Quantifying the impacts of higher water tables on pasture production

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agresearch
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Contents

1. Executive Summary

NIWA has contracted AgResearch to "Generate useable functions to quantify the impact of waterlogging and pugging damage induced by water table rise on pasture production". Key activities for the project covered in this report include the following:

1. Identify the key effects of waterlogging and associated livestock treading damage on soil properties and pasture production.
2. Develop a pasture treading damage and recovery function in APSIM (*AgPasture* module) based on the effect of weather and rising water tables on soil wetness.
3. Run pasture production simulations at six regional locations using NIWA's supplied water table depths and daily weather with soil types derived from online information.
4. Summarise the impacts of water table depth and potential treading damage, as affected by water table rise, suitable for incorporation into a hazard/risk framework.

The scope of this study considers the effects of waterlogging and livestock treading damage when soils are above field capacity. The major considerations are the direct effect of low soil aeration on plant roots under waterlogged conditions, and the effects of treading on the physical damage to soils (macroporosity and infiltration rate) and pasture swards ("wastage").

Based on a literature survey, the report covers waterlogging effects on pasture plant growth; livestock damage to soils; pasture growing points and vegetative tissue; and the recovery of soil properties over time since a damage event. The reduction in forage supply is the most relevant response variable for assessing the economic impacts of waterlogging and associated treading damage.

APSIM (the Agricultural Production SIMulator) is a process-based simulation model that consists of a set of interchangeable modules built around a core engine that enables the user to simulate desired combinations of climate, soil types, crops and management at a daily time step. A wide range of output variables are included, with the most commonly reported response variables including soil hydrology, carbon and nitrogen dynamics and crop productivity. *AgPasture* is an APSIM model designed to incorporate multiple pasture species into a perennial pasture sward, allowing simulation of key management activities (fertilization, irrigation, grazing and cutting).

The direct effects of waterlogging on plant growth via reduced soil aeration are already accounted for in the *AgPasture* model of APSIM. The direct effects of treading damage on soils are now coded into a new APSIM manager "*Damage*", which will interact with the "*SimpleGrazing*" module currently used to control pasture harvesting, and with the "Soil physical" module that describes the relevant properties of the soil profile (specifically drained upper limit and infiltration rate).

To generate simulations of waterlogging impacts on annual pasture production, six regional locations were chosen to represent coastal lowland areas that are susceptible to waterlogging as a result of future water table rise, where intensive pastoral systems are common. Within the regional locations, soil orders comprising over 12.5% of the area within any region were represented by specific profile descriptions. Across all the six regions and six soil types, simulations were run for 10 mean water table depths of 500, 750, 1000, 1250, 1500, 1750, 2000, 2500, 5000 and 10000 mm.

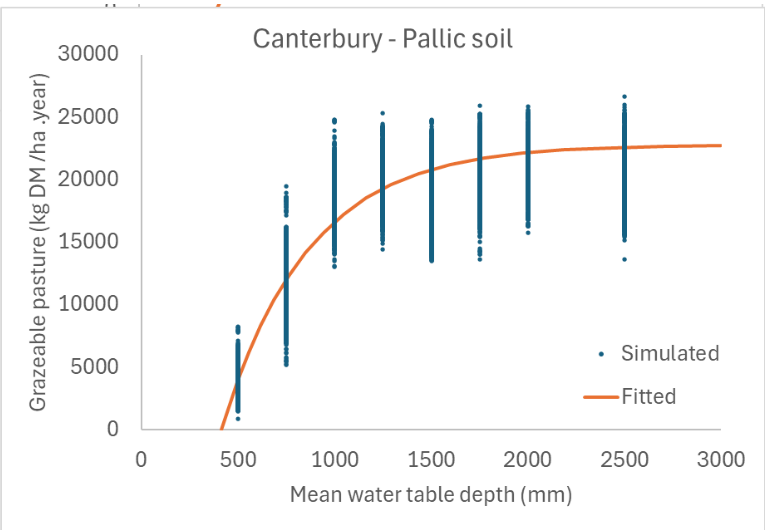
Simulated mean annual grazable pasture production under a non-limiting scenario (10m water table) was lowest in Northland and highest in Canterbury resulting from a combination

of climatic conditions and management (e.g., irrigation and fertiliser) assumptions. The soil order also affected production, with the lowest mean annual grazable pasture production on the Organic soil, likely due to nitrogen limitations.

