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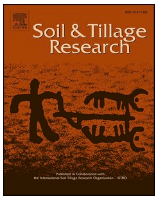

Simulating water and nitrogen runoff with APSIM

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ABSTRACT

To determine the impact of potential reductions of terrain-targeted nitrogen (N) fertilisation rates on N losses a simulation study was carried out using the Agricultural Production Systems Simulator (APSIM). To simulate N runoff a simple approach was used, in which runoff is based on the N concentration in the soil solution and an extraction coefficient. Firstly, APSIM parameters that have the largest effect on runoff of water and N were determined for terrains with different slopes for a poorly drained silt loam. A sensitivity analysis was then conducted to assess the effect of soil hydraulic properties and soil organic carbon content on runoff losses. Finally, APSIM was set up to simulate pasture production and water and N dynamics (including pasture N uptake, leaching and N runoff) for a farm on rolling hills in South Canterbury, New Zealand. Two different fertilisation approaches were used, either scheduled or based on the aboveground N concentration of the pasture. For the poorly drained silt loam, the rainfall intensity and the surface conductance had the highest effect on the amount of water lost by runoff. Soil hydraulic conductivity at saturation and field capacity, as well as plant available water content also controlled runoff of water and N, while the organic carbon content of the topsoil had less effect on N runoff. Both the extraction coefficient and the depth considered to exchange N with the runoff water affected the amount of N lost via runoff. Using the aboveground pasture N concentration prior to fertilisation had positive effects on pasture yield and reduced N runoff losses.

1. Introduction

The Canterbury region is of great significance to New Zealand's agricultural production, comprising about 20 % of New Zealand's farmland, with 1.2 million hectares in grassland (NZ, 2017). In the last three decades, the dairy industry has experienced a remarkable and sustained growth in the region, both through intensification and expansion into new areas, which were traditionally under sheep and beef farming. Importantly, the access to water for irrigation has allowed expansion onto lighter soils and foothill areas (Dynes et al., 2010). Such an intensification and expansion has come with negative environmental impacts, including loss of biodiversity and decline in soil and water quality, which reflects a worldwide trend (Hoekstra et al., 2020; Vibart et al., 2015). To respond to these environmental concerns, farmers need to increasingly conform to environmental regulations. Compliance with these regulations are, however, based on farm gate nutrient budgets, which can as Micha et al. (2020) pointed out, mask hotspots of environmental risk at the field scale. As such, to reduce environmental impacts the field scale, or even the sub-field scale, should be used as the management unit (McDowell et al., 2016; van Leeuwen et al., 2019). This is especially important for farming in foothill areas and hill country, with highly variable topography, soils, and climatic conditions. Defining appropriate land use and management strategies for such environments is challenging because of lack of data and transparency of current models that operate at a landscape scale (Tran et al., 2020). Identifying zones with different pasture production potentials and fertiliser requirements can assist with the development and implementation of better management practices. These can aid farmers to limit nutrient losses from zones that have large surplus and high risk for losses through leaching or runoff. Pasture production in the various terrains within hill country is driven by the differences in microclimates, aspect, slope, chemical and physical soil characteristics, including organic matter content and soil water content, as well as animal grazing behaviours and nutrient return via excreta (Hoogendoorn et al., 2016; Radcliffe, 1982).

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Process-based models, which offer the potential to gain more understanding of the dynamic processes operating in hill country, have been mainly developed for lowland pastures. The ability of these models to represent observed spatial patterns of pasture production in hill country, as well as the associated water and nitrogen balance, is generally poor. This is a major constraint for predicting the effect of management intensification on environmental outcomes, including nitrate leaching and N runoff from these systems. One of the main issues of sloping landscapes is the quantification of water and N runoff, which is driven by numerous factors including rainfall intensity (RI) and duration, soil type, soil hydraulic properties, soil moisture, land use, cover, and slope (Langer et al., 2020; Xiaoyan et al., 2005).

While many models have been developed and used successfully for predicting water movement and N cycling in cropping systems, most of these models (e.g. EPIC (Edwards et al., 1994); CERES (Ritchie, 1998)) use the empirical CN approach for simulating water runoff (Biggs et al., 2006; Mishra and Singh, 2004). Surface water runoff is often a short time-scale phenomenon, determined by sub-daily rainfall intensities (RI) and duration. As the CN for estimating water runoff is based on daily sums of water, the approach cannot be used for investigating the effect of RI. Furthermore, crop models often do not include N runoff. To overcome this, several studies have coupled crop models with erosion and runoff models. For example, Thayalakumaran et al. (2016) linked DairyMod with Howleaky to predict N runoff from a dairy catchment in Australia, and Tavakoly et al. (2019) combined the STICS model with the EauDyssée model to simulate N runoff from an intensive agricultural area in northern France, and Ledoux et al. (2007) linked the STICS model with to predict nitrate transport into surface and groundwater.

The Agricultural Production Systems Simulator (APSIM) provides deterministic modelling of cropping and pasture systems. APSIM has been successfully used to simulate pasture growth in lowland (Li et al., 2011) and hill country (Vogeler et al., 2016a), water balance (Snow et al., 2007), and N leaching in pastoral systems in New Zealand, including the simulation of leaching at the urine patch level (Romera et al., 2017). Soil water dynamics within APSIM can either be simulated with the APSIM-SoilWat model (Probert et al., 1998), a 'tipping bucket' water balance model, or by SWIM (Verburg et al., 1996), which is based on the Richards' equation. In SoilWat, surface water runoff is calculated by the CN approach, whereas in SWIM it is based on Manning's approach (Verburg et al., 1996); this offers a more systematic evaluation of management and soil conditions on water balance and crop growth, as well as the use of independently measured model parameters (Connolly et al., 2002). Currently, APSIM does not account for potential N losses with the surface runoff of water. To account for loss pathways, we implemented a simple approach, based on the AGNPS model (Young et al., 1989) for nutrient runoff. This approach takes into consideration the concentration of soluble nutrients in the upper soil profile, an extraction coefficient, and the amount of water runoff.

The objectives of this work were to (i) add a simple approach for simulating N runoff with the APSIM model, (ii) to determine the sensitive model parameters which govern water and N runoff in APSIM, (iii) to investigate if soil properties (physical and chemical) affect the sensitivity of the various runoff parameters, and (iv) to investigate, how variable rate N fertiliser application to different terrains of a farm or field with different soil properties, and different levels of pasture growth, would affect N losses compared with uniform application rates. For this APSIM was set up for a dairy farm in the South Canterbury region of New Zealand with three different terrains: low slope of 6°, medium slope (MS) of 18.5°, and high slope (HS) of 30°. The hypothesis was, that N runoff can be reduced when N fertilisation is matched with the temporal demand of the pasture, rather than using a pre-defined scheduled fertilisation strategy, in which N fertiliser was applied at an annual rate of 250 kg N ha^{-1}, with five equal splits applied in February, April, August, October, and December.

