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Development of the Moorepark St Gilles grass growth model (MoSt GG model): A predictive model for grass growth for pasture based systems

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ABSTRACT

In humid-temperate regions grazed grass is the most economical means of feeding ruminant livestock. Grass growth is often highly variable and therefore difficult to predict. It is influenced by many factors including climatic conditions, soil type and soil nutrients. The Moorepark St. Gilles Grass Growth model (MoSt GG model) is a dynamic model developed in C++ describing daily grass growth at the paddock level. It was developed by adapting an existing grass growth model to include a nitrogen (N) component and a soil water component. The model is effective in grazing and cutting scenarios. Inputs include weather data, grazing management decisions and N fertiliser application. Outputs include daily grass growth, soil mineral N content, grass N uptake, grass N content and NO_3^- leaching. The MoSt GG model was evaluated against measured data using 2 years data from an experimental farm; the predicted and measured biomass for each paddock was compared. The mean root mean square prediction error (RMSPE) at the measurement level was 505 kg DM/ha. When averaged by week of year, the RMSPE was reduced to 321 kg DM/ha. The MoSt GG model was also evaluated against a range of management scenarios including N fertiliser application rate (from 0 to 650 kg N/ha per year) and defoliation management, and weather conditions. The grass growth response to N fertiliser application was, on average, 9.6 kg DM/kg N applied with a minimum response of 0.8 kg DM/kg N applied and a maximum response of 16.2 kg DM/kg N applied, which is in the range of previously published studies. The MoSt GG model responds to daily weather conditions, patterns and methods of sward defoliation, and describes daily variations in soil mineral and organic N content.

1. Introduction

Food demand (including dairy products) is increasing due to global population growth (PopulationDivision, U. N., 2012). Grass provides the cheapest and best quality feed for dairy cows in temperate climates (Dillon et al., 2005; O'Donovan et al., 2011). Predictive grass growth models can improve the agronomic efficiency and animal output of dairy farms by aiding the decision making process at farm level. However, although a humid-temperate climate allows grass growth throughout the year, grass growth is highly seasonal and is strongly influenced by climatic conditions (Keane and Collins, 2004; Hurtado-Uria et al., 2013) and the interaction with soil characteristics. Management of pasture, in terms of nitrogen (N) fertilisation application rate, grazing or cutting intensity, rotation length, and spring and autumn management, is also an important factor influencing grass growth (Murphy, 1977; O'Donovan et al., 2011).

For pure grass stands, nitrogen fertiliser application is necessary to produce large quantities of high quality forage (Whitehead, 1995). However, N fertiliser is an expensive farm input, and potential losses are both financially and environmentally costly. Therefore, in the context of economic and environmental sustainability, modelling of N losses from grassland in tandem with grass growth would be valuable. Similarly, predictive grass growth models that incorporate current and future management decisions, as well as weather conditions, would be useful tools to increase farmer knowledge around grass supply on their farms. This would improved grazing management, and short to medium term feed budgeting.

Grass growth models have already been developed to predict the effect of a changing climate on grass production (e.g. Thornley and Cannell 1997; Holden and Brereton, 2002, and Fitzgerald et al., 2009), and to quantify the effects of changes to grassland management on annual and seasonal grass production (Brisson et al., 2003; Cros et al., 2003; Barrett et al., 2004, 2005; Herrmann et al., 2005; Jouven et al., 2006a). Most existing grass growths models are only used by researchers. For a grass growth prediction model to become a valuable grassland management decision support tool that can be widely used,

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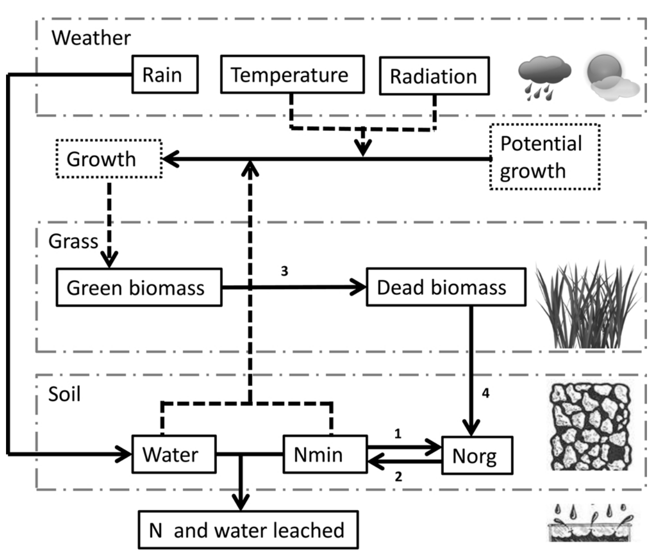
the model must be easily adaptable to a range of soil types and management conditions. To increase the likelihood of use at farm level, few input data should be required. The model must however respond to the main factors that influence grass growth including defoliation, N fertiliser application, N returned to soil from livestock faeces and urine, and soil water content. The Jouven model (Jouven et al., 2006a,b) was originally developed to predict grass growth from permanent grassland in the centre of France, and then adapted for use in Irish conditions (Hurtado Uria, 2013). The first objective of the present study was to develop the Moorepark St. Gilles Grass Growth model (MoSt GG model), a dynamic model capable of accurately simulating grass growth at field scale in a pasture based system, by improving the adapted Jouven model (Jouven et al., 2006a; Hurtado Uria, 2013) through the addition of soil, plant N and soil water sub-models. The second objective was to evaluate the model firstly by comparing the model prediction with two years of data measured on an Irish farm, and secondly by evaluating the agronomic consistency of the model by simulating different N-fertilisation and defoliation regimes during two contrasting weather years.

2. Materials and methods

The basic structure of the MoSt GG model is presented in Fig. 1. The model incorporates the grass growth model developed by Jouven et al. (2006a) and adapted by Hurtado-Uria et al. (2013). In the Jouven model, the supply of N is static and constant. A soil and plant N submodel was developed, based on previously published work (Mary et al., 1999; Valé, 2006), and added to the Jouven model to account for the cycling of N in pasture (Delaby et al., 1997; Hutchings et al., 2007). In addition, a soil and water sub-model was added to account for water fluxes in a number of soil types. The development of both the N and water sub-models and their interactions allowed NO_3^- leaching and N emission to be quantified. To accurately predict the impact of a grazing animal, an animal element was incorporated to account for localised urine and faeces deposition to pasture during grazing. The MoSt GG model was developed in the programming language C++.

2.1. Overview

The MoSt GG model is composed of a grass model and N uptake sub-model, and a soil sub-model. The model operates in a daily time step. To allow the model to take into account the heterogeneity of a grazed paddock resulting from the presence of livestock and their deposition of urine and faeces, each 2 m^2 of the paddock is represented individually. The size of the area of the urine patches and the size of the area influenced by the urine, known as effective area, are highly variable (Moir et al., 2011). The variability comes from the volumes and N content of urine deposited, wind, slope, antecedent soil moisture, and soil physical condition (Selbie et al., 2015). In the model, to allow for balance between agronomic accuracy and computational efficiency, the effective area of a urine or faeces deposition is 2 m^2.



[1] Immobilisation, [2] Mineralisation, [3] Senescence, [4] Abscission.

Fig. 1. Schematic representation of the basic interaction of Moorepark St. Gilles Grass Growth model (MoSt GG model) which describes the dynamics of grass growth, soil water and soil N content.

The main outputs of the model are daily grass growth (kg DM/ha per day), biomass (kg DM/ha), grass height (cm), grass N content (g N/kg DM), NO_3^- leaching (kg N/ha), soil mineral N and organic N content (kg N/ha) and soil water content (Table 1). The outputs of the model are at the paddock or at the 2 m^2 scale, and can be extracted on a daily, weekly, monthly or yearly basis, or the average of the yearly simulation.