The effect of reducing the water table depth on annual grazeable pasture production was minimal until the depth reached 1 m, at which point pasture production was substantially reduced. The simulated production vs water table depth data were fitted with a nonlinear 3-parameter curve of the form:

$$E(harv + \epsilon) = P_m \left(1 - \exp\left[\frac{wt_0 - WT}{\alpha}\right]\right); \qquad WT > wt_0.$$

An example of the pasture production results and the fitted relationship between annual average grazeable pasture production and water table depth is shown in the figure below (for a Pallic soil in Canterbury):



The range in key fitted curve parameters, across soil types and years, for each of the six regions simulated, is shown in the table below:

Region	P_m (t DM/ha/y)[1]	α (mm)[2]	wt_0 (mm)[3]
Northland	9.7 – 14.9	394 – 608	330 – 490
Waikato	15.0 – 18.3	442 – 776	330 – 488
Bay of Plenty	15.6 – 17.5	350 – 789	330 – 463
Manawatū	12.0 – 17.6	206 – 868	330 – 489
Canterbury	19.8 – 22.8	246 – 851	330 – 492
Southland	12.7 – 20.6	685 – 944	373 – 499

[1] maximum annual average grazeable pasture production, under the 10 m mean water table depths.
[2] shape of the curve (horizontal stretch).
[3] water table depth where the expected grazeable pasture production drops to zero

2. Project background

2.1 Objective

NIWA has contracted AgResearch to “Generate useable functions to quantify the impact of water table rise induced waterlogging and pugging damage on pasture production”.

2.1.1 Previous work

See Nichols (2024) for a literature review of waterlogging effects on pasture species.

2.1.2 Activities

Key activities for this project as per the contract include:

1. Identify the key effects of waterlogging and associated livestock treading damage on soil properties and pasture production.
2. Develop a pasture treading damage and recovery function in APSIM (*AgPasture* module) based on the effect of weather and rising water tables on soil wetness.
3. Run pasture production simulations at six regional locations using NIWA’s supplied water table depths and daily weather with soil types derived from online information.
4. Summarise the impacts of water table depth and potential treading damage, as affected by water table rise, suitable for incorporation into a hazard/risk framework.

2.1.3 Approach

The agreed approach for this project and structure for this report is as follows:

1. Identify the critical relationships between animal pressure and both soil and plant damage.
2. Outline the current structure of APSIM as it relates to soil wetness effects on pasture growth.
3. Verify that relevant APSIM parameters are amenable to modification in a dynamic way in response to treading events.
4. Adapt functions from existing biophysical and modelling literature that can be used within the current APSIM structure.
5. Code those functions into APSIM.
6. Verify/Validate the effects of the new relationships on pasture production, with reference to existing empirical data.
7. Complete the simulations for twelve selected sites (six regions with associated local climate files and two soil types for each region)[1].

[1] By agreement, this was later modified to six regions and six soil types that dominate those regions.

3. Relevant literature

The scope of this study is restricted to the effects of waterlogging and livestock treading damage under wet conditions, specifically when soils are above field capacity. In such circumstances the major considerations are the direct effect of low soil aeration on plant roots under waterlogged conditions, and the effects of treading on physical damage to soils and pasture swards. Under these conditions, soils are not compacted but deformed, with pastures experiencing immediate damage to tissue and growing points, and subsequently increased senescence of both shoot and root tissue.

