Reactive nitrogen emissions from agriculture: Model and Mesocosm experiments

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Introduction

The terrestrial biogeochemical nitrogen (N) cycle with its flux of nitrogen between the atmosphere and the land impacts the terrestrial carbon cycle, air and water pollution, and atmospheric aerosols and greenhouse gases including N_2O which is long-lived. Agriculture plays a key role in the corresponding N cascade. Agriculture dominates the creation of reactive N (Nr), is the largest emission source of NH_3, the largest anthropogenic source of N_2O and an important source of NO_x (NO and NO_2). Despite its importance, to our knowledge, a full representation of the biogeochemical N cycle, including the coupling of N fluxes between land and atmosphere has not been implemented in Earth System Models (ESMs). This challenges our understanding of how this cycle will change with climate and future agricultural practices.

The Flows of Nitrogen Model v2 (FANv2) (Vira et al., 2020, 2022) simulates the climate and meteorological dependence of agricultural NH_3 emissions within an Earth System Model. Here we couple FANv2 to the Community Land Model v5 (CLM5.0) to form FANv3. FANv3 simulates the global emissions of NO_x, N_2O and NH_3 including their dependence on agriculture. Here we show that (1) the resulting agricultural and natural emissions are within the range of other global inventories after the parameterization of Nr emissions within CLM5.0 has been corrected. (2) The simulation of NH_3 emissions, the largest agricultural Nr emission source and one seldom simulated in ESMs, results in significant modifications to the N cycle including the emissions of NO_x and N_2O. (3) Detailed comparisons to mesocosm measurements of corn reveal model deficiencies in simulating the agricultural emissions and cycling of N at a specific site.

CLM5.0*-FANv3 design and results

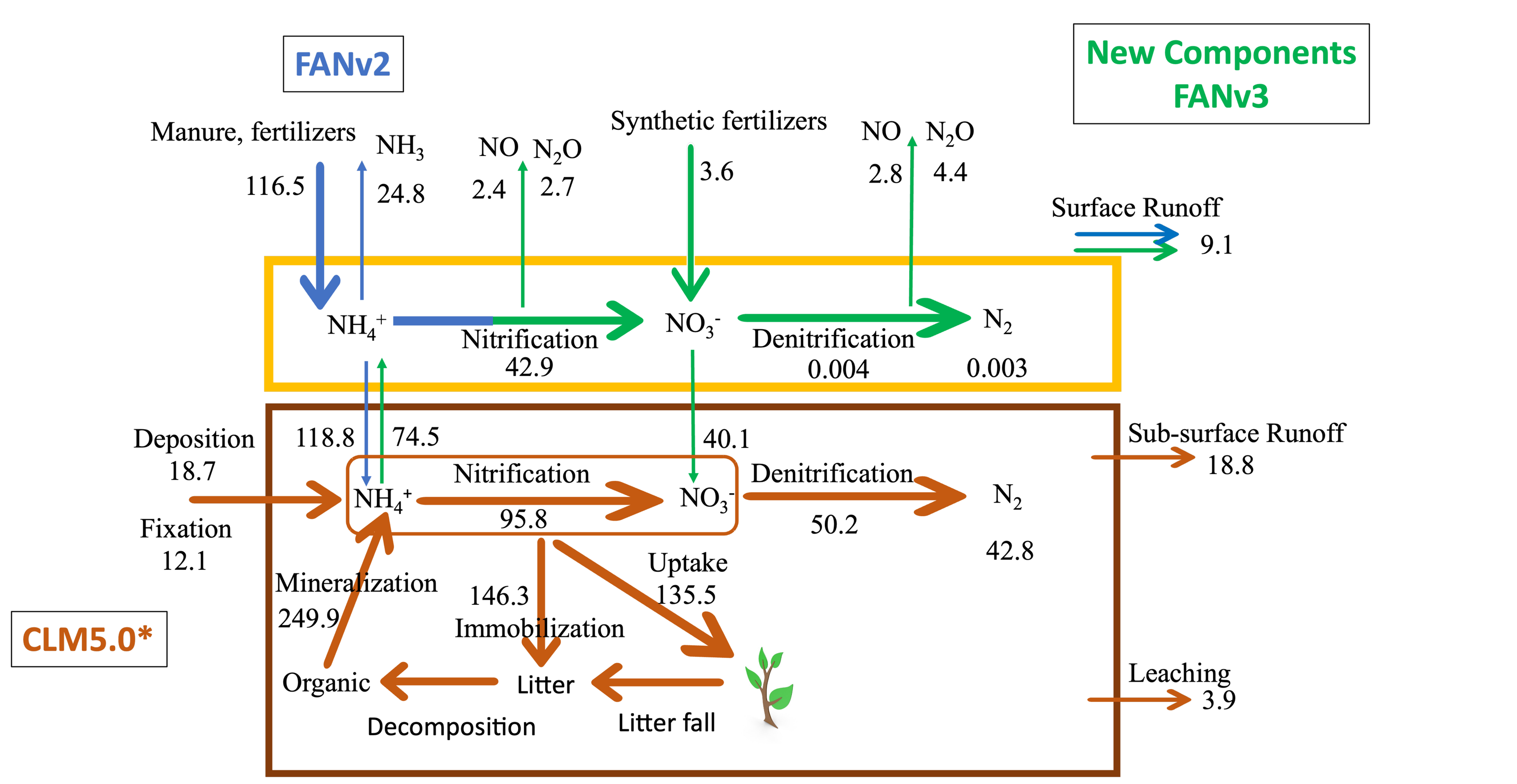
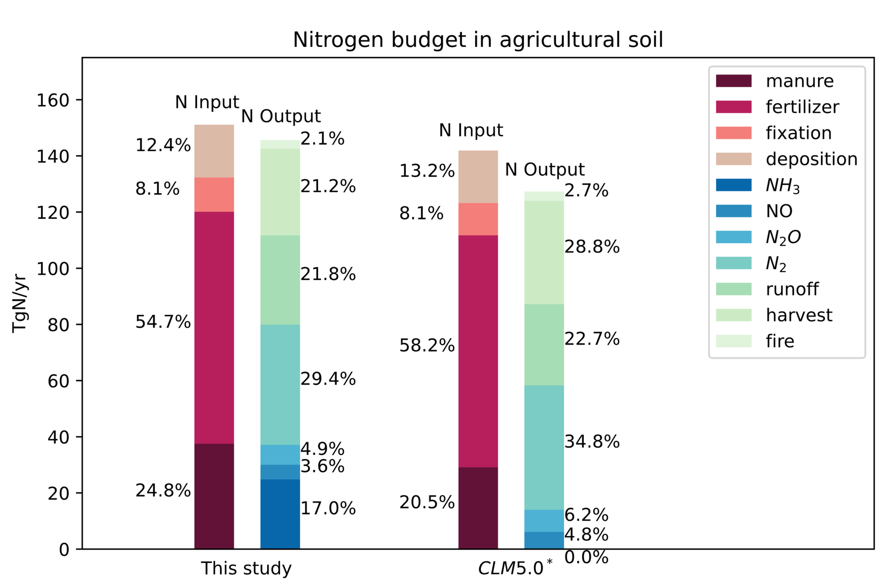


