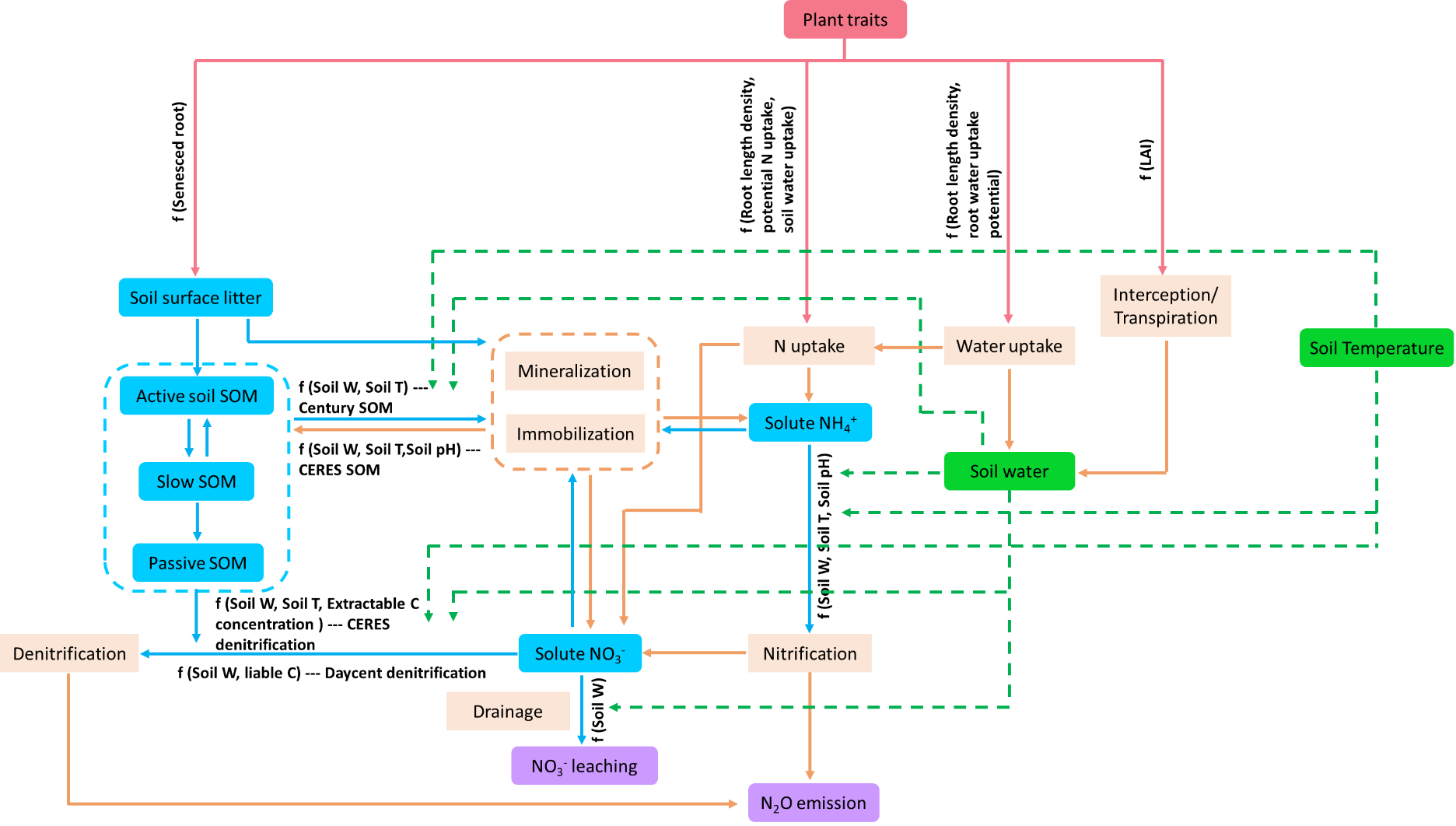
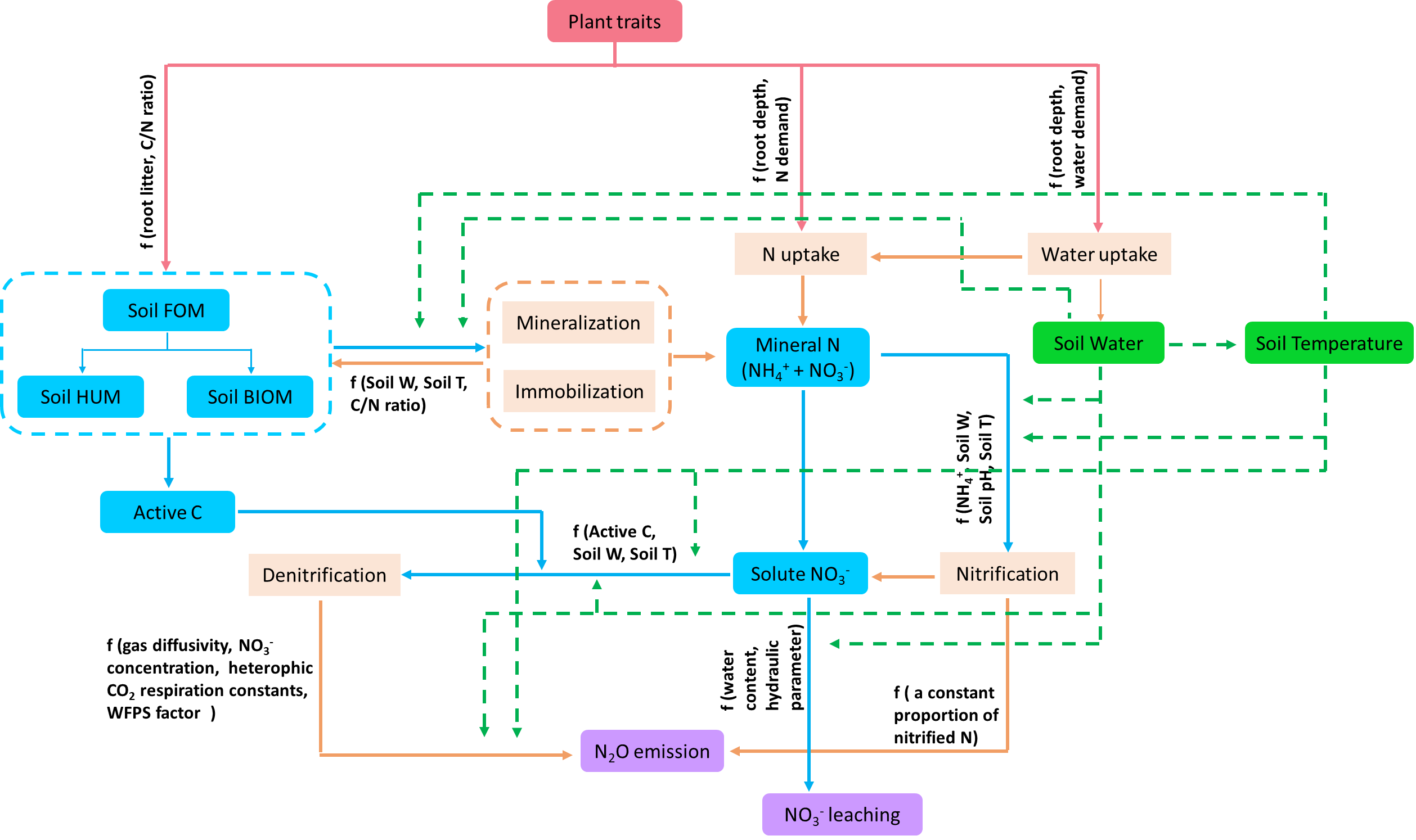
**A group of graphs with different colored