There are two categories of input data required – environmental (weather and soil type) and management (N fertilisation, grazing and cutting event) (Table 1). To facilitate the utilisation of the model and to make it flexible, five defoliation management options are available. The details of those options are presented in Table 1. Briefly, the user can choose to either give the day of each of the defoliation events, in that case the model will predict the number of animals present on the paddock, or the user can choose to enter the pre-grazing sward height of each defoliation event and the model will predict on which day of the year those events will occur. The first option is to allow the user to represent past farm management by inputting the actual date and number of animals for each grazing event. The second option allows the simulation of grazing management by technniques such as pre- and post-grazing sward height, fixed residence time or fixed grazing dates. It is also possible for grazing management data from other models such as the Pasture-Based Herd Dynamic Milk model (Ruelle et al., 2015) to be used in the MoSt GG model.

2.2. Soil sub model

The soil sub model describes the flux of N in the soil. Soil N mineralisation and immobilisation are the main two processes which determine the balance and efficiency of N utilisation (Murphy et al., 2003; Stark and Richards, 2008). The soil sub model quantifies gross mineralisation and gross immobilisation separately to describe the flux of N observed in permanent pasture (Soussana and Lemaire, 2014). Daily mineralisation and immobilisation are described using the coefficients Vp and Ip which are dependent on temperature (fT) and soil humidity (g0) (Mary et al. (1999); Valé (2006)). The distinction between mineralisation and immobilisation is novel, and contrary to Mary et al. (1999) allows the quantification of N immobilisation, and the impact of grassland on the fixation of organic N and carbon.

$$Mineralisation = Vp \times fT \times gO \quad (1)$$

With:

$$0 < \left[Vp = \left(0.0929 + (0.1833{-}0.0929) \times e^{-0.2173 \times \frac{Norg}{1000}} \right) \times \frac{Norg}{1000} \right] < 2.2 \quad (2)$$

where Norg = organic N in the soil in kg N/ha,

$$fT = e^{0.115 \times (T-15)} \quad (3)$$

where T = average temperature of the day in °C,
and

$$0 < \left[gO = (1{-}0.2) \times \frac{water{-}wiltingPoint}{waterCapacity{-}wiltingPoint} + 0.2 \right] < 1 \quad (4)$$

Table 1
Representation of the different inputs and outputs of the MoSt GG model.

Inputs				Outputs		
Soil/Paddock *Once*	Weather *Daily*	Defoliation *At each event*	Fertilisation *At each event*	Soil *Daily*	Grass *Daily*	Water *Daily*
N min (*kg/ha*) OM (%) Clay (%) Sand (%) Area (*ha*) Starting biomass (*kg DM/ha*)	Minimum temperature (*°C*) Maximum temperature (*°C*) Average temperature (*°C*) Rainfall (*mm*) Solar radiation (J/cm^2)	Day[a,b,c] Type: Grazing/Cutting[a,b,c,d,e] Pre-grazing or cutting height (*cm*)[d,e] Post-grazing or cutting height (*cm*)[a,b,c,d,e] Number of cow [a,c,e] Feeding information [a,b,c,d,e]	Day Type: mineral/organic Total quantity of N applied (*kg N/ha*) Percentage of mineral N (if organic)	Mineral Nitrogen pool (*kg N/ha*) Organic Nitrogen pool (*kg N/ha*)	Grass growth (*kg DM/ha*) Biomass (*kg DM/ha*) Grass height (*cm*) % of N in the grass	Soil water content N leaching (*kg N/ha*)

[a] Day of defoliation, length of the grazing event, post-grazing sward height and the number of animals are fixed by the user - > the model calculates the grass intake by the animal (kg DMI/animal/day).
[b] Day of defoliation, length of the grazing event, and intake is fixed by the user - > the model calculates the number of grazing animals.
[c] Day of defoliation, number of grazing animals, and intake is fixed by the user - > the model calculates the length of the grazing event.
[d] Pre-grazing sward height, length of the grazing event, and intake is fixed by the user - > the model calculates the number of grazing animals and the day of the defoliation event.
[e] Pre-grazing sward height, number of grazing animals, and intake is fixed by the user - > the model calculates the length of the grazing event and the day of the defoliation event.

where water = the water content of the soil on a given day (within the top 100 cm of soil); wilting point and water capacity depend on the soil structure (see Supplementary material section 1.4).

$$Immobilization = Ip \times fT \times gO \tag{5}$$

With:

$$Ip = 4 \times \frac{Nmin}{1000} \tag{6}$$

where Nmin = the soil mineral N content in kg N/ha.

In the MoSt grass growth model, Vp (Eq. (2)) is not constant and is adjusted based on the soil organic N content, where the higher the organic N content the greater the rate of N mineralisation. However, this increase in mineralisation is neither linear nor infinite ($Vp < 2.2$), representing the decline in the efficiency of mineralisation as soil mineral N content increases. In contrast, the coefficient Ip (Eq. (6)) is only dependent on the mineral N available in the soil with a constant linear coefficient. These two equations allow the model to take account of the permanent fluxes between the mineral N and organic N pools in pasture.

The soil sub model also considers soil water content. The soil water used to calculate NO_3^- leaching is that present in the top 100 cm of the soil, while the soil water available for grass growth is that present in the top 60 cm of the soil which corresponds to the soil depth in which most of the grass roots are present. Soil water content is described in terms of wilting point, field capacity and saturation, all of which are influenced by the soil's sand, clay and organic matter (OM) content (Dunne and Willmott, 1996) (Supplementary material section 1.5). Saturation point refers to the maximum quantity of water which can be contained in the soil. The equations and the details of the water sub model are presented in the supplementary material section 1.6.

Briefly, on a daily basis, the soil water content is calculated as the water in the soil on the previous day and the rainfall of the day minus the water lost through evaporation. If this value is higher than the saturation point, the surplus water either will remain on the paddock (20%) and be added to the following days' water stock, or will run off (80%) (Supplementary material section 1.6). The first state of soil water content is wilting point (Dunne and Willmott, 1996). If the soil water content is lower than the wilting point no water can be extracted by the plant and there will be zero grass growth. The second is the field capacity of the soil (Dunne and Willmott, 1996). If the water content of the soil is between wilting point and field capacity grass can grow but there is no leaching. The final state is saturation point (Dunne and Willmott, 1996); which is when soil is saturated and there is surplus water on the paddock.

Nitrate leaching occurs between field capacity and saturation point. Nitrate surplus to the requirements of the growing crop can potentially be lost through leaching or denitrification in the event of excess precipitation (Scholefield et al., 1991). The equations describing NO_3^- leaching and the calculation of the water leached are presented in the Supplementary material section 1.6. The model also describes soil N nitrification and denitrification (Supplementary material section 1.3 adapted from Mary et al. (1999)) and the rain N mineral deposition (Supplementary material section 1.4 adapted from Ryan et al. (2011)).

2.3. Grass growth and grass N content sub model (adaptation of the Jouven model)

The Jouven model (Jouven et al., 2006a) was designed for use in central France and later its parameters were adapted and the model was validated for use in Irish cut grass pastures (Hurtado Uria, 2013). The Jouven model, using the parameters adapted for conditions in Ireland, is referred to as the Adapted Jouven model. The model describes the effect of management (date and height of grass harvest) and weather on grass growth (Hurtado Uria, 2013). Root mass and root function are not represented in the model. Within this study, the Adapted Jouven model was used as a base and was further developed to take into account soil N and water availability. In the MoSt GG model, daily grass growth is calculated based on potential grass growth, an environmental factor and the availability of N in the soil (Eq. (7)):

$$growth = PotentialGrowth \times fParamEnv \times NdemandSatis \tag{7}$$

with growth and potential growth in kg DM/ha.