2. Methods

2.1. APSIM model description

The simulations were performed using the APSIM modelling framework (Holzworth et al., 2014), version 7.10. To account for the effect of slope and aspect of the terrain on radiation intercepted by the pasture, the values of incident radiation were adjusted based on the approach developed by Allen et al. (2006) and Revfeim (1978). This model firstly separates direct and diffuse components of the global radiation and then calculates the appropriate adjustment for them based on the slope and aspect angles of the terrain.

In SWIM, soil water movement is described based on a numerical solution of the Richards equation, and here a bimodal pore system was used. Water infiltration or runoff is controlled by the upper boundary condition and the runoff/pond settings (Verburg et al., 1996). Infiltration is driven by the matric potential and hydraulic conductivity of the surface, unless limited by the surface conductance. This approach generally represents surface sealing or crusting, and is used here as the top boundary condition, with water runoff calculated based on surface roughness and slope. The surface conductance should also be applicable for hydrophobicity, which can increase water runoff significantly (Bayad et al., 2022). If the RI exceeds the infiltration capacity, water runoff occurs. In APSIM, the daily rainfall is by default evenly distributed over the daily time-step, but its duration can be set to a shorter period, which implies greater intensity. Thus, RI can be set to a constant value (which means all rainfall events will have the same intensity), or alternatively use a manager script to calculate variable RI as a function of time and /or rainfall amount.

Runoff of water in SWIM is calculated from a runoff rate factor and the surface roughness (Verburg et al., 1996). Based on the Manning's approach, the runoff rate (R, mm/h) is calculated using:

$$R = a(h - h_o)^2 \tag{1}$$

where h is the excess surface water (m), h_o is the surface roughness or water storage capacity (m), and a the runoff rate factor, which is given by:

$$a = \frac{3600\sqrt{S}}{nL_0} \tag{2}$$

where S is the slope gradient (m m^{-1}), L_0 is the slope length (m), and n is the Manning's number (s $m^{-1/3}$), which is an empirical roughness parameter characterising the soil grains, clods, and plant parts. Manning's number varies from 0.015 for bare soil to 1.50 for forest, with typical values for pasture ranging from 0.025 to 0.050.

Surface roughness plays a major role in determining the rate of water infiltration and runoff by generating surface ponding (Blevins and Frye, 1993). In SWIM, roughness (h_o) defines the water storage capacity in the soil surface above which runoff of water is initiated. The most widely used soil surface roughness index is a statistical index known as random roughness (RR), which is defined as the standard deviation of individual soil heights after the slope effect has been removed (Allmaras et al., 1966). Borselli and Torri (2010) found a negative exponential relationship between water storage and slope (for slopes of up to 30°) for different values of RR given by:

$$h_0 = 0.157 + 0.55\exp(1.011RR) * \exp(-0.155S) \tag{3}$$

With RR values measured on a sheep and beef farm in NZ ranging between 1.25 and 1.85 cm, h_o values range between 3.7 mm for flat terrain and 0.15 mm for a slope of 30° (Betteridge et al., 1999).

To describe potential N loss via runoff, a manager script (Moore et al., 2014) was written in APSIM, assuming that N runoff is proportional to the N concentration in the soil solution near the surface, and is controlled by an extraction coefficient. This approach is similar to that of the AGNPS (Agricultural NonPoint Source Pollution) model (Young

Table 1
Nitrogen concentrations (g N kg^{-1}), with Nmin being the minimum, Nopt the optimum and Nmax the maximum N concentrations, and with Pool representing the growing tissue, Pool 2 the mature tissue, and Pool 3 the senescing tissue.

	Nmin	Nopt			Nmax
		Pool1	Pool2	Pool3	
Ryegrass	1.2	4	2.8	2	5
White Clover	2.0	4.5	3.15	2.25	5.5

Table 2
Rooting depth, plant available water (PAW) in the rootyone, and growth limiting factor for phosphorus limitation based on soil fertility used in the Agricultural Production Systems Simulator (APSIM) simulations for terrain with low slope (LS; 6°), medium slope (MS; 18.5°), and high slope (HS; 30°).

	Rooting depth (mm)		PAW (mm)	Soil fertility (-)	
	Ryegrass	White Clover		Ryegrass	White Clover
LS	750	350	67	1.000	1.000
MS	450	300	46	0.925	0.682
HS	250	200	29	0.850	0.569

et al., 1989). In this model, chemical transport is divided into water soluble and sediment adsorbed phases. Here we only consider N runoff from the soluble phase, but include the transport of the various N forms: urea, ammonium (NH_4), and nitrate (NO_3). N runoff is triggered by water runoff amount (R; mm), and calculated using:

$$N_{Runoff,i} = C_{i,z} * Ex_i * f_z * R * 0.01 \tag{4}$$

Where N_{Runoff} is the amount of N transported by runoff water (kg N/ha), with i representing the various forms of N; $C_{i,z}$ is the N concentration in the soil solution (ppm); Ex is the extraction coefficient (kg/L), f_z is a depth factor, and 0.01 is the factor to convert mg m^{-2} to kg ha^{-1}. The extraction coefficient Ex describes the amount of N that can be exchanged between soil and runoff water, and ranges from zero to infinity. At infinity, all the resident N of the N form considered is transferred to the runoff water. As such, Ex is assumed to be high for inert solutes (Urea and NO_3), and low for adsorbed solutes, such as NH_4. The depth factor f_z describes the interaction between soil and runoff water, it varies between zero (no interaction) and one ('full contact', for soil surface) and is assumed to decrease with soil depth.

AgPasture is a model developed for simulating pasture growth within APSIM, based on the physiological model of Thornley and Johnson (2000), with the ability to simulate different pasture species. The pasture species are described as a set of organs, namely leaves, stem/-sheath, stolon/rhizomes and roots. The plant organs are described by a set of tissue pools representing developmental stages of each organ, namely growing, mature and senescing, plus the dead tissue. The flow of DM and its N through these pools is controlled by the turnover processes. The pools each have three N concentration levels, the minimum N concentration expresses the N of the structural, the optimum N content is that at which plant growth is not limited, and the luxury N content is the maximum N concentration of the tissue. The minimum N content cannot be remobilised, and any N above the optimum level is readily available to remobilisation from any tissue and stage (for more details see https://www.apsim.info/documentation/model-documentation/crop-module-documentation/agpasture/). In the original model N between minimum and optimum was available for remobilisation only upon tissue senescence, but this was recently refined (Vogeler et al., 2016b) to account for the decreasing N content of plants with increasing biomass, in line with the critical N concentration curve (Lemaire and Salette, 1984). The various N concentration levels are provided in Table 1.