dots

Description automatically generated**

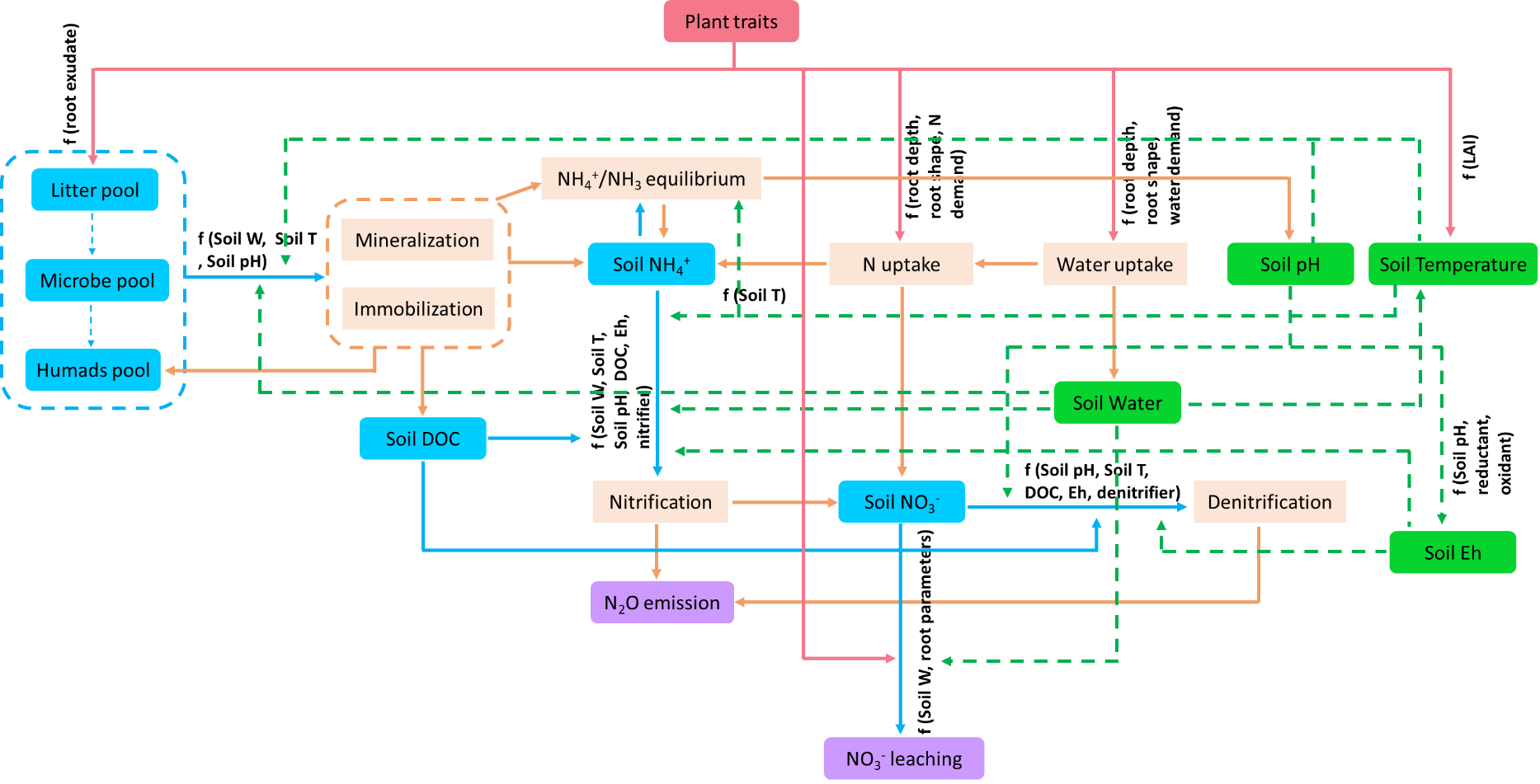
**Fig. 1.** Examples of quantitative relationships between nitrogen losses (N2O emissions and NO3- leaching) and root traits based on metadata from experiments (Table 1).