Potential grass growth (Eq. (8)) is influenced by daily radiation (J/cm^2) and the current biomass above 4 cm (Jouven et al., 2006a):

$$potentialGrowth = \frac{0.48 \times rad}{100} \times 2.1 \times (1 - e^{-0.6 \times lai}) \times 10 \tag{8}$$

where rad = radiation of the day (J/cm^2) and lai = leaf area index (Supplementary material section 2.2.1). The environmental factor (fParamEnv) comprises three different functions with values between 0 and 1 which are influenced by temperature, water available in the soil for the plant, and daily radiation (Supplementary material section 2.2.2 (Jouven et al., 2006a)). The last function (NdemandSatis; Eq. (9) and Fig. 2a) has been specifically developed for this model. The function reflects the proportion of potential grass growth that can be achieved

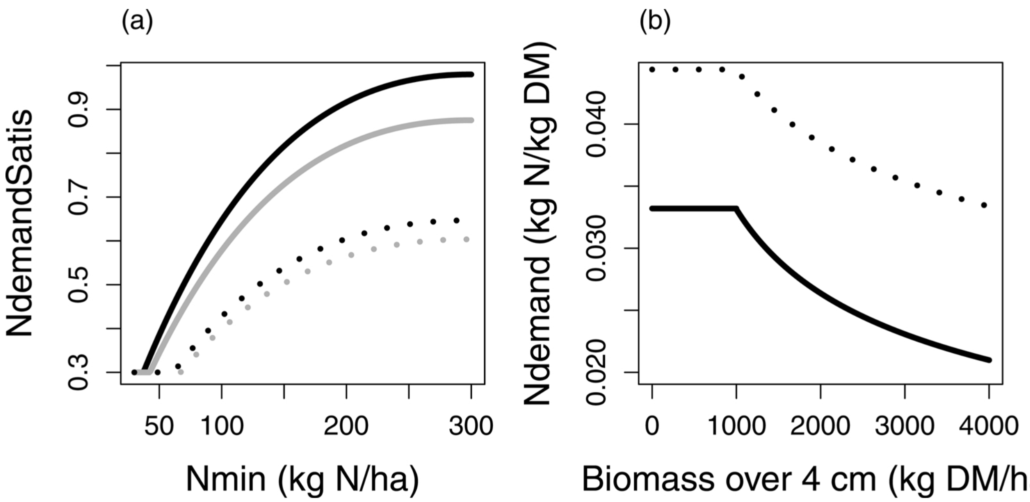


Fig. 2. Description of the a) variation of the proportion of potential grass growth that can be achieved (NdemandSatis) depending on the variation of mineral N in the soil, at either a biomass over 4 cm equal to 0 (grey) or 1.4 t DM/ha (black) at day 100 (plain line) or 300 (dotted line) of the year b) N requirement to produce 1 kg of biomass depending on the biomass over 4 cm at day 100 (plain line) or 300 (dotted line) of the year.

based on the availability of soil mineral N for the plant compared to what is required by the plant to grow 1 kg grass dry matter (**DM**), which corresponds to the reverse of the N dilution curve (Lemaire et al., 1984b,a; Gastal and Lemaire, 2002).

$$0.3 < \left[NdemandSatis = \frac{propNabs \times Nmin}{Ndemand} \right] < 1 \quad (9)$$

where propNabs = the proportion of the mineral N which can be absorbed by the plant:

$$propNabs = propNabs_0 \times (0.05 + (2{-}0.05) \times e^{-0.0036 \times Nmin} \quad (10)$$

where $propNabs_0$ is described in the section 2.2.3 of the Supplementary materials. The N dilution curve represents the decline in the quantity of N required to grow 1 kg DM grass as the quantity of accumulated biomass increases (Lemaire et al., 1984b,a; Gastal and Lemaire, 2002). The N demand to produce 1 kg DM (Ndemand) depends on heading date (day of year) and the plant biomass 4 cm above ground level (> 4 cm) (described in Supplementary material section 2.2.3 and Fig. 2b). The senescence and abscission of plant material are calculated using the equation from the Adapted Jouven model (Supplementary material section 2.4). A new development in the model is the prediction of the grass N content (Supplementary materials section 2.3). It has been assumed that the N content of the plant below 4 cm is 50% of the N content of material above 4 cm, and the N content of dead material was ascribed the fixed value of 8 g N/kg DM (Delagarde et al., 2000).

2.4. Description of the management component

2.4.1. Fertilisation

Nitrogen fertiliser can be applied in mineral or organic form. The model assumes that when mineral N is applied no losses occur and the entire N applied goes directly to the N mineral stock in each 2 m^2 area of the paddock. When organic N fertiliser is applied a portion of the application is volatilized at spreading, a portion remains as mineral N and the remainder is partitioned to the soil OM stock. The partitioning of N to the different compartments (mineral or organic) depends on the type of manure applied, the percentage of mineral N in the organic fertiliser, and of the efficiency of the application, which takes into account time and method of application when inputting data into the model (Supplementary material section 3.1).

2.4.2. Defoliation - cutting

For each cutting event, the post-cutting height is an input to the model. The biomass harvested is calculated based on the post-cutting sward height. The post-harvest biomass content of each of the four structural components is based on the cutting height and the previous proportions of the biomass in each structural component.

2.4.3. Defoliation - grazing

For each grazing event the numbers of daily urine and faeces patches are calculated based on the number of animals on the paddock and the residency time on the paddock. The quantity of N in the urine and faeces depends on the daily DM intake of each animal (input) and the N content of the grass and supplements (Eqs. (11) and (12) and Supplementary material equation section 3.2): (Delaby et al., (1997)

$$NtotalDung = NfacesRate \times AnimalDMI \quad (11)$$

where NtotalDung = the total N excreted through faeces during a day (kg N/animal per day); NfacesRate = 0.008 kg N/kg DMI (Cutullic et al., 2013); (Delaby et al., 1997)

AnimalDMI: the total DMI intake of the animal during the day (kg DM/day)

$$NtotalUrine = AnimalNintake{-}NtotalDung{-}Nmilk \quad (12)$$

where NtotalUrine = the total N excreted through urine per the animal during the day (kg N/animal per day); AnimalNintake = the total N ingested by the animal during the day (kg N/animal per day) which depends on the level of supplementation and the N content of the grass and supplements (INRA, 2010); and Nmilk = the total N excreted in the milk (considered here as 0.11 kg per cow per day for a N milk content of 0.005 kg N/kg milk and an annual average milk production of 22 kg/cow) (Delaby et al., 1997). The total number of urinations and faeces excretion events per animal per day were 12 and 14, respectively (Whitehead, 1995). The partitioning of the organic and mineral N from a urine or faeces deposition is presented in the Supplementary material section 3.2. Each faeces or urine deposition is randomly assigned to one of the 2 m^2 areas within the paddock. Fig. 3 shows the random distribution of the urine patches in a 1 ha paddock after a single year model simulation.