Table 3
Selected soil properties for the soil horizons used in the APSIM simulations. Those marked with * were only used for the sensitivity analysis to assess the effect of soil characteristics on water and N runoff. Where: Ksat and KDUL are the hydraulic conductivities at saturation and field capacity (−10 kPa). At some depths K_{sat} and K_{DUL} could not be measured due to lack of infiltration, and values were either based on pedotransfer functions (Cichota et al., 2013), or default values for slowly permeable soils in NZ (Vogeler et al., 2019).

Soil Name	Slope	Horizon	Soil Texture	Depth	PAW	K_{sat}	K_{DUL}
()	()		()	m		mm/d	mm/d
Timaru	LS	H1	silt loam	0.00–0.17	146	378	0.077
Timaru	LS	H2	silt loam	0.17–0.29	78	136	0.083
Timaru	LS	H3	silt loam	0.29–0.62	68	40	0.031
Timaru	LS	H4	silt loam	0.62–0.95	82	18	0.059
Timaru	LS	H5	silt loam	0.95–1.25	82	4	0.015
Timaru	LS	H6	silt loam	1.25–1.50	82	4	0.016
Timaru	MS	H1	silt loam	0.00–0.15	130	501	0.168
Timaru	MS	H2	silt loam	0.15–0.40	91	468	0.089
Timaru	MS	H3	silt loam	0.40–0.65	81	14	0.032
Timaru	MS	H4	silt clay loam	0.65–1.00	81	3	0.008
Timaru	MS	H6	silt loam	1.25–1.50	72	2	0.021
Timaru*	MS	H1	silt loam	0.00–0.15	119	319	0.121
Timaru*	MS	H2	silt loam	0.15–0.30	119	240	0.105
Timaru*	MS	H3	silt loam	0.30–0.56	147	133	0.053
Timaru*	MS	H4	silt loam	0.56–0.68	106	45	0.112
Timaru*	MS	H5	silt loam	0.68–0.76	103	16	0.075
Timaru*	MS	H6	silt loam	0.76–1.00	90	6	0.075
Timaru*	MS	H7	silt loam	1.00–1.25	89	3	0.025
Mangamahu*	HS	H5	silt loam	0.50–1.00	226	695	0.299
Ngamoko*	LS	H5	silt loam	0.75–1.00	226	720	0.302
Ngamoko*	MS	H5	silt loam	0.60–1.00	226	726	0.193
Wainui*	LS	H4	Silt clay	0.40–0.85	142	307	0.127
Wainui*	LS	H5	Clay loam	0.85–1.00	148	254	0.122
Wainui*	MS	H4	Clay loam	0.60–1.00	151	252	0.122
Wilford*	LS	H4	Silt clay loam	0.35–0.60	171	532	0.240
Wilford*	LS	H5	Silt loam	0.60–1.00	139	378	0.372
Wilford*	MS	H4	Silt loam	0.35–0.50	161	431	0.410
Wilford*	MS	H5	Silt loam	0.50–1.00	134	293	0.380
Wilford*	HS	H4	Silt loam	0.50–1.01	133	269	0.378

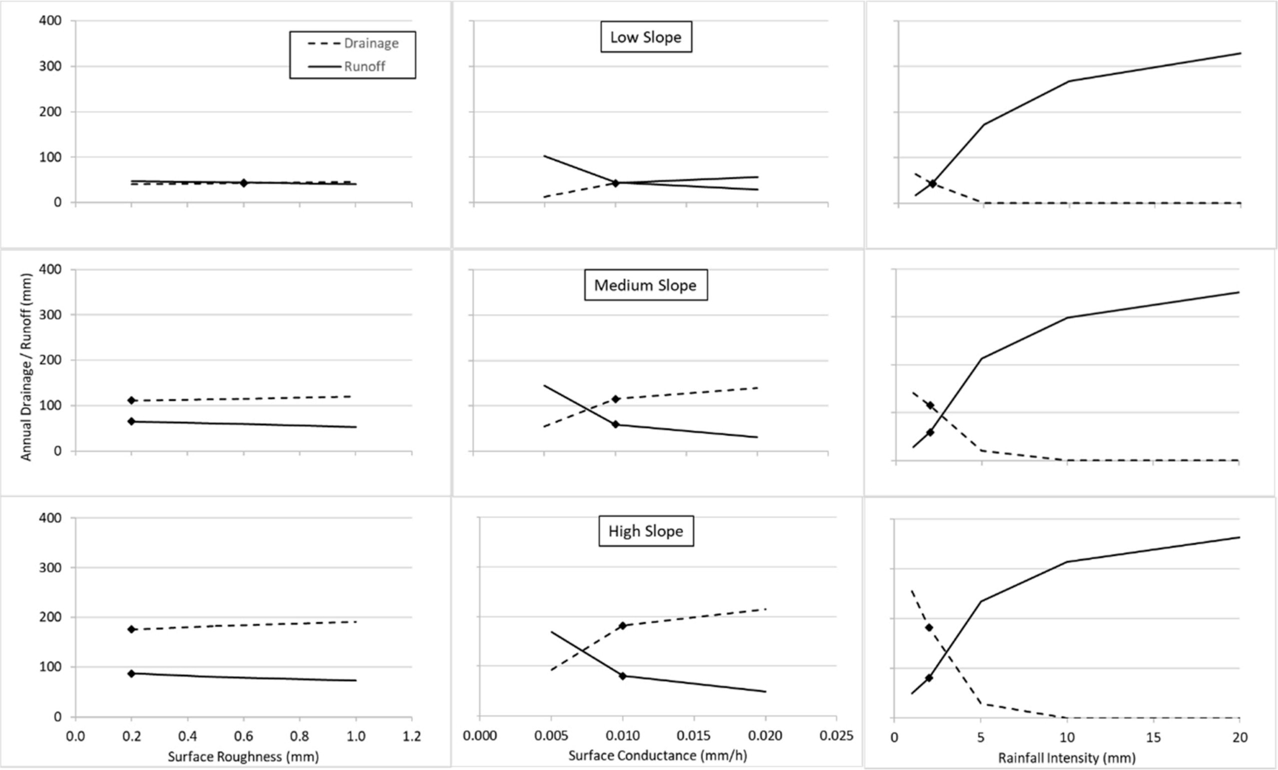

Fig. 1. Average annual drainage and runoff simulated by the Agricultural Production Systems Simulator (APSIM) over 20 years for terrains with different slopes dependent on (i) surface roughness with a conductance value of 0.01 mm h^{-1} and a rainfall intensity of 2 mm h^{-1}, (ii) conductance with a surface roughness of 0.5 mm and a rainfall intensity of 2 mm h^{-1}, and (iii) rainfall intensity with a conductance value of 0.01 mm h^{-1} and a surface roughness of 0.5 mm. The symbols indicate the values that were used for the APSIM simulations discussed below.