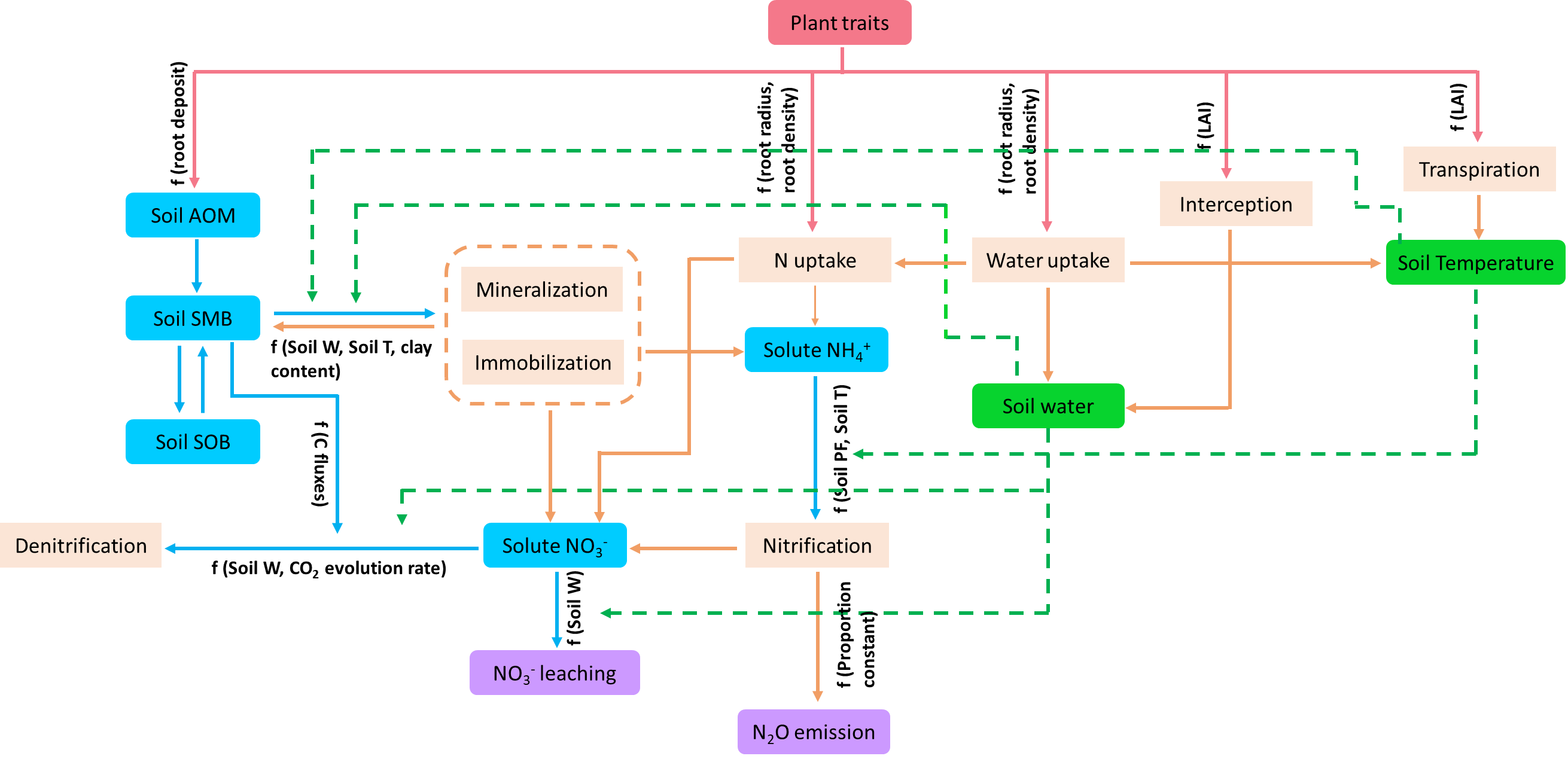
**Fig. 2**. Conceptual diagram depicting the potential effects of plant traits on nitrogen losses described in DSSAT. The red color box indicates plant traits; red solid arrows indicate the possible impact of plant traits; blue color boxes indicated the soil substrates; blue solid arrows indicate the possible biochemical processes in which the substrates are directly involved; green color boxes indicates soil abiotic factors and green dash arrows indicate possible processes affected by abiotic factors; light orange boxes indicate process related to soil C, N and water dynamics; light orange solid arrows indicate possible consequence of changes in processes.