2.5. Model evaluation

The model was evaluated in two steps. In the first step the model output was compared with measured data by reproducing an experiment conducted at an experimental farm during the years 2010 and 2011. The data was from the Teagasc Curtins Research Farm, Animal and Grassland Research and Innovation Centre, Moorepark, Fermoy, Co. Cork in the south of Ireland, latitude 50°07′ North, 8°16′ West. The starting date was either 1st January 2010 or 2011 and the soil mineral N content was 80 kg N/ha (decided upon through an iterative process aiming at having the same mineral N content at the start and end of the simulation in realistic simulation conditions). The sand, clay and OM

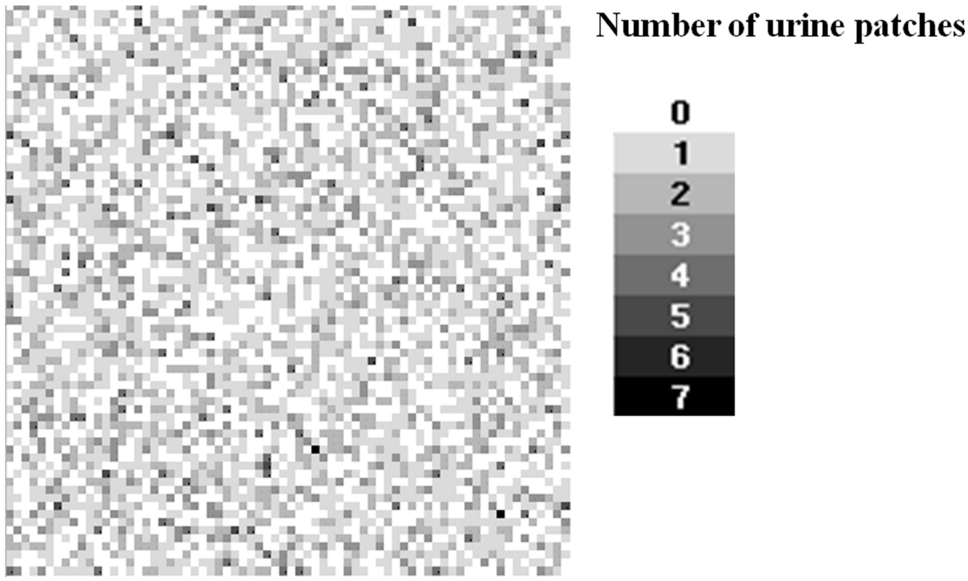


Fig. 3. Representation of the final random distribution of the urine patches on the different 2 m^2 blocks in a 1 ha paddock after a year of simulation of the MoSt GG model.

Table 2
Weather data from the Moorepark weather station for 2013 and 2015.

		J	F	M	A	M	J	J	A	S	O	N	D	Year
Average Temperature	2010	2.2	3.0	5.4	8.5	10.9	15.4	15.8	14.3	13.6	9.9	5.4	0.6	8.7
(°C)	2011	3.4	7.1	6.4	10.7	11.4	12.2	14.1	13.2	13.5	11.5	9.7	6.2	10.0
	2013	5.6	4.9	4.4	7.7	10.3	13.4	17.7	15.8	13.9	12.0	6.0	6.5	9.8
	2015	5.5	4.7	6.4	8.6	10.4	13.4	14.2	14.2	12.2	10.4	9.9	9.0	9.9
Rain	2010	107	39	88	59	38	53	143	23	102	83	98	37	869
(mm)	2011	57	92	28	26	81	62	55	35	99	83	157	81	856
	2013	118	46	85	71	64	35	61	52	38	150	54	172	946
	2015	109	61	78	19	111	34	97	104	92	70	110	324	1209
Average Radiation (J/cm^2)	2010	317	554	927	1388	1646	1815	1383	1494	974	605	306	227	970
	2011	279	423	989	1396	1470	1722	1475	1264	814	497	296	185	901
	2013	231	449	624	1243	1628	1768	1945	1395	938	589	326	209	945
	2015	288	478	927	1619	1543	1816	1409	1345	988	541	261	129	945

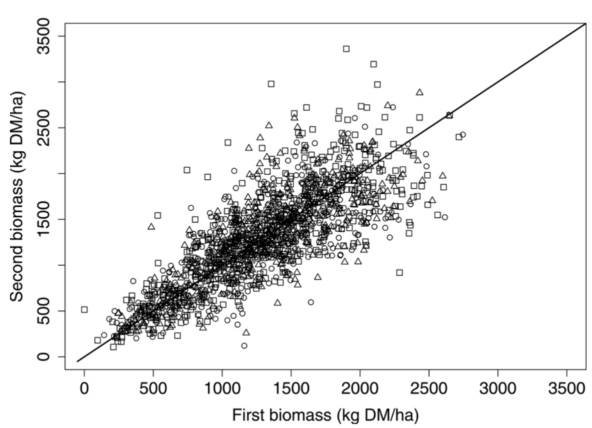


Fig. 4. Representation of the relationship between the two measurements within a paddock biomass estimation (kg DM/ha) showing the heterogeneity of paddocks. (Square = SR of 2.51 cow/ha; Circle = SR of 2.91 cow/ha; Triangle = SR of 3.28 cow/ha).

contents were 22%, 26% and 9%, respectively. Weather data were collected approximately 2 km from the experimental site (Table 2).

The second step in the evaluation involved simulating different management scenarios in terms of N fertilisation and defoliation management in two contrasting years (2013 and 2015; Table 2). The soil type was the same as in step 1 of the evaluation, and the weather data was sourced at the same location. The values and trends of simulated data were compared to literature data, to discuss the ability of the model to simulate grass growth, grass N content and N leaching in a range of realistic management practices.

2.5.1. Step 1: model validation

2.5.1.1. Experiment and dataset. Model predictions were validated against measured grass biomass from a grazing experiment undertaken at Teagasc Curtins Farm. The experiment is described in detail by McCarthy et al. (2013). Briefly, the objective of the experiment was to determine the impact of three stocking rates (SR) and two calving dates on key physical, biological and economic performance indicators. Separate farmlets of 18 paddocks were created and permanently fenced for each of the six treatments resulting in 108 individual paddocks totalling 48.1 ha. Grass species was predominantly perennial ryegrass. Mineral N fertilizer application rates for each treatment was 250 kg N/ha per year. Grazing management details were collected on all paddocks during each grazing rotation in each year. There were 23 cows per treatment. Pre-grazing herbage mass on each paddock was determined prior to grazing by harvesting two strips (1.2 m × 10 m) of grass with an Etesia mower (Etesia UK Ltd., Warwick, UK). The variability of biomass within a paddock was examined by comparing the two biomass estimations per paddock (cut 1 and cut 2; Fig. 4 and Table 3). The average of the two biomass estimations was used to give the measured biomass value on

Table 3
Comparison and evaluation between the two measurements taken during within each paddock during paddock biomass estimation (kg DM/ha).

	(kg DM/ha)		all	2010				2011			
				all	spring	summer	autumn	all	spring	summer	autumn
Actual	Average measured 1		1292	1229	687	1223	1422	1363	587	1461	1254
	Average measured 2		1297	1208	640	1205	1405	1398	534	1493	1265
	RMSPE		339	326	284	303	373	354	204	373	340
	Proportion	Mean	0.00	0.00	0.03	0.00	0.00	0.01	0.07	0.01	0.00
		Line	0.16	0.14	0.09	0.13	0.25	0.17	0.09	0.21	0.16
		Random	0.84	0.86	0.88	0.87	0.75	0.82	0.84	0.78	0.84

Spring: 1st Febuary–30 April; Summer: 1st May–31 July; Autumn: 1st August–31 October.

each individual paddock for comparison with the simulated data.

The model prediction of the yearly NO_3^- leaching and average annual grass N content for 2011 were compared with the data from McCarthy et al. (2015) who reported herbage N content and NO_3^- leaching for the years 2011–2013.

2.5.1.2. Simulation. Each of the 108 individual paddocks were recreated in the MoSt GG model. One simulation was run per paddock, per treatment (SR and calving date) and per year (2010 and 2011), resulting in 216 simulations. The following experimental data were used as inputs to the model:

- Weather: daily minimum, maximum and average temperature, daily total rainfall and radiation
- Grazing event: day, residence time (i.e. number of days grazing on the given paddock), daily access (i.e. time spent by animals on the paddock on a given day), post-grazing sward height and number of animals
- Cutting event: day and post-cutting sward height
- Fertilization event: day and quantity of N applied

The paddock biomass on each measurement occasion (1574 measured data points) in the grazing experiment was compared to the model prediction for the same day under the same climatic conditions.