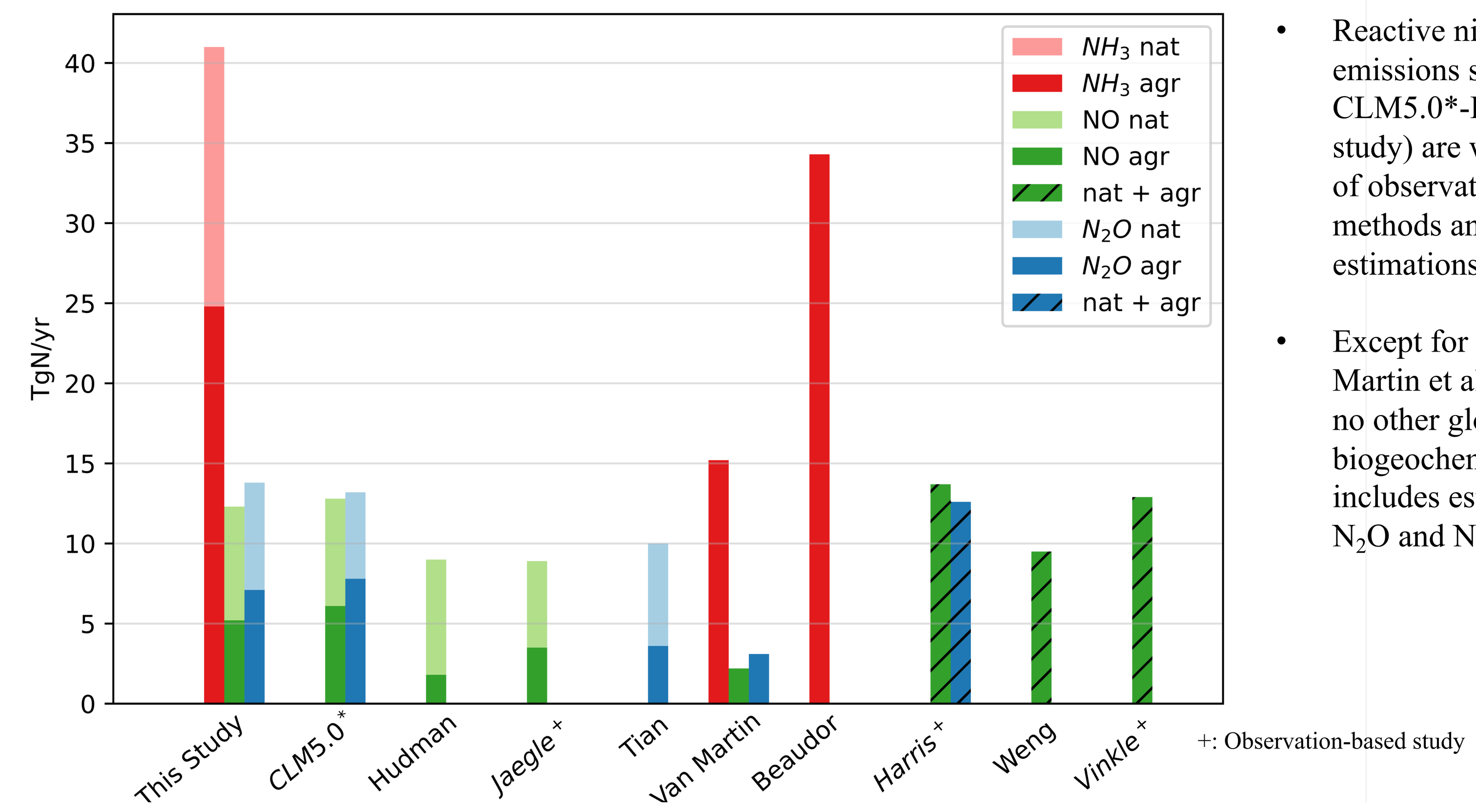
Figure 1 Agricultural fluxes of Nitrogen (N) in CLM5.0*-FANv3 (TgN/yr) averaged from 2010-2015. CLM5.0* has been modified from CLM5.0 by correcting the representation of diffusion in the nitrification/denitrification parameterizations. FANv3 (this study) adds nitrification/denitrification to FANv2 (Vira et al., 2020) and integrates the components into CLM5.0. The FANv2 components represent the flows of nitrogen at the land-atmosphere interface through fertilizer input and NH_3 volatilization.