**Fig. 3**. Conceptual diagram depicting the potential effects of plant traits on nitrogen losses described in APSIM. The red color box indicates plant traits; red solid arrows indicate the possible impact of plant traits; blue color boxes indicated the soil substrates; blue solid arrows indicate the possible biochemical processes in which the substrates are directly involved; green color boxes indicates soil abiotic factors and green dash arrows indicate possible processes affected by abiotic factors; light orange boxes indicate process related to soil C, N and water dynamics; light orange solid arrows indicate possible consequence of changes in processes.



**Fig. 4**. Conceptual diagram depicting the potential effects of plant traits on nitrogen losses described in DNDCv.CAN. The red color box indicates plant traits; red solid arrows indicate the possible impact of plant traits; blue color boxes indicated the soil substrates; blue solid arrows indicate the possible biochemical processes in which the substrates are directly involved; green color boxes indicates soil abiotic factors and green dash arrows indicate possible processes affected by abiotic factors; light orange boxes indicate process related to soil C, N and water dynamics; light orange solid arrows indicate possible consequence of changes in processes.



**Fig. 5**. Conceptual diagram depicting the potential effects of plant traits on nitrogen losses described in Daisy. The red color box indicates plant traits; red solid arrows indicate the possible impact of plant traits; blue color boxes indicated the soil substrates; blue solid arrows indicate the possible biochemical processes in which the substrates are directly involved; green color boxes indicates soil abiotic factors and green dash arrows indicate possible processes affected by abiotic factors; light orange boxes indicate process related to soil C, N and water dynamics; light orange solid arrows indicate possible consequence of changes in processes.

A graph of different colored lines

Description automatically generated

**Fig. 6**. Sensitivity analysis showing the potential effects of key root traits on nitrogen losses and crop nitrogen uptake in the models APSIM, DNDCvCAN, DSSAT, and Daisy, for spring barley (BA) or winter wheat (WH).

**Table 1**. Qualitative summary of relationships between root traits and nitrogen losses and plant nitrogen uptake reported in experiments.

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| *N cycling* | | *Trait* | | *Direction of N loss with increasing trait values* | *Scale* | *Plant/crop* | *References* |
| N loss | N2O emission | Architectural and morphological | Root biomass | Increase | Field | Rice | Baruah et al., 2010 |
| Decrease | Greenhouse Mesocosm | Grass | Oram et al., 2020 |
| Specific root length | Decrease | Greenhouse Mesocosm | Grass | Abalos et al., 2014, 2018; Oram et al., 2020; Fernandez Pulido et al., 2023 |
| Root Diameter | Increase | Greenhouse Mesocosm | Grass | Abalos et al., 2014, 2018; Fernandez Pulido et al., 2023 |
| Root length density | Decrease | Greenhouse Mesocosm | Grass | Abalos et al., 2018; Fernandez Pulido et al., 2023 |
| Root dry matter content | Increase | Greenhouse Mesocosm | Grass | Fernandez Pulido et al., 2023 |
| Root/shoot ratio | Increase | Greenhouse Mesocosm | Grass | Abalos et al., 2014 |
| Root tissue density | Decrease | Greenhouse Mesocosm | Grass | Oram et al., 2020 |