2.2. *APSIM model general setup with scheduled N fertilisation*

The South Canterbury area is dominated by rolling hills with soils derived from loess that generally have a dense, low permeable subsoil layer (Webb and Burgham, 1997). For both the sensitivity analysis and the effect of fertilisation regime on the various model outputs, APSIM was parameterised using field characterisation from a dairy farm in the region, reported by Langer et al. (2020). In brief, the soil is a moderately to poorly drained Timaru silt loam, which consists of a minimum of two loess layers over gravels. These loess layers are approximately 4.5 m thick in the valley, and contain a fragipan, which has a high bulk density and severely limits water percolation (Kear et al., 1967). Three different terrains were considered: low slope (LS) with a slope of 6°, medium slope (MS) with a slope of 18.5°, and high slope (HS) with a slope of 30°. For all slopes the soil profile was set up to a depth of 1500 mm. The LS area has soil an organic carbon (OC) content in the top layer of 2.6 %, and the MS and HS of 2.5 %. For calculating farm-scale outputs (including productivity, N inputs and losses), a farm with 80 % LS, 15 % MS and 5 % HS was set up, based on the farm described in Langer et al. (2020).

Meteorological data were obtained from the National Climate Database from New Zealand's National Institute of Water and Atmospheric Research (NIWA; https://cliflo.niwa.co.nz/), using the weather station at Timaru Airport (−44.303, 171.225). The pasture simulated was a ryegrass/white clover, using AgPasture with the modifications as described in Vogeler and Cichota (2016). Pasture grazing rules were set according to New Zealand dairy industry grazing management guidelines with flexibility incorporated to allow for variation in pasture growth rate. For winter (late May to August), pastures were cut every 60 days to a residual of 1.2 t dry matter (DM)/ha. For the remainder of the year, grazing residuals were set to 1.5 t DM/ha and cut when pasture biomass reached 2.7 t DM/ha. To keep within optimum grazing intervals for maintaining pasture persistence and quality, this biomass-based rule was over-ridden by an interval-based one. Grazings were triggered at intervals of 16–26 days in September and October, 20–30 days in November and December, 25–32 days from December to February and 30–40 days from March to early May. To limit complexity, the grazed pasture was simply removed off the field (as a cut and carry system) and no returns of urine or dung were considered. The pasture was under irrigation, which was applied according to the water deficit in LS. Irrigation was triggered when the deficit in the top 300 mm of the soil was 30 mm, with 20 mm applied per day at an intensity of 10 mm h^{-1}, and with a return period of 1 day. The irrigation season was defined as being from September to May. To account for the reduction in pasture growth under soil saturation conditions, the minimum macro-porosity for optimum plant growth was set to 15 %. The maximum rooting depths were assumed to decrease with slope class. To account for the generally lower nutrient levels, especially of phosphorus, a growth-limiting factor of AgPasture (Vogeler et al., 2016a) was used to capture the fertility limitation on pasture growth due to soil fertility, i.e. Olsen P. Maximum rooting depth, plant available water (PAW) in the rootzone, and growth-limiting factor for soil fertility limitations are provided in Table 2.

The total annual N fertiliser amount was set to 250 kg of urea N per hectare, which is within the range of N applied in New Zealand dairy farms (Beukes et al., 2019). This was split evenly in five applications on the 15th of February, April, August, October and December.

A series of manager scripts (Moore et al., 2014) were used to describe the pasture management, including the application of irrigation and fertiliser according to rules described above (with a uniformly scheduled N fertilisation rate). N leaching from each area was defined as the amount of N leached past a depth of 1 m, and the denitrification was defined as the sum over the soil profile of 1 m. The simulations were run continuously over a period of 20 farming years (1999/2000–2018/19).

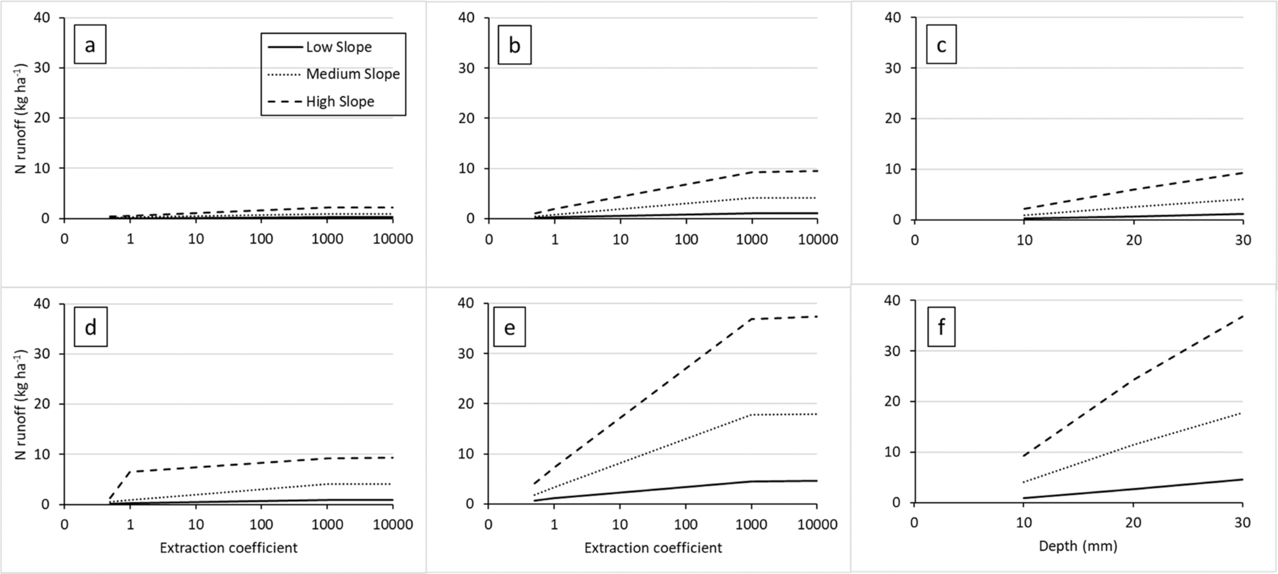

Fig. 2. Average annual N runoff simulated by the Agricultural Production Systems Simulator (APSIM) with either an annual N fertilisation rate of 100 kg N ha^{-1} (a-c) or 250 kg N ha^{-1} (d-f) over 20 years for terrains with different slopes dependent on the extraction coefficient (*Ex*), considering either a depth of 10 mm (a) or 30 mm (b), and (c) the depth considered for interacting with the runoff water.