Treading damage can also occur when soils are below field capacity. In such circumstances soil compaction (i.e., a reduction in bulk density) occurs. For the purposes of this exercise these effects are considered out of scope.

We further note that the scope of this study does not extend to the effects of prolonged grazing of soils in a vulnerable state to the point that the pasture is destroyed and cultivation and re-grassing is needed.

3.1 Direct effects of waterlogging on plant growth

Waterlogging affects plant yield (shoot biomass) and root growth primarily through the impact of decreased soil oxygen levels. Other impacts occur via shoot morphology (e.g. number of leaves and specific leaf area in plantain (Wilson et al., 2024) and plant physiological characteristics such as photosynthesis, water relations, root hydraulic conductance, and soluble sugar concentrations (Di Bella et al., 2022; McFarlane et al., 2003; Ploschuk et al., 2017; Shaw et al., 2013). Similarly, plants may adapt to waterlogging, for example through: the formation of root aerenchyma (air spaces); development of adventitious roots; increasing surface root mass while decreasing roots at depth; and the formation of barriers to oxygen loss in the roots (Donohue et al., 1984; Mui et al., 2021; Shaw et al., 2013).

The earlier review by Nichols (2024) was aimed at reviewing published and grey literature for information on the impact of waterlogging specifically on growth of perennial ryegrass, and according to varying waterlogging duration, water table depths, and pasture/plant age. There were very few studies that quantified the impacts of waterlogging on perennial ryegrass, which was consistent with data in several other recent publications on waterlogging in forage grasses (Braun & Patton, 2024; Di Bella et al., 2022).

Experimental conditions in the studies on perennial ryegrass were very variable for factors such as plant age, duration of waterlogging, depth of waterlogging or waterlogging treatment, plant material (plants grown from seed versus tillers, cultivars, genotypes) and recovery time. As a result, it wasn't possible to group the studies into ranges of impact depending on waterlogging conditions or plant factors. In general, changes in perennial ryegrass yield under waterlogging in the relevant studies reviewed by Nichols (2024) ranged from -59% to +34%, including some studies which found no significant impact. This likely reflects the variability in experimental conditions and plant material in these studies.

The impact of – or tolerance to – waterlogging varies between and within species (Braun & Patton, 2024; Di Bella et al., 2022). For example, the review of published data by Di Bella et al. (2022) reported median decreases in shoot biomass of 94% for perennial ryegrass, 87% for tall fescue and 80% for cocksfoot. In the case of white clover, which is normally grown in association with ryegrass in New Zealand's high productivity lowland pastures, the effect of waterlogging on nitrogen fixation (Pugh et al., 1995) is an additional consideration to the effect on growth.

Most of the reported studies were from pot experiments, with very little information from field trials. Therefore, the data on waterlogging impacts did not incorporate the interactive damaging effects of grazing on waterlogged soils.

3.2 Indirect effects of treading on soil properties

3.2.1 Treading pressure and damage to pastoral soils

Animal pressure on soils and pastures can be quantified with a combination of three key variables: livestock density (instantaneous animal numbers per hectare), livestock mean mass (kg liveweight per individual animal) and duration of grazing (generally a matter of hours). These three variables can be multiplied to derive a single measure of livestock pressure (Eqn. 1).

Pressure (t LW/ha.hr) = SR (head/ha) × LW (kg LW/head) × GD (hr) / 1000 (Equation 1)

Where SR is the instantaneous stocking rate of the animals in the paddock, LW is the mean liveweight of the animals in the herd, and GD, grazing duration, is the length of time the animals are in the paddock.