2.5.1.3. Statistical analyses. Predicted and actual data were compared using mean square prediction error (MSPE) and the root mean square prediction error (RMSPE). The MSPE is the sum of three components, namely, the mean bias $(M_m - P_m)^2$, the line variation $S_P^2\ (1 - b)^2$ (the deviation of the slope of the regression line of P regressed on M) and the random variation about the line $S_M^2\ (1 - R^2)$. Each is expressed as a proportion of the total MSPE:

$$MSPE = \frac{\sum (M-P)^2}{n} = (M_m - P_m)^2 + S_p^2(1-b)^2 + S_M^2(1-R^2) \quad (13)$$

where n is the number of measured (M) and predicted (P) pairs compared; M_m and P_m are the means of M and P, respectively; $S_M^2$and S_P^2 are the variances of M and P, respectively; b is the slope of the line of P regressed on M; and R^2 is the determination coefficient of the line (Rook et al., 1990). A high mean bias indicates that the predicted values are consistently higher or lower than the measured values. The RMSPE is the root of the MSPE.

The model outputs were evaluated at the paddock level (on measurement dates and average annual measurements) and farm level (weekly). Those evaluations were conducted at a bi-annual, annual or seasonal resolution with the spring defined as week 1–13 of the year, summer as weeks 14–30 of the year, and autumn as weeks 31–45 of the year.

2.5.2. Step 2: management scenarios

The model was evaluated at four N fertiliser application rates (0, 150, 300, and 650 kg N/ha/yr), two contrasting weather years (2013 - total rainfall of 946 mm and average temperature of 9.8 °C; and 2015 - total rainfall of 1209 mm and average temperature of 9.9 °C) (Table 2), and two defoliation managements. The number of grazing or cutting events per year for the different defoliation managements were 6 (1st April, 1st May, 15th June, 1st August, 15th September and 1st November) and 11 (8th March, 29th March, 19th April, 10th May, 31th May, 21st June, 12th July, 2nd August, 23rd August, 13th September and 1st November). The post-grazing and post-cutting sward height was fixed at 4 cm. Nitrogen fertiliser was applied on the 16th February and the day after each cut (for all but the last cut of the year) as 1/6 or 1/11 of the total annual N fertiliser application. The number of animals for each daily grazing event was calculated based on the pre-grazing sward height calculated by the model and a daily DM intake of 16 kg DM/livestock unit (LU) per day. The outputs investigated were total net grass grown per year (kg DM/ha), NO_3^- leached per year (kg N/ha), and average annual grass N content (g/kg DM).

3. Results

3.1. Evaluation of MoSt GG model predictions against measured data (step 1)

3.1.1. Measured data - within paddock heterogeneity

The results are presented in Fig. 4 and Table 3. The overall RMSPE of the two paddock measurements in the grazing experiment on a given day was 339 kg DM/ha. The mean bias did not explain any of the MSPE. The random component explained 84% of the MSPE and the line bias explained 16% (Table 3). The RMSPE was similar for the two years and no clear relationship with season was found.

3.1.2. Model evaluation

When the predicted biomass was compared with the corresponding measured data for each measurement, the RMSPE was 505 kg DM/ha (Table 4 and Fig. 5). The majority of the error was in the random component (52%) and the line bias component (47%). The predictions were similarly accurate for 2010 and 2011, with a RMSPE of 499 and 512 kg DM/ha, respectively. Similar to measured data, the MoSt GG model predicted a greater biomass in 2011 compared to 2010 (168 kg DM/ha greater for the measured value compared to 155 kg DM/ha greater for the predicted value).

The RMSPE was reduced to 321 kg DM/ha when the weekly measured biomass was compared with the weekly prediction (Table 4 and Fig. 6). The RMSPE was slightly greater in 2011 (+37 kg DM/ha) than in 2010 and was greater in summer (378 kg DM/ha) than in autumn (298 kg DM/ha) and spring (211 kg DM/ha).

The RMSPE was 200 kg DM/ha when the annual measured biomass was compared to the annual predicted biomass, and was greater in 2011 (219 kg DM/ha) than 2010 (178 kg DM/ha) (Table 4).

The model predicted an average grass N content of 3.14 and 3.17% in 2010 and 2011, respectively. This shows a small underestimation compared to the observed value which were 3.33 and 3.47% respectively (McCarthy personal communication). In terms of N leaching the

Table 4
Comparison between the measured biomass and biomass predicted by the MoSt GG model (kg DM/ha).

	(kg DM/ha)		all	2010				2011			
				all	spring	summer	autumn	all	spring	summer	autumn
all[a]	Average measured		1034	955	412	963	1146	1123	311	1224	1296
	Average predicted		999	926	201	980	1109	1081	301	1110	1326
	RMSPE		505	499	273	458	503	512	315	562	506
	Proportion	Mean	0.00	0.00	0.60	0.00	0.01	0.01	0.00	0.04	0.00
		Line	0.47	0.53	0.01	0.60	0.43	0.43	0.70	0.54	0.57
		Random	0.52	0.47	0.39	0.40	0.56	0.56	0.30	0.42	0.42
paddock yearly average[b]	Average measured		1031	947	465	1150	1149	1115	553	1316	1401
	Average predicted		1020	931	233	1283	1144	1110	360	1436	1471
	RMSPE		200	178	281	299	301	219	368	322	326
	Proportion	Mean	0.00	0.01	0.68	0.20	0.00	0.00	0.27	0.14	0.05
		Line	0.49	0.48	0.04	0.47	0.50	0.62	0.22	0.49	0.43
		Random	0.51	0.52	0.27	0.33	0.50	0.38	0.51	0.37	0.52
Weekly average[c]	Average measured		1056	984	476	1139	1249	1129	296	1173	1328
	Average predicted		981	903	240	1261	1131	1059	259	1052	1309
	RMSPE		321	302	254	362	284	339	167	394	312
	Proportion	Mean	0.06	0.07	0.86	0.11	0.17	0.04	0.05	0.09	0.00
		Line	0.38	0.38	0.00	0.82	0.06	0.39	0.80	0.50	0.64
		Random	0.57	0.55	0.13	0.07	0.77	0.57	0.15	0.41	0.35

Spring: 1st Febuary–30 April; Summer: 1st May–31 July; Autumn: 1st August–31 October.
[a] Each measurement is compared with the corresponding figure of the simulation.
[b] The average of each measurement for a paddock within a year is compare to the equivalent figure of the simulation.
[c] The measurement conducted within a week for all the paddock are averaged and compared to the equivalent figure of the simulation.

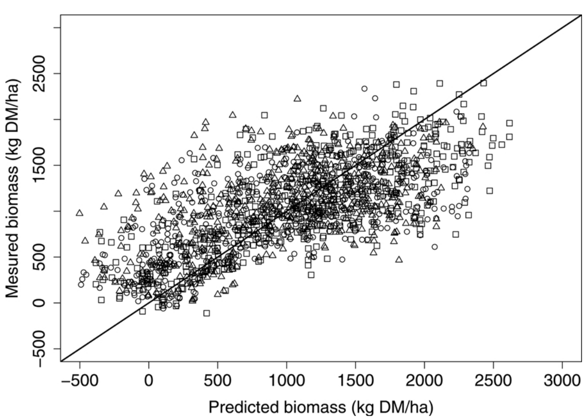


Fig. 5. Comparison between the measured biomass and the biomass predicted by the MoSt GG model (kg DM/ha) where one point represents a measurement and its equivalent in the simulation. (Square = SR of 2.51 cow/ha; Circle = SR of 2.91 cow/ha; Triangle = SR of 3.28 cow/ha).