| Physiological and chemical | Root C/N ratio | Decrease | Greenhouse Mesocosm | Grass | Oram et al., 2020 |
| Root N concentration | Increase | Greenhouse Mesocosm | Grass | Oram et al., 2020; Fernandez Pulido et al., 2023 |
| Root C concentration | Decrease | Greenhouse Mesocosm | Grass | Oram et al., 2020 |
| NO3- leaching | Architectural and morphological | Deep root biomass | Decrease | Sand\_tube | Wheat | Ehdaie et al., 2010 |
| Shallow root biomass | Decrease | Sand\_tube | Wheat | Ehdaie et al., 2010 |
| Root/shoot ratio | Decrease | Sand\_tube | Wheat | Ehdaie et al., 2010 |
| Greenhouse Mesocosm | Sugarcane | Takaragawa et al., 2022 |
| 0-0.3 m root biomass | Decrease | Greenhouse Mesocosm | Sugarcane | Takaragawa et al., 2022 |
| 0.3-1.0 m root biomass | Decrease | Greenhouse Mesocosm | Sugarcane | Takaragawa et al., 2022 |
| 0-0.1 m root biomass | Decrease | Greenhouse Mesocosm | Grass | Popay & Crush, 2011 |
| 0.1-0.2 m root biomass | Decrease | Greenhouse Mesocosm | Grass | Popay & Crush, 2011 |
| > 0.2 m root biomass | Decrease | Greenhouse Mesocosm | Grass | Popay & Crush, 2011 |
| Root biomass | Decrease | Sand\_tube | Wheat | Ehdaie et al., 2010 |
| Greenhouse Mesocosm | Grass | Popay & Crush, 2011; Moir et al., 2012 |
| Increase | Greenhouse Mesocosm | Sugarcane | Takaragawa et al., 2022 |
| Root length density | Decrease | Greenhouse Mesocosm | Grass | Fernandez Pulido et al., 2023 |
| Increase | Vegetation filter strips | Grass | Sheng et al., 2021 |
| Maximum root depth | Increase | Sand\_tube | Wheat | Ehdaie et al., 2010 |
| Root depth | Decrease | Vegetation filter strips | Grass | Sheng et al., 2021 |
| 0-0.1 m root length | Decrease | Greenhouse Mesocosm | Grass | Popay & Crush, 2011 |
| 0.1-0.2 m root length | Decrease | Greenhouse Mesocosm | Grass | Popay & Crush, 2011 |
| > 0.2 m root length | Decrease | Greenhouse Mesocosm | Grass | Popay & Crush, 2011 |
| Root length | Decrease | Greenhouse Mesocosm | Grass | Popay & Crush, 2011 |
| 0-0.1 m root diameter | Decrease | Greenhouse Mesocosm | Grass | Popay & Crush, 2011 |
| 0.1-0.2 m root diameter | Increase | Greenhouse Mesocosm | Grass | Popay & Crush, 2011 |
| > 0.2 m root diameter | Increase | Greenhouse Mesocosm | Grass | Popay & Crush, 2011 |
| Root diameter | Increase | Greenhouse Mesocosm | Grass | Popay & Crush, 2011; Fernandez Pulido et al., 2023 |
| Root dry matter content | Decrease | Greenhouse Mesocosm | Grass | Fernandez Pulido et al., 2023 |
| Specific root length | Increase | Greenhouse Mesocosm | Grass | Popay & Crush, 2011; Fernandez Pulido et al., 2023 |
| Center of gravity of the root system | Decrease | Greenhouse Mesocosm | Sugarcane | Takaragawa et al., 2022 |
| Physiological and chemical | Root N content | Increase | Greenhouse Mesocosm | Grass | Fernandez Pulido et al., 2023 |
| Denitrification | Physiological and chemical | Root C exudation | Positive/Increase | Controlled light exposure and soil moisture | Wheat, barley and ryegrass | Maurer et al., 2021 |
| Root N exudation | Positive/Increase | Controlled light exposure and soil moisture | Wheat, barley and ryegrass | Maurer et al., 2021 |
| Nitrification | Architectural and morphological | Specific root length | Negative/ Reduction | Greenhouse Mesocosm | Grasses | Cantarel et al., 2015 |
| Physiological and chemical | Root N content | Positive/ Increase | Greenhouse Mesocosm | Grasses | Cantarel et al., 2015 |