2.3. APSIM model setup for sensitivity analysis

To evaluate the effect of APSIM runoff parameters on the water balance, a sensitivity analysis was performed, including the various runoff parameters of Eqs. 1 to 3, namely Manning's number (*n*), surface roughness, and surface conductance (*G*). In the sensitivity analysis, one of the parameters was changed at a time and for the other two parameters the mean value was used. Additionally, to investigate the effect of the RI (mm h^{-1}) on runoff, RI was varied between 1 and 20 mm h^{-1}, with 2 mm h^{-1} as the base value used for all simulations, in which the other factors were changed. This RI range was used to encompass storm events, with maximum 30 min RI in the region of 6.9 mm h^{-1} (Klik et al., 2015). APSIM simulations were run for 20 years based on the setup described above. For the sensitivity analysis, *n* was varied between 0.025 and 0.045 (typical values for pasture), the slope length L_0 was taken as 10 m, and average slopes were 6° (LS) and 18.5° (MS), and 30° (HS). This resulted in SWIM runoff rate factors of 47, 33 and 26 for LS; 83, 60 and 46 for MS; and 109, 78 and 61 for HS. For the surface roughness parameter (h_o), values between 0.2 and 1 mm, within the range of values given by Borselli and Torri (2010), were used. For *G*, values between 0.005 and 0.02 mm h^{-1} were used, which is at the lower measurement range reported by Connolly et al. (2002) for cropping systems.

Similarly, a sensitivity analysis was performed for the computation of the runoff of N (Eq. 4), and assuming that only urea and NO_3 are prone to runoff. Ammonium, which is adsorbed by the soil, has been shown to

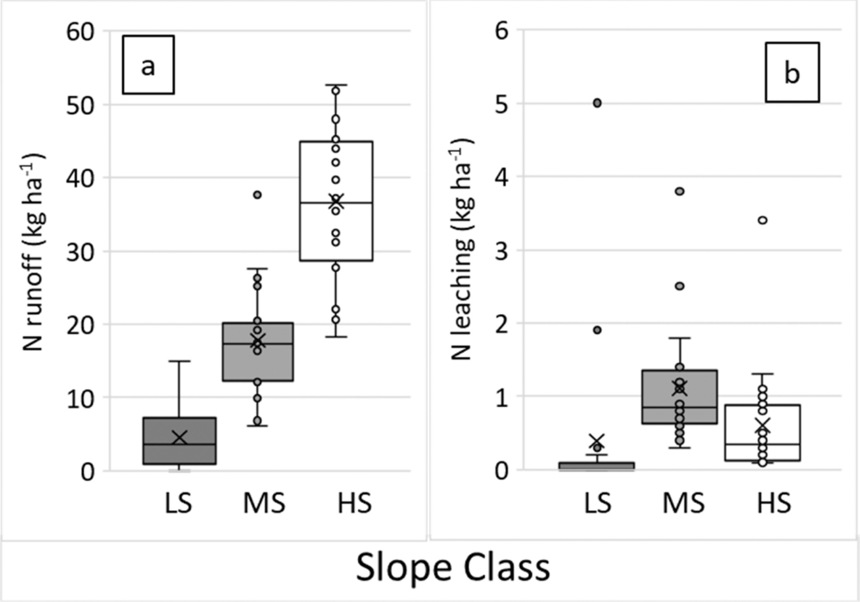

Fig. 3. N runoff (a) and NO_3 leaching (b) simulated by the Agricultural Production Systems Simulator (APSIM) with an annual N fertilisation rate of 250 kg N ha^{-1} over 20 years for terrains with different slopes with an extraction coefficient (*Ex*) of 1000 and considering a depth of 30 mm for interacting with the runoff water. Slopes are low slope (LS) 6°; medium slope (MS) 18.5°; high slope (HS) 30°.

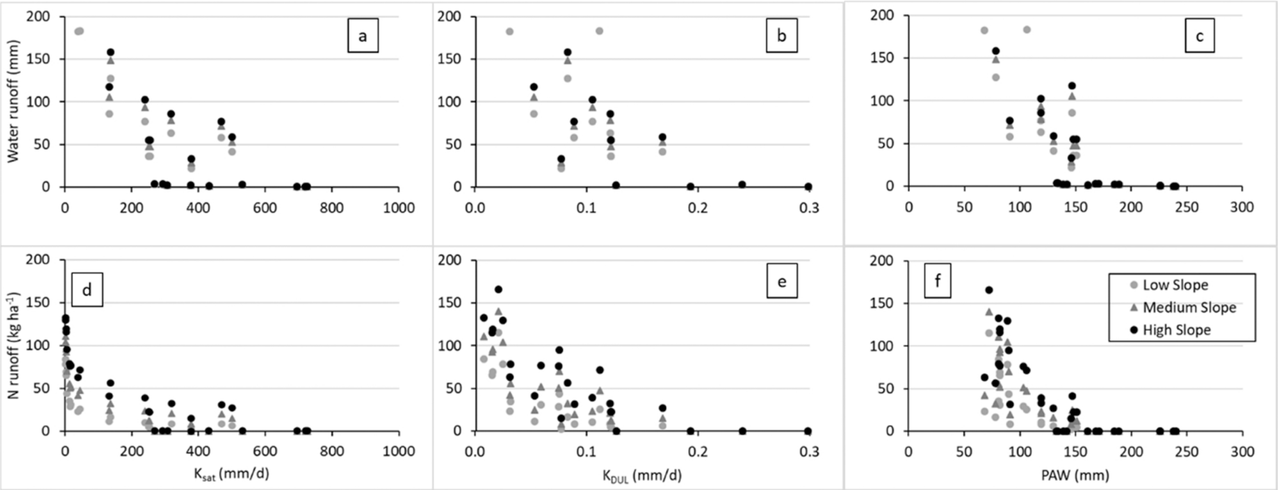

Fig. 4. Average water and N runoff simulated by the Agricultural Production Systems Simulator (APSIM) over 20 years using uniform soil profiles as function of (a) saturated hydraulic conductivity (K_{sat}), (b) hydraulic conductivity at field capacity (K_{DUL}), and (c) plant available water content (PAW) in a profile of 1 m depth for different slopes: low slope (LS) 6°; medium slope (MS) 18.5°; high slope (HS) 30°.

contribute negligibly to N runoff (e.g. Zhang et al., 2010). For the simulation runs for sensitivity analysis, the value of *Ex* was varied between 1 and 10.000, the depth from which N runoff can occur between 10 and 30 mm, and f_z was either assumed constant with depth, or decreasing with depth. Water runoff parameters for this analysis were kept constant for each slope: h_o was set to 0.6 mm for LS, 0.17 mm for MS and 0.16 mm for HS following the approach suggested by Borselli and Torri (2010), and measurements of the roughness index for a sheep and beef farm in New Zealand by Betteridge et al. (1999). The surface conductance was set to 0.01 mm h^{-1} and Manning's number *n* was set to 0.035 for all slopes. A RI of 2 mm h^{-1} was used. Annual N fertilisation was either applied at a rate of 100 or 250 kg N ha^{-1}, to assess any effect of the fertilisation rate on the sensitivity of model parameters on N runoff.