- NH_3 emission accounts for about 17% of total nitrogen soil losses in CLM5.0*-FANv3 (This study) and is omitted in the default CLM5.0 model.
- All nitrogen loss pathways (except NH_3) are decreased in CLM5.0*-FANv3 versus CLM5.0* relative to the inputs. The decrease for NO, N_2O, N_2 runoff, and harvest is 25%, 21%, 16%, 4% and 26% respectively when NH_3 emissions are included.
- Runoff and denitrification represent 50% of the total N loss globally.

Figure 2 Nitrogen inputs and outputs on agricultural land in CLM5.0*-FANv3 (this study) and CLM5.0*. Synthetic fertilizer inputs are from the gridded datasets in both simulations. In CLM5.0* manure nitrogen is assumed to be input at a constant rate (0.002 KgN/m^2/yr) onto agricultural lands. In CLM5.0*-FANv3 manure nitrogen is input from a global gridded dataset based on livestock populations.

Model results (global)



- Reactive nitrogen gas emissions simulated by CLM5.0*-FANv3 (this study) are within the range of observation-based methods and satellite estimations.
- Except for the study by Van Martin et al, we are aware of no other global biogeochemistry model that includes estimates for NH_3, N_2O and NO_x.

Figure 3 Global emissions (TgN/yr) of NH_3, N_2O and NO in CLM5.0*-FANv3 on natural and agricultural land in various observationally based and modelling studies.