| Root affinity for NH4 | Positive/ Increase | Greenhouse Mesocosm | Grasses | Cantarel et al., 2015 |
| Exudation of nitrification inhibitors | Negative/Reduction | Chamber | Brachiaria humidicola | Subbarao et al., 2007 |
| Negative/Reduction | Greenhouse Mesocosm | Rice, Wheat,Elymus sibiricus | Pariasca Tanaka et al., 2010; O’Sullivan et al., 2016; Sun et al., 2016 |
| N uptake | N uptake | Architectural and morphological | Root surface area | Increase | Chamber | Rice, Cotton | Chen et al., 2020; Iqbal et al., 2020 |
| Hydroponic condition | Wheat | Zhang et al., 2015 |
| Decrease | Greenhouse Mesocosm | Rice | Fan et al., 2010 |
| Field | Maize | Mu et al., 2015; Guo et al., 2022 |
| Root biomass | Increase | Chamber | Rice, Cotton | Chen et al., 2020; Iqbal et al., 2020 |
| Field | Maize, Rice | Ju et al., 2015; Mu et al., 2015; Yu et al., 2015; Chu et al., 2022; Guo et al., 2022 |
| Hydroponic condition | Wheat | Zhang et al., 2015 |
| Greenhouse Mesocosm | Grass, Rice, Sugarcane | Fan et al., 2010; Moir et al., 2012; Takaragawa et al., 2022 |
| Sand\_tube | Wheat | Ehdaie et al., 2010 |
| Root biomass (0-10) | Increase | Field | Rice | Ju et al., 2015; Chu et al., 2022 |
| Root biomass (10-20) | Increase | Field | Rice | Ju et al., 2015; Chu et al., 2022 |
| Root biomass (0-0.3 m) | Decrease | Greenhouse Mesocosm | Sugarcane | Takaragawa et al., 2022 |
| Root biomass (0.3-1.0 m) | Decrease | Greenhouse Mesocosm | Sugarcane | Takaragawa et al., 2022 |
| Deep root biomass | Increase | Sand\_tube | Wheat | Ehdaie et al., 2010 |
| Shallow root biomass | increase | Sand\_tube | Wheat | Ehdaie et al., 2010 |
| Center of gravity of the root system | Decrease | Greenhouse Mesocosm | Sugarcane | Takaragawa et al., 2022 |
| Root/shoot ratio | Increase | Sand\_tube | Wheat | Ehdaie et al., 2010 |
| Field | Maize, Rice | Yu et al., 2015; Ju et al., 2015; Chu et al., 2022 |
| Decrease | Greenhouse Mesocosm | Grass, Sugarcane | Abalos et al., 2014; Takaragawa et al., 2022 |
| Chamber | Cotton | Iqbal et al., 2020 |
| Root depth | Increase | Chamber | Cotton | Iqbal et al., 2020 |
| Decrease | Vegetation filter strips | Grass | Sheng et al., 2021 |
| Sand\_tube | Wheat | Ehdaie et al., 2010 |
| Root Diameter | Increase | Greenhouse Mesocosm | Grass | Abalos et al., 2014 |
| Chamber | Cotton, Rice | Chen et al., 2020; Iqbal et al., 2020 |
| Field | Rice | Chu et al., 2022 |
| Root length density | Increase | Field | Maize, Rice | Ju et al., 2015; Mu et al., 2015; Chu et al., 2022 |
| Vegetation filter strips | Grass | Sheng et al., 2021 |
| Root volume | Increase | Field | Rice | Chu et al., 2022 |
| Hydroponic condition | Wheat | Zhang et al., 2015 |
| Chamber | Rice, Cotton | Chen et al., 2020; Iqbal et al., 2020 |
| Root length ratio | Decrease | Chamber | Cotton | Iqbal et al., 2020 |
| Root thickness | Increase | Chamber | Cotton | Iqbal et al., 2020 |
| Specific root length | Increase | Field | Rice | Chu et al., 2022 |
| Decrease | Greenhouse Mesocosm | Grass | Abalos et al., 2014 |
| Root length | Increase | Field | Maize, Rice | Ju et al., 2015; Chu et al., 2022; Guo et al., 2022 |
| Hydroponic condition | Wheat | Zhang et al., 2015 |
| Greenhouse Mesocosm | Rice, Grass | Fan et al., 2010; Moir et al., 2012 |
| Chamber | Rice | Chen et al., 2020 |
| Root tip number | Decrease | Chamber | Rice | Chen et al., 2020 |
| Root density | Increase | Chamber | Cotton | Iqbal et al., 2020 |