A third sensitivity analysis was carried out to investigate the effect of physical soil properties on N runoff. This included the effect of the hydraulic conductivity at saturation (K_{sat}) and field capacity (K_{DUL}; −10 kPa), plant available water to a depth of 1 m (PAW). For this, soil profile descriptions measured in hill country in New Zealand were used. To circumvent the problem of the influence on underlying horizons on water dynamics and runoff losses, profile descriptions were set up uniformly with any of the 56 soil horizons available. Out of these 56 horizons, for 29 horizons APSIM simulations showed runoff of water and N (Table 3), with the water runoff parameters given above.

Finally, a sensitivity analysis was carried out to investigate the effect of the soil organic matter content on N runoff. For this analysis organic carbon in the top-soil was varied between 1.9 % and 10 % C, the range that has been measured in Hill Country in New Zealand (Langer et al., 2020; Mackay et al., 2021; Schipper et al., 2011).

2.4. APSIM model setup for the effect of fertilisation regime

For investigating the effect of fertilisation regime, another set of APSIM simulations was set up as above. In these, fertilisation was either scheduled, with a uniform annual application of 250 kg N ha^{-1}, split into five applications, or varied across the terrain based on a multi-variate model developed previously (Vogeler and Cichota, 2017). This approach uses the pasture N content (g N/kg DM) prior to fertilisation, the month, the expected yield in that month, and a target threshold of the maximum yield:

$$N_{r,Ncont} = \ln\left(\frac{(Y_{\max} - Y_T)}{(Y_{\max} - (a + bN_{cont}))}\right) \Big/ (c - dN_{cont}) \quad (5)$$

where $Y_{\max}$ is the maximum or potential yield under the climatic and edaphic conditions and *a*, *b*, *c*, and *d* are fitting parameters. The values of all these five parameters should depend on environmental growth conditions and are also assumed to vary with time, i.e. by month. For the simulations here, the values derived for an irrigated ryegrass on a Templeton silt loam in the Canterbury area (Lincoln) were used (Cichota et al., 2018). Two simulation runs with this algorithm were set up targeting a maximum yield of either 80 or 90 % for all terrains. Water runoff parameters were setup as in the sensitivity analysis for N runoff. For N runoff the following parameters were used: RI = 2 mm h^{-1}, *Ex* = 1000, and the depth considered for runoff = 30 mm, with $f_z = 1$ for all soil layers.

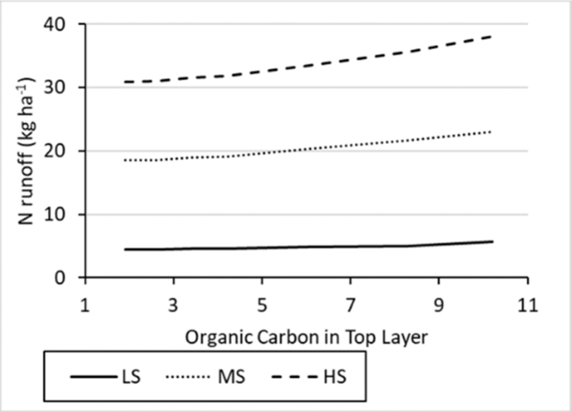

Fig. 5. Average N runoff simulated by the Agricultural Production Systems Simulator (APSIM) over 20 years based on the organic carbon content (OC) of the top layer (150 mm) for different slopes: low slope (LS) 6°; medium slope (MS) 18.5°; high slope (HS) 30°.

Table 4
Agricultural Production Systems Simulator (APSIM) simulation results of average annual dry matter (DM) production (kg ha^{-1}), nitrogen (N) fertiliser application (kg ha^{-1}), N fixation (kg ha^{-1}), water runoff (mm) and N runoff (kg ha^{-1}) over a simulation period of 20 years, and based on either scheduled fertilisation or an algorithm based on the N content of the pasture and the month of the year and targeting either 90 % or 80 % of the potential (pot) yield. Simulations were done for three slope classes (low slope, LS 6°; medium slope, MS 18.5°, high slope, HS 30°), and farm scaled (F_{scale}) values are also.

	Scheduled				Algorithm (90 % pot yield)				Algorithm (80 % pot yield)			
	LS	MS	HS	F_{scale}	LS	MS	HS	F_{scale}	LS	MS	HS	F_{scale}
DM	10,229	8274	6909	9770	12,597	11,053	8503	12,161	10,398	8568	7027	9955
N fert	250	250	250	250	334	355	295	336	211	225	204	213
Fixation	120	67	21	107	114	32	12	97	146	62	20	127
Drainage	40	109	173	57	59	113	172	73	65	114	176	78
Runoff	44	66	89	50	47	65	87	52	49	66	88	53
N runoff	4	18	36	8	2	7	15	4	1	3	7	2
N leaching	0.7	1.3	0.7	0.8	0.4	0.5	0.3	0.4	0.4	0.5	0.2	0.4
Denitrification	3.4	13.0	14.9	5.5	1.4	3.4	3.7	1.8	1.0	2.8	1.6	1.3

3. Results and discussion

3.1. Effect of runoff parameter values on water runoff based on sensitivity analysis

The results showed that variations in Manning's number affected water runoff by less than 1 %, and thus results with these parameters are not further discussed here. Increasing the surface roughness (h_o) from 0.2 to 1 mm also had little effect, decreasing water runoff by 7 mm for LS, 12 mm for MS and 15 mm for HS (Fig. 1). The surface conductance had a much larger effect, with an increase in water runoff of 74 mm for LS, 112 mm for MS and 120 mm for HS at the lowest conductance of 0.005 mm h^{-1}. The RI had the largest effect on water runoff and drainage, increasing drainage by about 300 mm for all slopes at the highest intensity of 20 mm h^{-1}. However, RI are rarely available in weather data or inadequate at sub-daily resolution (Kandel et al., 2004).

The relative high sensitivity of the surface conductance regarding water runoff suggests that such measurements are needed for accurately simulating water runoff in Hill Country, where a compact surface layer can develop through destruction of soil aggregates by both raindrop impact and water flowing over and the surface, and thereby placing fine particles between larger ones and reducing the size of pores (Eisenhauer et al., 1992). Surface conductance can, especially when also used as a proxy for hydrophobicity, vary throughout the year, and this temporal variation needs to be investigated. The sensitivity also reveals the high effect of the rainfall intensity on simulated water runoff. By default, APSIM assumes an even distribution of the daily rainfall. Especially with the likely occurrence of increased precipitation extremes, higher timely resolution is needed to improve water runoff predictions by simulation models.

