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Increasing the spatial scale of process-based agricultural systems models by representing heterogeneity: The case of urine patches in grazed pastures

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ABSTRACT

We sought to extend the spatial scale of soil-plant models by including, rather than ignoring, heterogeneity using the deposition of urine patches as an example. Our “pseudo-patches” approach preserves the most important biophysical effects but is computationally-tractable within a multi-paddock simulation. It explicitly preserves the soil carbon and nitrogen heterogeneity but does not require independent simulation of soil water and plant processes and is temporal in that the patches of heterogeneity can appear and disappear during the simulation. The approach was tested through comparison to simulations that more-closely represented field conditions and which contained independent urine patches. The testing was successful, reducing substantial error in the simulation of pasture grazed and leaching for modest increases in simulation execution time but we recommend additional testing under very low and very high stocking densities. The approach is applicable to any heterogeneity in soil nitrogen or carbon such as in spatially-managed fertiliser applications.

1. Introduction

Almost all process-based soil-crop simulation models have been developed using deterministic equations so that for any given combination of states and parameters only a single outcome can emerge. As a result of this, the various soil and plant states can only have a single value at any point in time and so they inherently operate at a ‘point’ in space – a scale at which lateral dimensions are conceptually ignored such that the soil and plant states are considered to vary only in the vertical and time dimensions. Despite that it is well known that lateral heterogeneity, even within relatively short spatial scales, can be significant (Strong et al., 1997; Nielsen et al., 1973; Vauclin et al., 1983), point-based models are routinely applied at paddock scale and in doing so model users implicitly adjust model parameters and/or inputs to values more relevant to these larger scales. This approach to increasing the lateral scale of soil-crop models is almost ubiquitous in the modelling community.

When users of point-scale models seek to explicitly include aspects of heterogeneity they tend to use one of the three approaches described by Batchelor et al. (2002): overlay a regular grid and independently simulate each grid point with a point-scale simulation; analyse the area to define irregularly-shaped zones of similarity that are not necessarily contiguous and independently simulate each zone with a single point-scale simulation; or link the point-based model to a spatial model to calculate lateral transfers of mass and energy and simulate the area as a interlinked system.

There appear to relatively few attempts to explicitly include lateral heterogeneity within the structure of the model in an attempt to expand the spatial scale of the model itself to something larger than point. Notable exceptions to this include highly detailed soil-root models such as HYDRUS (Šimůnek et al., 2012) or ROOT-MAP (Dunbabin et al., 2002) and models specialising in tree systems in which the root systems and/or canopies are large and isolated from neighbours (Forrester, 2014; Van Noordwijk and Lusiana, 1998; Battaglia et al., 2004).

Heterogeneity within the scale of a paddock or field can be subdivided into either transient or persistent causes of heterogeneity. Persistent causes are those that endure indefinitely relative to the length of the simulation and would typically include:

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topographic variation sufficient to lead to lateral redistribution of water and/or nutrients or to areas of the paddock experiencing variation in the meteorological environment; variation in soil physical properties sufficient to influence plant growth and development; and persistent management variation such as the differential treatment of headlands. In most cases, persistent variation can be included in a modelling study using the zone-based approach. The exceptions to this would be where the state of one zone affects the management of others zones, for example if the water status of a particularly sandy part of a paddock was used to decide the irrigation timing across the whole paddock.

Transient heterogeneity refers to areas of the paddock that deviate from the paddock average for limited durations, usually in response to a management action, which temporarily causes its states and/or processes to deviate from the paddock norm before returning to some typical state. Examples of this include heterogeneity caused by spatially uneven irrigation or fertiliser inputs. While this heterogeneity often can be modelled using independent zones, this would come at a potentially significant computing expense because for substantial durations most of the independent simulations would be replicas of each other and so would be redundant. The challenges with modelling transient heterogeneity using independent simulations expand when the magnitude, area or timing of the variation is itself a result of the simulation conditions. The heterogeneity caused by the return of excreta, particularly that of urine deposition by ruminants, to grazed paddocks is one particularly challenging example of transient heterogeneity (Eckard et al., 2014; Snow et al., 2014).

Grazing ruminants harvest N in pasture from the entire paddock and then deposit >50% of the ingested N into urine patches with patch-level N loading of 200–2000 kg N ha^{-1} that cover only 2–4% of the paddock area (see studies summarised by Selbie et al., 2015; Haynes and Williams, 1993). This deposition behaviour causes extreme spatial and temporal fluctuations in mineral N in the soil across a paddock, the urine patches are the primary sources of N leaching (Selbie et al., 2015) and N_2O (Marsden et al., 2016) emission and they also substantially affect pasture growth, grass-legume dynamics, organic matter cycling. The relationship between N concentration in the soil and many soil processes is non-linear so that a paddock-average, such as would result from a paddock-wide or uniform deposition of N, is not a reasonable reflection of the true dynamics.