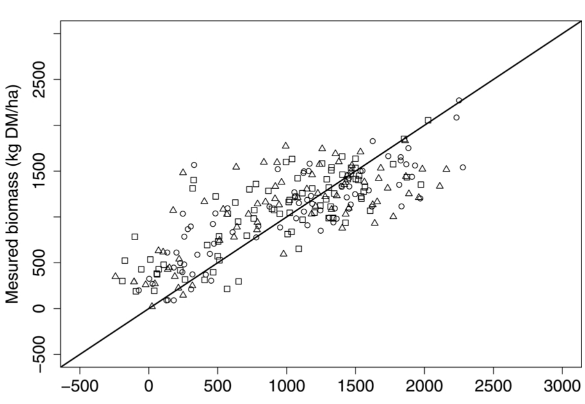


Fig. 6. Comparison between the measured biomass and the biomass predicted by the MoSt GG model (kg DM/ha) averaged by week of the year (Square = SR of 2.51 cow/ha; Circle = SR of 2.91 cow/ha; Triangle = SR of 3.28 cow/ha).

model estimated an average value of 89 and 98 kg NO_3^- leached/ha per year compared to the average of 118 kg NO_3^- leached/ha for the year 2011 (no measures in 2010) and an average for the year 2011–2013 of 108 kg NO_3^- leached/ha per year (McCarthy et al., 2015).

3.2. Evaluation of MoSt GG model with different management scenarios (step 2)

The management scenario results are presented in Table 5 and Figs. 6 and 7. Overall, in all simulations with a fixed day for cutting and grazing, the model predicted a grass growth of 12.2 t DM/ha per year, 161 kg NO_3^- leached/ha per year and an average annual grass N content of 3.09%. The average grass growth for 2013 and 2015 for the four N fertiliser application rates are presented in Table 5.

3.2.1. Year effect

Year had an effect on all of the variables predicted by the model. This was due to the different weather conditions in each year with a warmer summer in 2013 and greater rainfall in 2015 (Table 2). The average quantity of grass grown was 1.8 t DM/ha greater in 2015 compared to 2013 (Table 5 and Fig. 7). When no N was applied, grass grown was 1.4 t DM/ha greater in 2015, while when 650 kg N/ha were applied grass grown was 2.3 t DM/ha greater in 2015 (Table 5). Weather also affected the response to N fertiliser. The response was greater in 2015 compared to 2013 (average response of 8.9 and 10.3 kg DM/kg N, respectively) (Table 5). Similarly, the weather impacted the quantity of NO_3^- leached, which was lower in 2013 (average of 150 kg N/ha) compared with 2015 (average of 171 kg N/ha). Grass N content was slightly greater in 2013 (3.2%) compared to 2015 (3.0%). The net mineralisation pattern was different in each year (Fig. 8).

3.2.2. Effect of defoliation management

Average annual grass growth was greater (+0.6 t DM/ha per year) under grazing management compared to cutting. Grazing increased the quantity of mineral N applied to the paddock by an average of 95 kg N/ha compared to cutting due to urine deposition (Table 5). Grazing management also resulted in increased leaching (+44 kg N/ha per year) and greater average grass N content (+0.21%) compared to cutting management.

Table 5
Impact of the number of cutting or grazing events, level of nitrogen supplementation and weather (from the Moorepark weather station for the year 2013 and 2015) on the main outputs of the model.

Number cutting events	Number grazing events	N fertilisation (kg N/ha)	Grass growth (t DM/ha)		Average pre cutting/grazing height (cm)		Average N content of the grass cut/grazed (%)		Percentage of the paddock affected by urine deposition (%)		N on the paddock due to urine (kg/ha)		Leaching(NO_3^-/ ha)	
			2013	2015	2013	2015	2013	2015	2013	2015	2013	2015	2013	2015
0	6	650	13.4	16.2	12.4	14.4	3.9	3.7	82	87	139	152	273	292
		300	12.8	15.0	12.0	13.6	3.4	3.2	81	86	107	112	170	192
		150	11.4	13.3	11.1	12.5	3.1	2.9	77	83	80	83	136	159
		0	9.3	10.9	9.8	10.9	2.7	2.6	71	76	50	51	107	131
	11	650	12.7	14.8	8.2	8.8	3.8	3.7	81	85	127	141	276	295
		300	12.5	14.2	8.0	8.6	3.4	3.3	80	84	103	110	170	193
		150	11.2	12.8	7.6	8.1	3.1	3.0	77	81	78	83	135	159
		0	9.3	10.6	6.9	7.3	2.7	2.6	71	76	49	51	107	131
6	0	650	14.1	16.6	12.8	14.6	3.8	3.5	0	0	0	0	182	196
		300	11.9	13.8	11.5	12.8	3.2	3.0	0	0	0	0	127	147
		150	10.3	12.0	10.4	11.6	2.9	2.7	0	0	0	0	109	131
		0	8.2	9.7	9.1	10.1	2.5	2.4	0	0	0	0	93	116
11		650	13.6	15.5	8.4	9.0	3.7	3.6	0	0	0	0	188	201
		300	11.7	13.2	7.8	8.3	3.1	3.0	0	0	0	0	128	148
		150	10.2	11.6	7.3	7.7	2.8	2.7	0	0	0	0	110	131
		0	8.2	9.4	6.6	6.9	2.5	2.4	0	0	0	0	94	117

3.2.3. Effect of frequency of grazing or cutting

The frequency of grazing or cutting affected grass growth. Increasing the number of grazing events from 6 to 11 reduced grass growth by 0.5 t DM/ha per year. Eleven grazing events reduced the pre-grazing sward height by an average of 4.1 cm. Increasing the number of cutting events from 6 to 11 reduced grass grown (−0.4 t DM/ha) and average pre-cutting height (−3.9 cm). Increasing the number grazing and cutting events from 6 to 11 had almost no effect on the N variables reported (Table 5).

3.2.4. Nitrogen fertiliser application rate

The model response to N fertiliser application rate was calculated based on the difference between two consecutive N fertiliser application rates: between 0 and 150 kg N/ha, between 150 and 300 kg N/ha, and between 300 and 650 kg N/ha. The grass growth response to N fertiliser application was, on average across all years, number and type of defoliation events, and fertilisation levels, 9.6 kg DM grown/kg N fertiliser applied. This response was greater at lower N fertilisation levels (average response of 14.4 kg DM/kg N applied at 150 kg N/ha, and average difference in response rate of 4.2 kg of DM/kg N applied between 300 and 650 kg N/ha; Fig. 7). The average response to N fertiliser application was greater under cutting (10.6 kg DM/kg N applied) than under grazing (8.6 kg DM/kg N applied), and was greater when 6 defoliation events took place (10.2 kg DM/kg N applied) compared to 11 defoliation events (9.0 kg DM/kg N applied).

On average, NO_3^- leached increased by 0.18 kg N/kg N applied. The effect of fertiliser application on NO_3^- leached was greater under grazing (0.24 kg N leached/kg N applied) than cutting (0.12 kg N leached/kg N applied). The increase in nitrate leached was lower at low N fertiliser application rates (0.1 kg N/kg N applied at the 150 kg N/ha level) than at higher N application rates (0.2 kg N/kg N applied as N application rate increased from 300 to 600 kg N/ha). Increasing N fertiliser application reduced net mineralisation (Fig. 8).

