***Supplementary files***

**Towards an improved representation of the relationship between root traits and nitrogen losses in process-based models**

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**Table S1.** Process-based models commonly used for simulations of crop production and nitrogen losses in agroecosystems.

|  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| ***Category*** | ***Models' name*** | ***Crop growth*** | ***Root traits*** | ***Soil C dynamics*** | ***Soil N dynamics*** | ***Soil water flow*** | ***NO3- leaching*** | ***N2O emission*** | ***Spatial resolution*** | ***Temporal resolution*** | ***References*** |
| Crop models | APSIM | √ | √ | √ | √ | √ | √ | √ | Plot | Daily | Wang et al., 2002; Keating et al., 2003 |
| AQUACROP | √ | √ | × | × | √ | × | × | Plot | Daily | Raes et al., 2009; Steduto et al., 2009 |
| CropSyst | √ | √ | × | × | √ | × | × | Plot | Daily | Stöckle et al., 2003; Camargo et al., 2016 |
| DSSAT\_CERES | √ | √ | √ | √ | √ | √ | √ | Plot | Daily | Jones et al., 2003 |
| DSSAT\_CROPSIM | √ | √ | √ | √ | √ | √ | √ | Plot | Daily | Jones et al., 2003 |
| EPIC | √ | √ | √ | √ | √ | √ | √ | Plot/Regional | Daily | Williams et al., 1989 |
| Expert-N-CERES | √ | √ | √ | √ | √ | √ | √ | Plot | Daily | Frolking et al., 1999; Priesack et al., 2006 |
| Expert-N-GECROS | √ | √ | √ | √ | √ | √ | √ | Plot | Daily | Priesack et al., 2006; Biernath et al., 2011 |
| Expert-N-SPASS | √ | √ | √ | √ | √ | √ | √ | Plot | Daily | Priesack et al., 2006 |
| Expert-N-SUCROS | √ | √ | √ | √ | √ | √ | √ | Plot | Daily | Priesack et al., 2006 |
| FASSET | √ | √ | √ | √ | √ | √ | √ | Farm | Daily | Olesen et al., 2002; Doltra et al., 2015 |
| GLAM | √ | × | × | × | √ | × | × | Regional | Daily | Challinor et al., 2004 |
| HERMES | √ | √ | × | √ | √ | √ | √ | Plot | Daily | Kersebaum, 2007, 2015 |
| INFOCROP | √ | √ | √ | √ | √ | √ | √ | Plot | Daily | Aggarwal et al., 2006 |
| LINTUL | √ | √ | × | √ | √ | × | × | Plot | Daily | Shibu et al., 2010 |
| LOBELL | √ | √ | × | × | × | × | × | NA | NA | Gourdji et al., 2013; Asseng et al., 2015 |
| LPJmL | √ | √ | √ | × | √ | × | × | Global | Monthly | Gerten et al., 2004; Beringer et al., 2011 |
| MCWLA-Wheat | √ | √ | × | × | √ | × | × | Plot | Daily | Tao et al., 2009 |
| MONICA | √ | √ | √ | √ | √ | √ | √ | Plot | Daily | Nendel et al., 2011 |
| OLEARY | √ | √ | √ | √ | √ | √ | × | Plot | Daily | O'Leary et al., 1985 |
| SALUS | √ | √ | √ | √ | √ | √ | √ | Plot | Daily | Basso et al., 2006 |
| SIMPLACE | √ | √ | √ | √ | √ | √ | × | Plot | Daily | Gaiser et al., 2013 |