Notes: All NH_3 emissions are only from agricultural soil, barn or indoor emissions are excluded; Natural NH_3 emissions in CLM5.0*-FANv3 are due to grazing on pastureland; **Van Martin et al (2023)** is also based on CLM5.0 but include several alternate parameterizations and the default manure scheme; **Tian et al (2023)** use several modelling results and atmospheric inversions;

MESOCOSM vs CLM5.0*-FANv3 (setup)

Mesocosm experiments measured soil N loss as a function of the urea fertilization rate (123 KgN/ha, 168 kgN/ha and 213 kgN/ha) in two representative soil types under corn cultivation in central Iowa. The measured N losses include NO, N_2O, N runoff, and plant N uptake. Soil inorganic and several environmental scalars (e.g. soil temperature, soil moisture) were also measured.

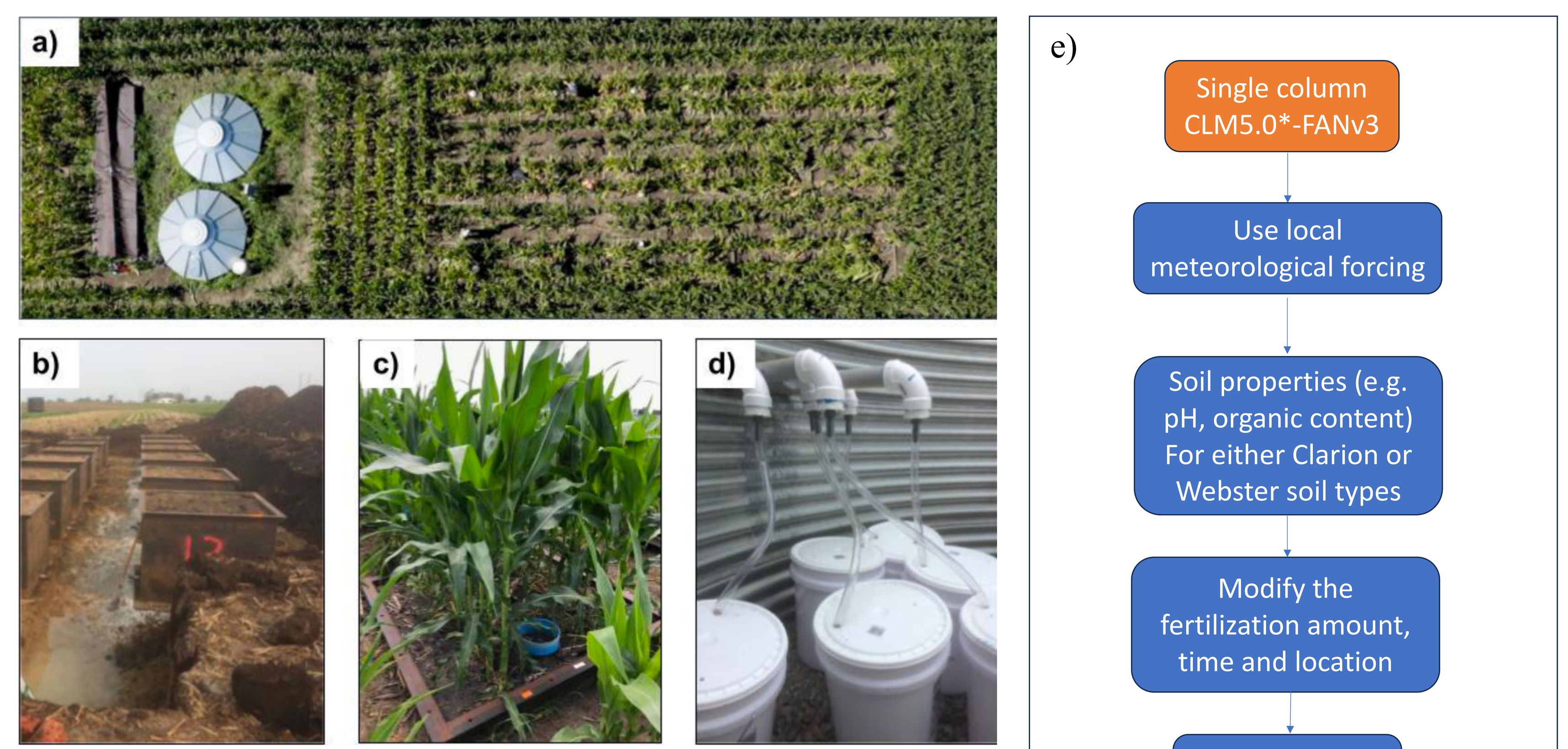
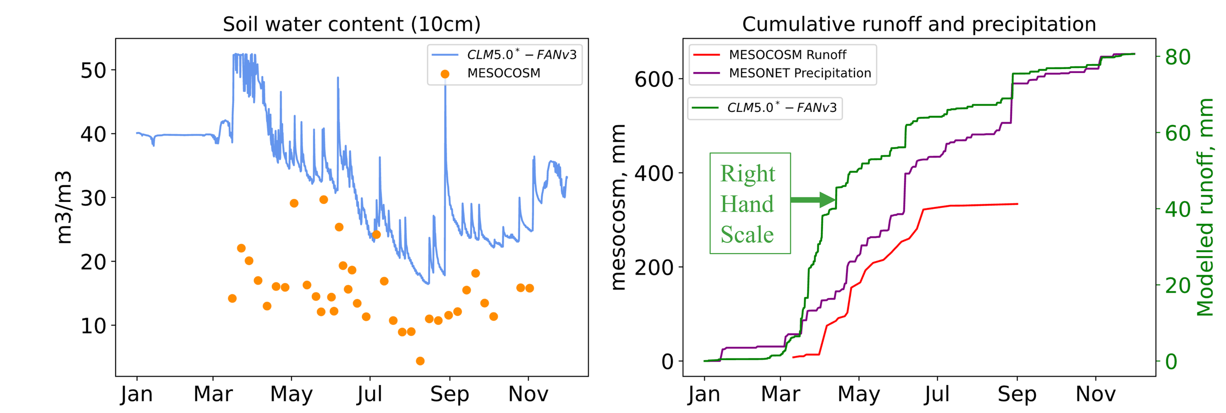


