13.7 |
| FL-SH | Time between first flower and first pod (photothermal days) | 7 |
| FL-SD | Time between first flower and first seed (photothermal days) | 13.5 |
| SD-PM | Time between first seed (R5) and physiological maturity (photothermal days) | 43.37 |
| FL-LF | Time between first flower and end of leaf expansion (photothermal days) | 47 |
| LFMAX | Maximum leaf photosynthesis rate at 30 C, 350 vpm CO2, and high light (mg CO2/m2-s) | 1.28 |
| SLAVR | Specific leaf area of cultivar under standard growth conditions (cm2/g) | 240 |
| SIZLF | Maximum size of full leaf (three leaflets) (cm2) | 16 |
| XFRT | Maximum fraction of daily growth that is partitioned to seed + shell | 0.78 |
| WTPSD | Maximum weight per seed (g) | 0.58 |
| SFDUR | Seed filling duration for pod cohort at standard growth conditions (photothermal days) | 25 |
| SDPDV | Average seed per pod under standard growing conditions (#/pod) | 1.65 |
| PODUR | Time required for cultivar to reach final pod load under optimal conditions (photothermal days) | 13 |
| THRSH | The maximum ratio of (seed/(seed + shell)) at maturity. | 78 |
| SDPRO | Fraction protein in seeds (g(protein)/g(seed)) | 0.27 |
| SDLIP | Fraction oil in seeds (g(oil)/g(seed)) | 0.51 |

**Table S15** Validation metrics for the calibrated crop models

| Crop |  | Days to anthesis | Days to maturity | Tops weight | Yield |
| --- | --- | --- | --- | --- | --- |
| Rice | Obs | 79 | 103 | 7604 | 4220 |
| Sim | 81 | 103 | 7470 | 4273 |
| RMSE | 3.7 | 4.2 | 1492 | 1099 |
| nRMSE | 4.7 | 4.1 | 19.6 | 26.0 |
| MBE | 2.5 | -0.1 | -134.3 | 52.6 |
| Lentil | Obs | 54 | 112 | 4178 | 1358 |
| Sim | 56 | 106 | 4495 | 1514 |
| RMSE | 4.7 | 6.7 | 448 | 332 |
| nRMSE | 8.8 | 6 | 10.7 | 24.5 |
| MBE | 1.5 | -5.7 | 156.3 | 317.3 |
| Groundnut | Obs | 30 | 95 | 9051 | 2718 |
| Sim | 30 | 93 | 7448 | 2697 |
| RMSE | 1.3 | 3.3 | 1750 | 418 |
| nRMSE | 4.3 | 3.5 | 19.3 | 15.4 |
| MBE | 0.3 | 1.8 | -1603 | 21.2 |
| Maize | Obs | 105 | 139 | 13286 | 7979 |
| Sim | 105 | 139 | 14475 | 8081 |
| RMSE | 1.6 | 3.2 | 2060 | 1204 |
| nRMSE | 1.5 | 2.3 | 15.5 | 15.1 |
| MBE | 0.1 | 0.1 | 1189 | 102 |
| Wheat | Obs | 91 | 131 | 6603 | 2402 |
| Sim | 91 | 130 | 7835 | 2767 |
| RMSE | 0.7 | 1.4 | 1394 | 457 |
| nRMSE | 0.7 | 1.1 | 21.1 | 19.0 |
| MBE | -0.4 | -1.1 | 1231 | 365.5 |

Tops weight, yield are in kg ha-1; RMSE and MBE have same unit as the parameter; nRMSE is in per cent

**Table S16** Validation metrics for mustard

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Crop |  | Days to anthesis | Days to maturity | Canopy height | Yield |
| Mustard | Obs | 44 | 93 | 1.2 | 978 |
| Sim | 44 | 93 | 1 | 926 |
| RMSE | 1.3 | 2.8 | 0.15 | 89.2 |
| nRMSE | 2.9 | 3.0 | 13.0 | 9.1 |
| MBE | -0.3 | 0.1 | -0.2 | -52 |

Yield is in kg ha-1; Canopy height is in m; RMSE and MBE have same unit as the parameter; nRMSE is in per cent

**Table S17** Validation metrics for potato

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Crop |  | Days to tuber initiation | Tuber fresh weight | Tuber dry yield |
| Potato | Obs | 35 | 20.5 | 4014 |
| Sim | 37 | 19.9 | 3972 |
| RMSE | 3.2 | 1.1 | 350.3 |
| nRMSE | 9.3 | 5.6 | 8.7 |
| MBE | 2.5 | -0.7 | -42 |

Tuber fresh weight is in Mg ha-1; Tuber fresh weight is in kg ha-1; RMSE and MBE have same unit as the parameter; nRMSE is in per cent