| SIRIUS | √ | √ | × | √ | √ | √ | × | Plot | Daily | Jamieson et al., 1998 |
| SiriusQuality | √ | × | × | √ | √ | × | × | Plot | Daily | Ferrise et al., 2010 |
| STICS | √ | √ | × | √ | √ | √ | √ | Plot | Daily/Yearly | Brisson et al., 2003 |
| WHEATGROW | √ | √ | × | √ | √ | × | × | Plot | Daily | Cao et al.,2015 |
| WOFOST | √ | √ | × | × | √ | × | × | Plot | Daily | De wit et al., 2019 |
| Ecosys | √ | √ | √ | √ | √ | × | × | Ecosystem | Hourly | Grant et al., 2011 |
| SSM-Wheat | √ | √ | × | × | √ | × | × | Plot | Daily | Manschadi et al., 2022 |
| ARMOSA | √ | √ | √ | √ | √ | √ | √ | Plot | Daily | Perego et al., 2013 |
| LINTUL-FAST | √ | √ | × | √ | × | × | × | Regional | Daily | Angulo et al., 2013 |
| Biogeochemical models | DNDC | √ | √ | √ | √ | √ | √ | √ | Plot | Daily/Yearly | Grant et al., 2015 |
| DayCent | √ | √ | √ | √ | √ | √ | √ | Plot | Daily/Yearly | Grant et al., 2015 |
| DAISY | √ | √ | √ | √ | √ | √ | √ | Plot | Hourly | Hansen et al., 1991 |
| Biome\_BGC | √ | √ | √ | √ | √ | √ | √ | Plot/Regional | Daily | Thornton et al., 2002 |
| CANDY | √ | √ | √ | √ | √ | √ | √ | Plot | Daily | Franko et al., 1995 |
| CENTURY | √ | √ | √ | √ | √ | √ | √ | Plot | Monthly/Yearly | Parton et al., 1993 |
| SUNDIAL | √ | NA | NA | NA | √ | √ | √ | Plot | Weekly/Yearly | Bradbury et al., 1993 |
| DLEM | √ | × | √ | √ | √ | √ | √ | Plot/Regional | Daily/Yearly | Tian et al., 2010 |
| NCSOIL | √ | NA | NA | NA | √ | √ | √ | Plot/Farm | Daily | Molina et al., 1983 |
| CHN | √ | √ | √ | √ | √ | √ | √ | Plot | Daily | Laberdesque et al., 2017 |
| MOMOS | √ | √ | √ | √ | √ | √ | √ | Plot | Daily | Kherif et al., 2021 |
| SPACSYS | √ | √ | √ | √ | √ | √ | √ | Plot | Daily | Wu et al., 2007 |
|  | WHCNS | √ | × | √ | √ | √ | √ | √ | Plot | Daily | Liang et al., 2016 |
| Agro-hydrological models | APEX | √ | √ | √ | √ | √ | √ | √ | Regional | Daily | Gassman et al., 2010 |
| HYDRUS | × | × | × | × | √ | √ | √ | Plot/Regional | Secondly/Yearly | Šimůnek et al., 2006 |
| NLEAP | √ | × | × | √ | √ | √ | × | Plot | Monthly | Karaman et al., 2005 |
| GLEAMS | √ | × | × | √ | √ | √ | √ | Regional | Daily | Knisel et al., 1995 |
| LEACHM | √ | √ | × | √ | √ | √ | × | Plot | Daily | Asada et al., 2013 |
| RZWQM | √ | √ | √ | √ | √ | √ | × | Plot | Hourly/Yearly | Cameira et al., 1998 |
| NTRM | √ | √ | × | √ | √ | √ | √ | Plot | Daily | Radke et al., 1991 |
| HSPF | × | × | × | √ | × | √ | × | Regional | Daily/Monthly | Liu et al., 2021 |
| SWAT | × | × | √ | √ | √ | √ | √ | Regional | Daily | Vaghefi et al., 2017 |
| WNMM | √ | √ | √ | √ | √ | √ | √ | Plot/Regional | Daily | Li et al., 2007 |