3.2. Effect of N runoff parameter values based on sensitivity analysis

The sensitivity of the N runoff parameters showed little N runoff from the LS (Fig. 2d to f), with a maximum of and 0.9 kg N ha^{-1} for an annual fertilisation rate of 250 kg N ha^{-1}, for the scenario in which N runoff only occurs from the top 10 mm and all urea and NO_3 resident in the top 10 mm interacts with the runoff water. This assumption would include runoff of non-dissolved fertiliser N. Increasing the depth from which runoff would extract N to 30 mm increased runoff to 1.1 and 4.6 kg N ha^{-1}. If instead it is assumed that the N concentration in the runoff water is in equilibrium with that of the soil solution ($Ex = 1$), only 0.1 and 0.3 (depth of 10 mm) or 0.3 and 1.2 kg N ha^{-1} (depth of 30 mm) are lost via runoff for the two fertilisation rates. N runoff from MS and HS are as expected higher, with values reaching 18 and 37.3 kg N ha^{-1} for MS and HS (with all NO_3 and urea in the top 30 mm prone to transport via runoff). Changing the depth factor f_z to decrease with depth, only had a very minor effect on N runoff losses (data not shown). With a reduced annual N fertilisation rate of 100 kg N ha^{-1}, the extraction coefficient seems less sensitive to the amount of N runoff, and only the depth considered seems to effect N runoff (Fig. 2a to c). The amount of N runoff reveals, as expected, a high year-to-year variability, especially on the HS, with values ranging from 18 to 53 kg N ha^{-1}, when using an Ex of 1000 and a depth of 30 mm (Fig. 3). N leaching also shows some variability but is always ≤ 5 kg N ha^{-1}.

The simulated values for N runoff are within the range reported by

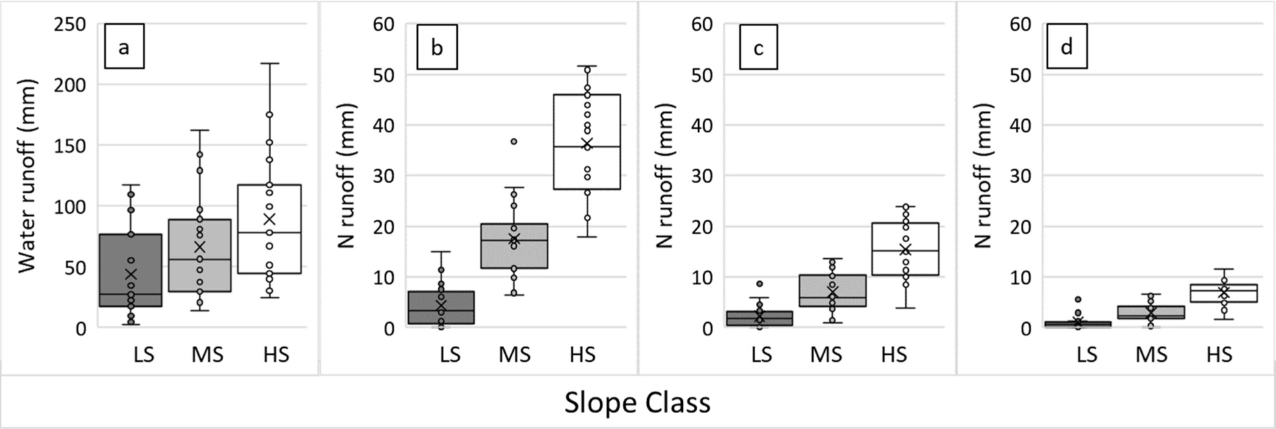

Fig. 6. APSIM simulation results of (a) water runoff (mm) and N runoff (kg ha^{-1}) over a simulation period of 20 years, and based on either scheduled fertilisation (b) or an algorithm based on the N content of the pasture and the month of the year and targeting either 90 % (c) or 80 % (d) of the potential yield. Simulations were done for three slope classes (low slope, LS 6°; medium slope, MS 18.5°, high slope, HS 30°).

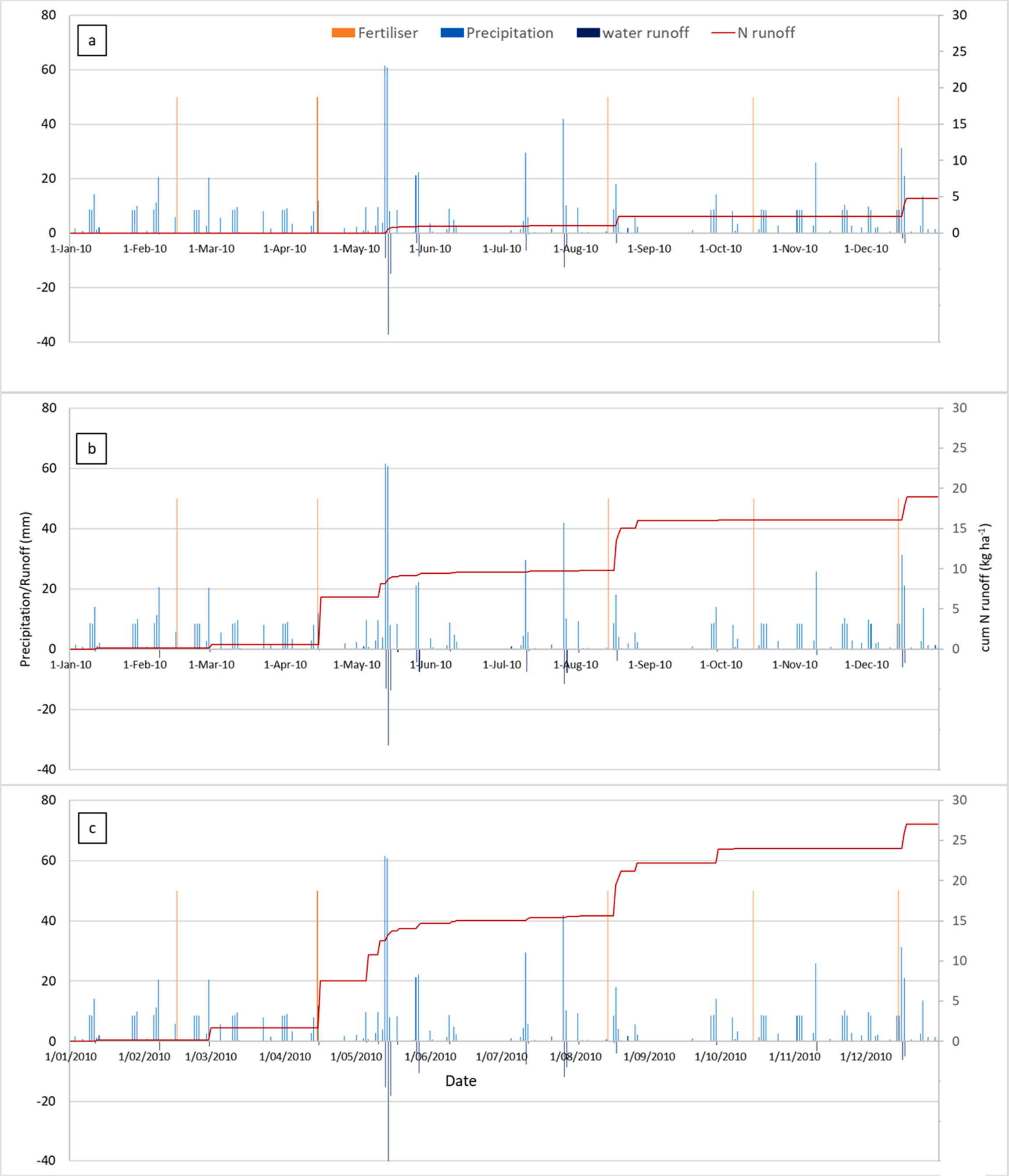

Fig. 7. Temporal dynamics of some of the water and N components for three slope classes (low slope, LS 6°; medium slope, MS 18.5°, high slope, HS 30°) over a period of one year.