Figure 4: The Iowa State University soil block mesocosm facility and the CLM5*-FANv3 setup for comparison to the mesocosm measurements. The mesocosm contains 36 undisturbed soil monoliths (Clarion and Webster series) with individual drains a): Aerial view of the full mesocosm experiment; b): View of multiple "soil blocks" during drainage installation, c): An individual soil block planted with corn, d): Drainage collection from individual soil blocks, e): setup of CLM5.0*-FANv3 for comparison to the mesocosm.

Evaluation by MESOCOSM (single site)



- CLM5.0*-FANv3 overestimates the soil moisture and underestimates the runoff. Nitrate runoff is also underestimated (see **Figure 7**).
- Soil moisture and runoff simulation are critical parameters in determining the loss of N and the rates of nitrification/denitrification

Figure 5: Simulated soil water content (10 cm) m3/m3 for CLM5.0*-FANv3 (blue line) and measured content for mesocosm (dots) and simulated cumulative water runoff (mm) for CLM5.0*-FANv3 (green line, right y-axis) and measured mesocosm runoff (red line), and measured precipitation at mesonet site for the year 2022.

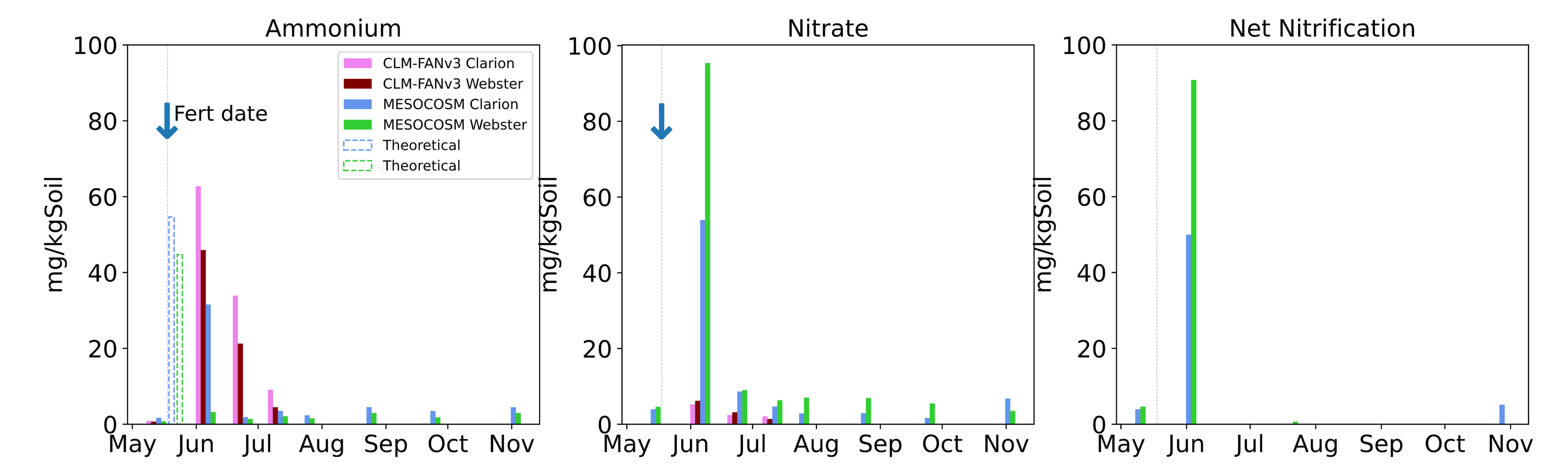


Figure 6: Comparison of the simulated inorganic nitrogen concentration with mesocosm measurements for the year 2022. Theoretical values are calculated from the fertilizer amount divided by 20 cm applied depth; Net Nitrification is an estimated nitrification production over the period between measurements.

