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Improving APSIM modules for enhanced-efficiency fertilizers to simulate N_2O emissions in vegetable systems

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Abstract: Enhanced-efficiency fertilizers (EEFs), including nitrification inhibitors and controlled-release fertilizers (CRFs), can improve nitrogen (N) use efficiency and reduce nitrous oxide (N_2O) emissions. The APSIM model has been adopted to simulate EEF effects on N cycling, but current implementations remain oversimplified. For example, dicyandiamide (DCD) has been described with concentration effect functions and first-order decay, while the 3,4-dimethylpyrazole phosphate (DMPP) module relied on fixed half-lives and bioactivity thresholds, which are poorly constrained and varied with soil and climate conditions (Vilas et al., 2019). CRFs have often been described by laboratory-based release curves with assuming linear or staged patterns, lacking responsiveness to soil moisture (Verburg et al., 2025). Such simplifications, mostly applied in pasture and sugarcane systems, constrain extrapolation to other crops. Vegetable production systems, with some of the highest N inputs per unit area, intensive management and frequent irrigation, are hotspots of N_2O emissions yet remain largely neglected in modelling (Qasim et al., 2021).

To address these limitations, we developed new APSIM NextGen modules for DMPP and CRFs in vegetable systems. A global dataset on EEF effects on vegetable N_2O emissions was compiled to generate parameter distributions. For DMPP, persistence and concentration–effect functions were redesigned with environmentally responsive parameters for temperature, moisture, and soil properties, replacing fixed half-lives. For CRFs, staged release was extended to include dynamic responses to both soil temperature and moisture. Modules were validated against the global database and further refined using field data from a celery site at Boneo, Australia.

The improved modules substantially enhanced model performance, reducing biases associated with static assumptions. Validation against the global database confirmed that the revised structures more reliably reproduced mitigation effects and emission dynamics. Application to the Boneo celery site in Australia showed that DCD and DMPP consistently reduced cumulative N_2O emissions compared with conventional urea, while CRFs provided more moderate reductions depending on soil water conditions and release patterns. The model captured the extended persistence of DMPP under warm, moist conditions and the capacity of CRFs to delay nitrate accumulation, consistent with field evidence.

By embedding global evidence into a process-based model and validating against independent observations, this study establishes a robust framework for quantifying the agronomic and environmental benefits of EEFs in vegetable systems. The outcomes will provide new insights into when and where EEFs are most effective, thereby supporting decision-making for sustainable N management.

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