Thayalakumaran et al. (2016) based on modelling for a catchment in Australia, with similar slope ranges of 1°–17° with annual N runoff losses from poorly drained soils of up to 18 kg N ha^{-1}. Barlow et al. (2007) measured annual N runoff from a pasture in Australia with a slope of 2° ranging from 0.06 to 11.9 kg N ha-1, which is in the range simulated for LS.

These sensitivity simulations were based on a RI of 2 mm h^{-1}, higher intensities would increase both water and N runoff. Other parameters that affect the amount of N runoff are even less known, such as the depth over which the runoff water interacts with the soil, and how the N resident in the soil interacts with the runoff water. To further advance modelling of N runoff, these parameters need to be measured in controlled experiments.

3.3. Effect of soil properties on N runoff

Apart from the surface conductance and the rainfall intensity, hydraulic properties also affect the amount of water runoff, with decreasing runoff with higher values of K_{sat}, K_{DUL}, and PAW (Fig. 4). This can be explained by the effect of these on water movement and drainage when using the smoothed version of the Brooks and Corey model for the water retention and hydraulic conductivity functions, and accounting for dual porosity (Vogeler et al., 2021). Driven by the effect of the soil hydraulic parameters on water runoff, the runoff of N also decreases with increases in hydraulic conductivity and PAW. This sensitivity analysis reveals that for accurate predictions of water and N runoff measurements of hydraulic properties are also important.

The soil organic carbon content of the soil also affects the N runoff (Fig. 5). While the effect is low on LS, N runoff increases with increasing SOC from 1.9 % to 10.2 % C on MS by 4.4 and on HS by 7.1 kg N ha^{-1}, on average over the 20 years simulated. This is due to increased mineralisation, which increases the mineral N concentration in the soil solution, and when this occurs at a time of water runoff, increases the risk of N runoff.

3.4. *Effect of fertilisation management on pasture yield, water and N balance analysis*

The annual average irrigation was estimated to be 281 mm, ranging from 180 mm to 420 mm for the 20 years simulated. This amount was based on the water deficit simulated for the LS. When using the algorithm for N fertilisation and targeting 90 % of the potential yield, the average annual N fertiliser application rate was about 30 % higher and the average yield about 25 % higher compared with the scheduled N fertilisation (Table 4). This shows that N fertilisation is better matched to the pasture demand when fertilisation is based on the algorithm, which takes the N content of the pasture prior to fertilisation into account. N losses through leaching were negligible (<1 kg N ha^{-1}). Denitrification losses estimated by APSIM ranged from 1 to 15 kg N ha^{-1}, and were reduced when the fertiliser algorithm was used. N runoff losses were substantially reduced, especially at the HS, from 36 to 15 kg N ha^{-1} when using the algorithm. Both runoff of water and N showed high annual variations (Fig. 6), with higher variability with increasing slope. For example, under scheduled fertilisation of 200 kg N ha^{-1} N losses from the HS range from 18 to 52 kg N ha^{-1}. Using the fertiliser algorithm reduces the annual variation to 4–24 kg N ha^{-1} with a targeted yield of 90 %, and to 2–12 kg N ha^{-1} with a targeted yield of 80 %.

Temporal dynamics of some of the water and N components are shown in Fig. 7 for period of one year, and for the different slopes. This shows, that when N fertiliser is applied shortly before a water runoff event, such as happened on the 18th of August 2010 (with N fertiliser applied three days prior), some of this N is lost via runoff, with higher amounts lost at higher slopes. However, N runoff can also occur much later than the N fertilisation, as can be seen in the large runoff event in the middle of May, one month after the last N application. Most of the N runoff occurs in autumn and winter (between middle of April and August), suggesting that N fertilisation should be avoided during this time in terrains with higher slopes to reduce N losses via runoff.

Farm-scaled N runoff losses, taking account of the area proportions of the various terrains, were also reduced from 8 kg N ha^{-1} at the scheduled fertilisation to 4 kg N ha^{-1}, when using the algorithm and targeting 90 % of the potential yield (Table 4). N runoff losses could be further reduced by using the fertiliser algorithm and targeting a lower yield, as shown for 80 % of the potential yield. In this case, N runoff was reduced to 7 kg N ha^{-1} in the HS and the farm-scaled N runoff was decreased to 2 kg ha^{-1}, with only a small impact on DM yield and a reduction in N fertilisation of 15 %, almost 30 kg N ha^{-1}.

Direct leaching from the fertiliser was negligible in all cases. However, in grazed dairy pastures most of N leaching originates from urine patches (Li et al., 2012; Romera et al., 2017), which were not considered here. Urine patches could similarly increase the risk of N runoff. Urine patches will be included in future studies. The use of the multi-variate algorithm would enable to target N fertilisation at the urine patch scale, with reduced or no N application in these areas.

4. Conclusions

We developed an approach within APSIM to simulate runoff of N based on the amount of water runoff and the concentration of N in the top soil. This approach takes into account the depth from which runoff can occur, the form of N (either urea, NH_4 or NO_3), as well as a factor for the interaction, or extraction, of solute from the soil and the runoff water. A sensitivity analysis indicated the factors that have the highest influence on water and N runoff. While there are some data on the value for the parameters that govern water runoff, there is even less information for N runoff. Thus, detailed runoff experiments should be set up, measuring N concentrations in the soil and the fraction of these lost via runoff based on soil properties and RI. Such information is needed when deterministic models, such as APSIM, are used for evaluating the effects of different N fertilisation practices on pasture production, N losses and runoff on a site with different terrains. Using a fertilisation algorithm based on the N content in the pasture is a promising approach for improving N fertiliser application on sloping terrain, as it can reduce N losses from runoff with no losses or even gains in biomass production.

Declaration of Competing Interest

The authors certify that they have no conflict of interest.

Data availability

Data will be made available on request.

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