Previous work has shown the importance of explicitly modelling urine patches (Snow et al., 2009; Hutchings et al., 2007; McGechan and Topp, 2004; Cichota et al., 2013a). Based on these previous studies, pasture production and/or animal intake may be in error by 5–30% and N leaching by 5–85% with the magnitude of the error strongly dependent on the conditions simulated and of lower magnitude where larger amounts of N fertiliser were used. Despite this, almost all process-based simulation models assume uniform return of N to the soil (Snow et al., 2014). Dynamic simulation models (e.g. Brown et al., 2002; Cichota et al., 2012, 2013a) can be applied at the scale of a urine patch. One innovative application nested a dynamic patch-level simulations within a paddock-level model (Romera et al., 2012) but the resulting model was slow and cumbersome to use. Other models explicitly considering urine patches within the paddock (Hutchings et al., 2007; Snow et al., 2009; Bryant et al., 2011) do so at significant, perhaps prohibitive, complexity and computational cost.

The complexity and computational cost of simulating urine patches arises because of the large number of patches within a single paddock. A typical urine patch created by a dairy cow covers an area of about 0.25 m^2 but might result in about 0.7 m^2 of pasture affected by the high soil N (Selbie et al., 2015) so that a regular patch-sized grid would require that over 14,000 patches per hectare be simulated. Considerable computational savings can be made by considering the paddock in zones of N deposition rather than as a spatially-explicit grid. If all urine events within a single grazing day or event are considered to be equal (even though high animal-to-animal, diurnal and seasonal variability exists, Hoogendoorn et al., 2010; Selbie et al., 2015) then the number of zones or categories needed to represent the urine patches steadily increases with simulation time and the number of grazing events. Given this, a scheme to deal with amalgamation of zones (e.g. Cichota et al., 2013a) is needed even for relatively short simulation durations (Hutchings et al., 2007). While advanced computation approaches (e.g. Zhao et al., 2013) can reduce computational time by several orders of magnitude, that approach still is not a practicable solution for routine simulations and useful schemes to capture the major effects while retaining as much simplicity as possible are needed.

We sought a tractable solution to extend soil-crop models from a point-scale to a paddock-scale with respect to the soil carbon and nitrogen simulation using the example of the urine patches in grazed pasture as a test case. A tractable solution would retain the rich legacy of development in the soil-plant processes, preserve the most important biophysical effects of the heterogeneity and be computationally efficient within long-term simulation. We term our proposed solution “pseudo-patches” in that they explicitly preserve the soil carbon and nitrogen heterogeneity, and therefore the impacts of the non-linear concentration-dependent processes, but do not require complete independent simulation of the soil water and plant processes. More specifically pseudo-patches maintain the extreme heterogeneity of the soil C and N processes but consider only paddock-average soil water and plant processes. Our objective in this study was to implement pseudo-patches in the APSIM simulation model (Holzworth et al., 2014) and to test the performance, simulation accuracy and execution time, of the pseudo-patches against fully-explicit patches. From this we also develop a recommendation for more general implementation in dynamic simulation models.

2. Patching model description

The simulation model APSIM, Agricultural Production Systems Simulator (Holzworth et al., 2014), was used for the work described here. In particular, the patching model was implemented within the SoilNitrogen model. SoilNitrogen is the .NET port of the original Fortran SoilN model described by Probert et al. (1998). Below, with additional detail in Appendix 1, we describe the patching model in a level of detail appropriate to understand how the model was implemented and what assumptions were made. For additional detail, the source code is available at http://apsrunet.apsim.info/websvn/listing.php?repname=apsim.

Within an APSIM simulation the smallest unit that is simulated, disregarding layers in the soil, is referred to as a “*paddock*” and usually is conceptualised as a particular physical paddock (italics will be used to differentiate the simulated unit from the physical land section). The *paddock* corresponds to an area that is managed under a particular set of rules or that has different resources to distinguish it from other *paddocks* in the simulation. Within a simulation, the *paddocks* are isolated from one another and only interact through intervention from an upper level, termed “*APSIM Simulation*” level. From this level, simulation rules can transfer matter or impose conditional actions that cause *paddocks* to interact indirectly.

While *paddocks* would normally be construed as physical paddocks, the APSIM platform is sufficiently flexible that users can set them up as any physically-isolated area, including different areas within the same paddock. In this way it is possible to account for