- Mesocosm suggests most of NH_4^+ was nitrified to NO_3^- within two weeks.
- The model can't reproduce the measured transformations between NH_4^+ and NO_3^- following fertilization.

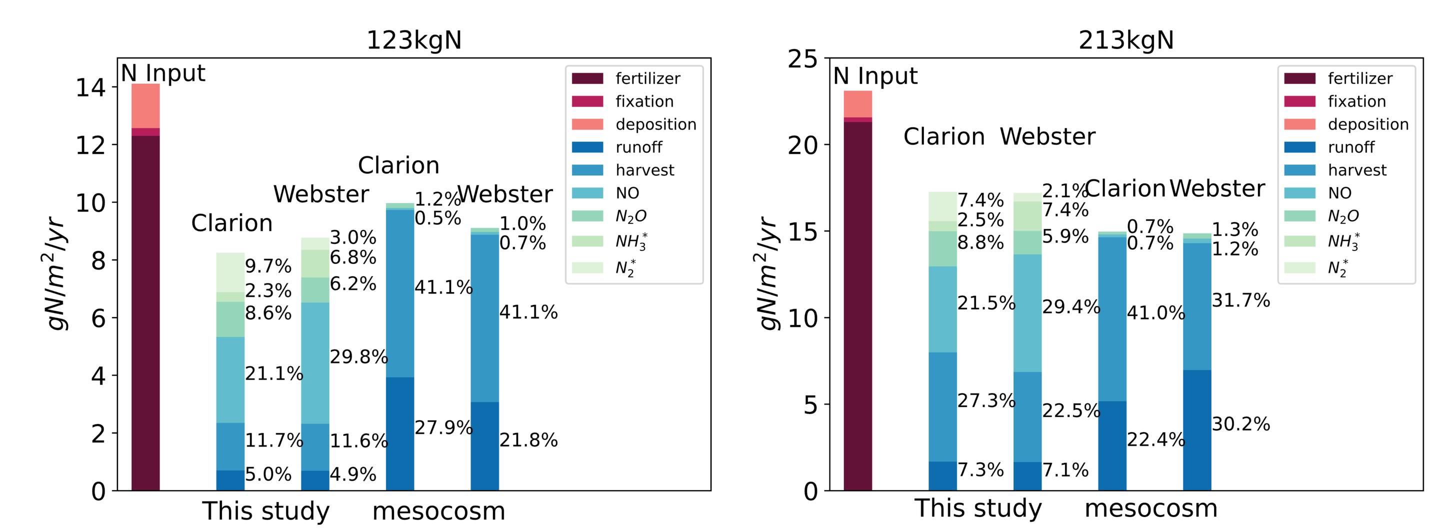


Figure 7: Measured and simulated CLM5.0*-FANv3 N inputs and losses (gN/m2/yr) for Webster and Clarion soils for two different urea fertilization rates. Percentages are given in terms of fertilizer input. N deposition, fixation and NH_3 and N_2 emissions are not measured. Differences between inputs and outputs indicate N retained in soil pools or losses not measured.

- CLM5.0*-FANv3 simulates larger NO and N_2O emissions than measured and smaller losses from runoff and harvest.
- The overall % simulated nitrogen loss in CLM increases with increasing fertilizer but the measurements suggest little change.

Conclusion and future works

- Implementation of FANv3 in CLM5.0* simulates NO, N_2O and NH_3 emissions on the global scale consistent with available measurements and model studies
- The inclusion of NH_3 emissions in ESMs significantly decreases the emissions of NO and N_2O as well as runoff and harvest Nr losses
- Detailed comparisons to mesocosm measurements of corn reveal model deficiencies in simulating the agricultural emissions and cycling of N at a specific site.
- Future work is to reconcile mesocosm measurements with CLM5.0*-FANv3 simulations.

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