3.2.5. Impact of urine and faeces deposition on the paddock at the 2 m^2 scale

The impact of urine and faeces deposition across the paddock at a 2 m^2 scale was examined using the 2015 climatic data, applying 300 kg

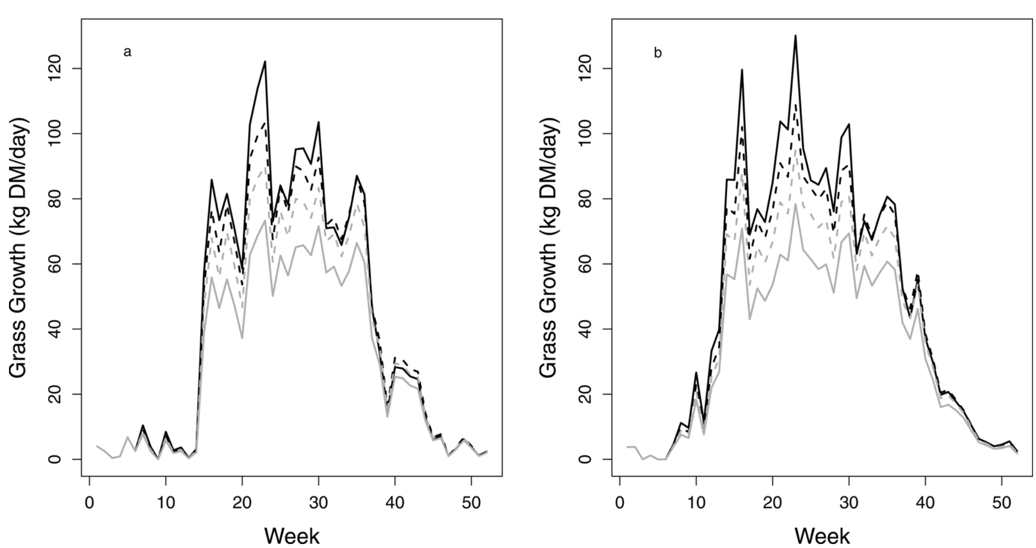


Fig. 7. Net grass growth (kg DM/ha) predicted by the MoSt model in 2013 (a) and 2015 (b) for the simulations with 6 grazing event at 0 (grey continuous line), 150 (grey dotted line), 300 (black dotted line) and 650 (black continuous line) kg N applied/ha.

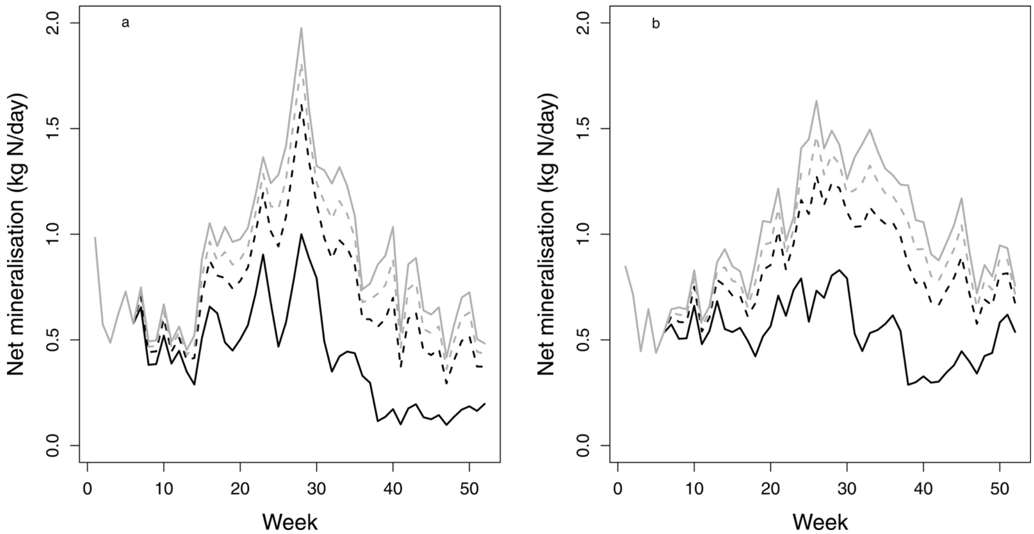


Fig. 8. Net mineralisation (mineralisation-immobilisation) predicted by the MoSt model in 2013 (a) and 2015 (b) for the simulations with 6 grazing events at 0 (grey continuous line), 150 (grey dotted line), 300 (black dotted line) and 650 (black continuous line) kg N applied/ha.

N/ha and imposing 6 grazing events. The results showed that the maximum number of urine depositions across the grazing season on a single 2 m^2 area was 9, while the maximum number of faeces depositions was 8. The minimum number of both urine and faeces deposition was zero. On average, there were 1.9 urine depositions per 2 m^2, and 80% of the paddock had at least 1 urine deposition. The minimum net grass growth for a 2 m^2 area was 14.7 t DM/ha and the maximum was 17.9 t DM/ha. The average maximum biomass (above ground level) on a 2 m^2 area on any given day was 3514 kg DM/ha and the minimum was 3338 kg DM/ha. The small difference is likely due to the fact that at each grazing the paddock height is reset to the paddock post-grazing sward height, therefore making the paddock height uniform. The lowest quantity of NO_3^- leached from a 2 m^2 area was 146 kg N/ha and the greatest was 486 kg N/ha.

4. Discussion

4.1. Development of the MoSt grass growth model

The MoSt GG model was developed based on the model described by Jouven et al. (2006a) and adapted by Hurtado-Uria et al., 2013 for Irish conditions. Soil and N components were incorporated into the Adapted Jouven Model allowing it to recreate sensible responses to N fertilisation. The simulation at the 2 m^2 level will allow users to follow the "life" of a urine or faeces patch, and to examine its direct impact on the grass growth, NO_3^- leached and other important agronomic components.

4.2. Evaluation of the model

4.2.1. Comparison of model predictions with measured data

Comparing model predictions with measured data is a key method for validating the accuracy of the prediction. The measured data that was compared with the predicted data in this study came from grazed paddocks. The comparison of the two measurements taken in each paddock showed large variation (Fig. 4). The poor within paddock comparability of measurements was reflected in the individual comparisons of the measured and predicted paddock biomass (average RMSPE of 505 kg of DM/ha). Within paddock variation is due to the heterogeneity observed in paddocks grazed by cattle, though that may not be the only influencing factor as soil type may also vary within paddock and farm. However, those comparison were more accurate than those of the Jouven model, which has a RMSPE of 720 kg of DM/ha when comparing the prediction of the production per cutting date and per plot (Jouven et al., 2006b). On a weekly basis, using the data for all of the paddocks each week, the predictions were more accurate (average RMSPE was 321 kg DM/ha).

When the N leaching and the N content of the grass measured was compared with model predictions, the predictions had a similar range but with some underestimation. The underestimation could be because the soil Nmin content used at the beginning of the simulation (80 kg N) for each year was too low compared to the experimental site. However, no measure of soil Nmin at the site is available for use in the model. As the Nmin at the start of a simulation was always 80 kg N/ha, the impact of previous years management and weather was not incorporated.

4.2.2. Management scenario evaluation

Across simulations, the cumulative annual growth rates ranged from 8.2 t DM/ha in 2013 for the cutting simulation receiving zero N to 16.6 t DM/ha in 2015 for the 6 grazing simulation receiving 650 kg N/ha. This is within the range of previous published studies. Enriquez-Hidalgo et al. (2016) showed a variation of between 7.4 and 11.5 t DM/ha of herbage removed for a zero N treatment grazed 8–9 times per year to between 10.5 to 16.0 t DM/ha for a treatment receiving 240 kg N/ha grazed 8–9 times per year between the years 2011 to 2013 at a nearby research farm. At the Curtin's Farm annual grass DM production was 12.8 t DM/ha in 1984, 12.5 t DM/ha between 2001–2005, 14.7 t DM/ha in 2007 and 15.7 t DM/ha in 2009 for N application rates of 423, 300, 305 and 246 kg N/ha, respectively (O'Donovan et al., 2011). Along with changes in N application rate, changes in grazing management (rotation length, post-grazing sward height, pre-grazing herbage mass, stocking rate, grazing season length) also occurred at Curtins Farm during the periods reported.