| Root projected area | Decrease | Chamber | Cotton | Iqbal et al., 2020 |
| Root angle opening | Increase | Field | Maize | Guo et al., 2022 |
| Root maximal width | Increase | Field | Maize | Guo et al., 2022 |

**Table 2**. Main root traits in a selection of dynamic models (APSIM, DNDCvCAN, DSSAT, and Daisy) with potential effects on nitrogen losses.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| *Trait Category* | *Trait* | *Models* | *Default values* | *Units* |
| Architectural and morphological | Initial root depth | APSIM | 100 | mm |
| Maximum root depth | APSIM, DNDCv.CAN | 1000; 1.51 | mm; m |
| Root depth growth rate | APSIM, DSSAT | (0, 5.0, 30, 30, 30, 30, 0.0, 0.0, 0.0,0.0,0); 3.0 | mm/d; cm/d |
| Root fraction of total biomass | DNDCv.CAN | 0.15 | fraction |
| Maximal root/shoot ratio | Daisy | c(0.5, 0.5, 0.25) | ratio |
| Density distribution of root shape | DNDCv.CAN | 5 | function number |
| Root length weight ratio | DSSAT | 0.98 | cm/g |
| Penetration rate parameter of root | Daisy | 1 | cm/dg C/d |
| Physiological and chemical | NO3- uptake/root length | DSSAT | 0.006 | mg/cm |
| Conversion efficiency of root | Daisy | 0.69 | g DM-C/g Ass-C |
| Fraction of assimilate for growth to root | Daisy | c(0.5, 0.45, 0.4) | fraction |
| Root respiration fraction | DSSAT | 0.4 | fraction |
| Critical root N concentration | APSIM | 0.02 | gN/gDM |
| Root C/N ratio | DNDCv.CAN | 85 | ratio |

**Table 3**. General information of the dataset setups for the sensitivity analysis with process-based models.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| *Models* | *Crop* | *Site* | *Soil texture* | *Nitrogen input (kg/ha)* | *Water regime* | *Reference* |
| DSSAT | Spring barley | Dundee (56.45°N, 3.07°W) | Loam | 120 | Irrigated | Cammarano et al., 2019 |
| APSIM | Spring barley | Foulum (56.30° N, 9.35° E) | Sandy loam | 140 | Rainfed | Vogeler et al., 2023 |
| DNDCv.CAN | Spring barley | Quebec (48.85°N, 72.54°W) | Silty clay | 70 | Rainfed | Jégo et al., 2024 |
| Daisy | Winter wheat | Foulum (56.30° N, 9.35° E) | Sandy loam | 150-165 | Rainfed | Gyldengren et al., 2020 |

|  |  |
| --- | --- |
| **Table 4**. Research needs for improving model representation of the relationship between root traits and nitrogen losses. | |
| *Item* | *Action* |
| Experiments – common traits | Document resource investment traits (e.g., root N concentration, specific root length) more consistently |
| Experiments – complex traits | Include complex indicators of root N uptake such as net and maximum NO3- and NH4+ uptake rates |
| Evaluation of synergies and trade-offs | Consider interactive effects of e.g., root traits on C and N cycling |
| Development of 3D root component | A 3D root trait module can better represent the spatial configuration of the root system (e.g., root branching and elongation directions and rates) |
| Integration of phenotyping and functional gene detection into process-based models | Determine the genetic control of root phenotype; develop association between key genes/QTLs and model input parameters |
| Biological exudation of nitrification and denitrification inhibitors | Explore opportunities to incorporate this important root trait into process-based models |
| Soil microbial communities | Use easily observable root morphological traits in process-based models as proxies to predict changes induced by plants on soil microbial communities related to N cycling |