**2. Sensitivity analysis of root traits in models**

***a. Overview of root traits in models***

We classified the root traits with potential to affect N losses into three categories depending on the possible mechanisms related to N cycling: (1) architectural and morphological, (2) physiological and biochemical, and (3) stress factors (Table S2). The first category normally contains the traits related to the three-dimensional arrangement of roots, diversity connections and topology between roots, and the physical changes/components, such as root depth, root weight, root/shoot ratio, root length density, root distribution shape/branching, and proportion of root senescence (Table S2). The second category generally covers the traits related to the chemical elements in roots, such as N and C, the uptake capacity, such as soluble N and water, and physiological characteristics such as root respiration. The last category covers the effect of soil water, soil oxygen, and soil N on root growth.

**Table S2.** Root traits in a selection of process-based models (APSIM, DSSAT, DNDC, Daisy).

|  |  |  |
| --- | --- | --- |
| *Trait Category* | *Trait* | *Models* |
| Architectural and morphological | Root depth growth rate | DSSAT, APSIM |
| Root lignin | DSSAT |
| Root length weight ratio | DSSAT |
| Root senescence | DSSAT |
| Root respiration fraction | DSSAT |
| Root length/Root depth growth ratio | DSSAT, APSIM |
| Root weight at emergence | APSIM |
| Initial depth of roots | APSIM |
| Root branching factor | APSIM |
| Fraction of root lost at harvest | APSIM |
| Root/shoot ratio | APSIM, Daisy |
| Maximum root depth | APSIM, Daisy,DNDC\_CAN |
| Root weight (residue) | APSIM |
| Root fraction | DNDC\_CAN |
| The shape of root density distribution | DNDC\_CAN |
| Penetration rate parameter | Daisy |
| Maximum penetration depth | Daisy |
| Physiological and biochemical | Reserves above which CH2O overflows to roots | DSSAT |
| NO3- uptake/Root length | DSSAT, Daisy |
| NH4+ uptake/Root length | DSSAT, Daisy |
| Minimum root N concentration | DSSAT, APSIM, Daisy |
| Critical root N concentration | DSSAT, APSIM, Daisy |
| Maximum root N concentration | APSIM, Daisy |
| Initial N concentration in the root | APSIM |
| Fraction detached from root of a dead plant per day | APSIM |
| Fraction of senesced root detached each day from live plants | APSIM |
| Dry matter fraction senesced for the root of canopy senesced | APSIM |
| Root C/N ratio (residue) | APSIM |
| N concentration factor on root growth | DSSAT |
| Maximum water uptake rate | DSSAT |
| Root C/N ratio | DNDC\_CAN |
| Fraction of assimilate for growth that goes to the roots | Daisy |
| Maintenance respiration coefficient of root | Daisy |
| Conversion efficiency of root | Daisy |
| Stress factor | Air filled pore space factor for root depth growth | APSIM |
| Water stress factor for root depth growth | APSIM |
| Temperature effect on root advance | APSIM |
| Nitrogen concentration factor on root senescence | APSIM |
| Soil factor on root growth | DSSAT |
| Water factor on root growth | DSSAT |

Note: **for DSSAT, the root parameters are based on the CERES model.**

***b. Field datasets used for sensitivity analysis***

For DSSAT, detailed information about the experimental data used is reported in Cammarano et al. (2019). Briefly, the field experiment was carried out at the James Hutton Institute experimental farm in Dundee (56.45°N, 3.07°W), Scotland. The soil texture is loam, and Dundee belongs to a marine west coast and warm summer climate. This experiment adopted the spring barley cultivar Concerto and consisted of 4 treatments which included 2 levels of N (0 and 120 kg N per ha) and 2 levels of water (irrigated and rainfed). Detailed calibration and validation procedures are also provided in Cammarano et al. (2019), which showed good performance of DSSAT in simulating the phenology, biomass, soil water content and N uptake of barley.

For APSIM, one field experiment was carried out at the Aarhus University experimental station in Foulum (56.30° N, 9.35° E) of Denmark (Vogeler et al., 2021). The soil texture was sandy loam, with 9.9% clay, 11.5% silt, 41.5% fine sand, and 34.5% coarse sand. The climate in FU is humid and temperate, the long-term average annual rainfall is around 663 mm and the average annual temperature is 8.3 oC. The experiments were carried out during 2016 to 2019. The experiment used spring barley with an N rate of 140 kg N per ha. Detailed calibration and validation procedures are provided in Vogeler et al. (2023), which showed good performance of APSIM in simulating the biomass, barley N uptake and NO3- leaching.

For DNDCv.CAN, the data was obtained from an experiment carried out at the Normandin Research Farm of Agriculture and Agri-Food Canada (48.85°N, 72.54°W) in the province of Quebec, Canada (Maillard et al., 2016). The area is characterized as having a cool temperature and moist climate, with mean annual temperature of 1.1oC and mean annual precipitation of 849 mm. The soil texture is silty clay soil, with a bulk density of 1.3 g per cm3. A split-split plot factorial experiment was initiated in 1989 with two crop rotations (continuous spring barley, and a 3-yr cereal perennial forage rotation) as main plots, two primary tillage practices (CP: chisel plowing, and MP: moldboard plowing) as sub-plots, two nutrient sources (MIN: mineral fertilizer, and LDM: liquid dairy manure) as sub-sub-plots, and four replicates. For the whole period of treatment application (1990-2010), the plots with the MIN treatment, the one we selected for our modelling exercise for consistency with the other datasets, barely received 70 kg N per ha. The results of the model calibration and validation can be found in Jégo et al. (2024).

For Daisy, the field experiment was also conducted at the Aarhus University experimental station in Foulum, Denmark, and included two winter wheat growing seasons (2012-2014) (Gyldengren et al., 2020). The soil at Foulum is a sandy loam, the climate is humid and temperate, and the wheat cultivar was Hereford. The N fertilizer rate during the experiment was 150 kg N per ha in 2013, and 165 kg N per ha in 2014. The results for the Daisy calibration and validation were reported in Gyldengren et al. (2020).

A screenshot of a computer

Description automatically generated

**Figure S1.** Pearson correlations between nitrogen losses (NO3- leaching and N2O emissions) and crop N uptake among root traits in the different models.

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