The variation in growth predicted by the model between the years 2013 and 2015 occurred mostly as a result of lower grass growth in summer 2013 (Fig. 7) when high temperatures and low rainfall occurred in July and August in 2013 (Table 2). The N leached was greater in 2015 due to greater rainfall in 2015 than in 2013 (+263 mm of rain), especially during November and December (+208 mm of rain). While it might seem contradictory that the highest grass growth occurred in the same year as the highest leaching, the simulation was run over a single year, and the consequences of the previous year and on the following year were not examined. 2015 was likely a favourable climate year for mineralisation and high rainfall favours both grass growth and nitrate leaching. The soil mineral N content at the end of the simulation was, on average, 66 kg N greater in 2013 compared to 2015 which would, under the same weather and management conditions, result in greater grass growth following 2013 than following 2015.

The herbage production response to N fertiliser application decreased as N fertiliser application increased, similar to published data including Enriquez-Hidalgo et al. (2016); Deenen and Lantinga (1993); Jackson and Williams (1979) and Ryan (1974). The herbage production responses to N fertiliser application predicted by the MoSt GG model using the Moorepark Research Farm soil type and weather conditions are within the range of that measured in previous experiments at Moorepark. The MoSt GG model predicted an average herbage production response of 13.7–14.7 kg DM/kg N applied in cut plots receiving 150 kg N/ha which was slightly less than the 16.8 kg DM/kg N applied at a N fertiliser application rate of 150 kg N/ha reported by Hennessy (2005) at nearby Moorepark Research Farm. The slightly lower response could be due to the high growth of the 0 treatment (8.9 t kg of DM) permitted by a high OM content of the soil (9%) which probably resulted in greater than average N mineralisation. Under grazing, the MoSt GG model predicted an average herbage production response of 14.6 kg DM/kg N applied at a rate of 150 kg N/ha. This is in the range of the 8.0–28.3 kg DM/kg N found by Enriquez-Hidalgo et al. (2016) when 120 kg N/ha was compared to zero N fertilizer application on grazed plots. Differences in the response to N fertiliser between those predicted by the MoSt GG model and that recorded in previous studies could have occurred for a variety of reasons including defoliation (cutting or grazing) management, weather conditions, age of sward, soil type and soil N content.

The starting soil mineral N content in the MoSt GG model for the simulations reported was 80 kg N, which impacts on the N available for uptake and growth, and on the residual soil mineral N content at the end of the year. High rainfall in spring or autumn can move mineral N below the rooting zone thereby reducing herbage production and soil mineral N content in the rooting zone.

The response to N predicted by the MoSt GG model was greater under cutting than under grazing, similar to Jackson and Williams (1979). A lower response to N fertiliser application under grazing is largely due to higher quantities of background N resulting from N in urine and faeces, as well as the decomposition and senescence of plant material not grazed (Gordon, 1974; Whitehead, 1995). However, the difference in the response to N application between grazing and cutting was low; this was due to the high OM content of the test soil. Lower soil OM content would likely result in a higher response to N fertiliser application.

The decrease in grass growth rate and DM yield described by the MoSt GG model with increasing frequency of defoliation (cutting or grazing) agrees with Tuñon et al. (2014); Pontes et al. (2007); Herrmann et al. (2005) and Frame and Hunt (1971). While smaller differences were predicted by the MoSt GG model, growth rate and DM yield were greater with fewer defoliation events.

The variation in N content of the grass predicted by the model ranged from 2.4% for the cutting simulation receiving zero N in 2015 to 3.9% for the 6 grazing events receiving 650 kg N/ha in 2013. This is within the range of previous published studies including Delaby (2000) who reviewed data from six different experiments in western France. The grass N content ranged from 2.0 to 3.8% with N fertiliser application ranging from 0 to 400 kg of N/ha. Hennessy et al. (2008) found a range of between 3.0 to 3.5% for the Teagasc Grange research farm (heavy soil type) and 2.6 to 3.1% for the Teagasc Moorepark research farm (free-draining soil type) in the years 2002 and 2003 at N fertiliser application rates ranging from 0 to 250 kg N/ha. In the MoSt simulation, grass N content at a given annual N application rate was similar, regardless of regrowth interval. This was because N application rate was reduced for each application when 11 cuts/grazing events occurred compared to when 6 events occurred. For example, at 300 kg N/ha, 6 applications of 50 kg N/ha occurred, while 27.3 kg N/ha were applied when 11 applications occurred. Herbage N content was greater under grazing compared to cutting, similar to Hennessy et al. (2008), due to the recycling of N in urine and faeces excreted by grazing livestock. Similar to previous research (Morrison et al., 1980; Delaby, 2000; Hennessy et al., 2008) herbage N content increased as N fertiliser application increased. The N content response to N fertiliser application predicted by the model was from 0.01 to 0.03%/kg N applied, while the range was from 0 to 0.08%/kg N applied in Delaby (2000) and from 0.01 to 0.03%/kg N applied in Hennessy et al. (2008).

The percentage of the paddock affected by urine deposition during the year was between 71 and 87%. These results were similar to Hutchings et al. (2007), who reported that 85 and 98% of the paddock was affected by urine deposition at the end of the first and second year of that simulation, respectively (urine patch size of 0.68 m^2).

4.3. Future use of the MoSt GG model and limitations

The MoSt GG model can be used in its current format by researchers (Ruelle and Delaby, 2017; Ruelle et al., 2017). To allow wider usage, for example by farmers and advisors, the development of a graphical interface is on-going, as well as the creation of a website and a mobile web application. The MoSt GG model has been incorporated in the Pasture Based Herd Dynamic Milk (PBHDM) model (Ruelle et al., 2016, 2018). The PBHDM model is dynamic and represents the life of a dairy animal in grazing scenarios. Each animal, as well as each paddock, is represented individually in the PBHDM model and the MoSt GG model is now used to predict the individual paddock grass growth. In the near future, the model will be incorporated into PastureBase Ireland (PBI) (Hanrahan et al., 2017). PastureBase Ireland is a farm management Decision Support Tool which includes a backend database to increase the decision making process at farm level. The incorporation of the MoSt GG model in conjunction with weather forecast will permit the prediction of grass growth for the next 7 days, facilitating the on farm decision on a day-to-day basis.

One of the main limitations of the MoSt GG model is that it does not consider pasture species other than gramineaous as perennial ryegrass. The MoSt GG model only considers soil N and does not take into account soil pH, P or K, and while this increases the usability of the model by minimising the inputs required it does limit the functionality of the model. Animal faeces and urine deposition is random and is not linked to animal behaviour or to the structure of the paddock. A similar assumption was made in Hutchings et al. (2007). Contrary to other existing grass growth models such as GrazeGro (Barrett et al., 2005), STICS (Brisson et al., 2003), and LINGRA (Schapendonk et al., 1998) model inputs are easily accessible to permit its utilisation by farmers and advisers as well as researchers. Overall, the MoSt Grass Growth model predicts the trend in grass growth (increase, decrease, static) from week to week. This information is very valuable for short term feed budgeting for farmers who operate grass-based feeding systems, regardless of the accuracy of the absolute value predicted.

5. Conclusions

The MoSt GG model responds to daily weather conditions, patterns and methods of sward defoliation, and describes daily variations in soil mineral and organic N content. The range of the response to environment and management conditions by the MoSt GG model is coherent with values reported in the literature from experiments, and therefore the MoSt GG model can be used for the short or long term exploration of variations in both climate and management conditions.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.eja.2018.06.010.

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