An additional factor is required to quantify damage in terms of the impact on sward and soil properties (Finlayson et al., 2002). This has commonly been measured as the proportion of the grazed area affected by hoof impact, which can take several forms: puddling, ridge/clod, skid, cleft and compacted . A number of studies have measured this damage directly, either in terms of the percentage of surface area affected (Sheath & Boom, 1997), or indirectly via the “chain method” which uses the decrease in the distance between the end points of a fixed length of a chain laid along a rough soil surface as a proxy for damage extent (Pande, 2002; Zegwaard, 2006). These measures provide a useful index of impact on soils, which is shown on the y-axis in *Figure 1*

The damage value is scaled to a proportion of surface area. This surface damage proportion is distinct from the proportion of bare soil, which is also typically measured in such studies. Bare soil cover is also present in normal undamaged swards, and its estimation is dependent on pasture mass (i.e., greater bare ground proportion is observed at lower pasture cover). So in itself, bare ground is not a useful measure of damage extent, and the relativity between damaged and undamaged pastures in experiments must account for this.

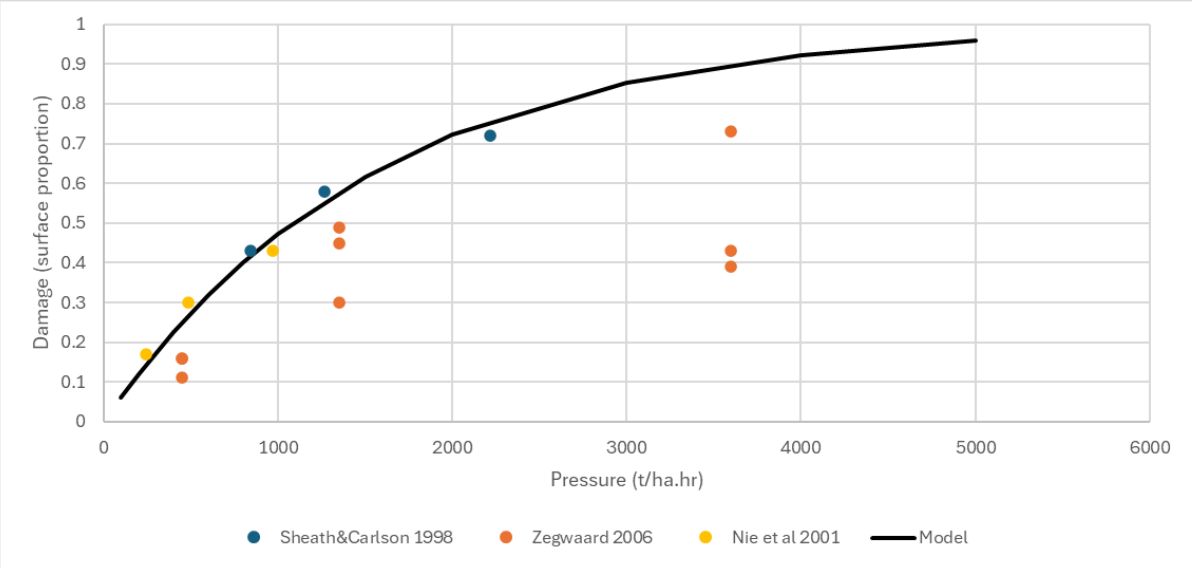


Figure 1: Data from three studies on different soil types, of the impact of animal pressure on soil surface damage. Growth function model fitted to Sheath & Carlson (1998) and Nie et al. (2001) data (Eqn. 2).

In Figure 1, the data points from three separate studies that measured animal pressure and soil damage are shown. The upper bound of the data, effectively the 1998 and 2001 studies, has been fitted with a growth function of the form $y = 1 – e^{(bx)}$ that reflects their apparent non-linear form (Eqn. 2).

$$\text{Damage} = 1 - \exp(-0.639471 \times 10^{-3} \times \text{Pressure}) \qquad \text{(Equation 2)}$$

This form is broadly consistent with the estimates of the hourly rate of increase in damaged ground being 4.5 %/hr in the first 9 hours of treading and 0.7 %/h after that (Zegwaard, 2006). There is a lower bound of 0.0 on the damage score that represents no animal damage and an upper bound of 1.0 on the damage score that constrains it to total surface damage.

While there is evidence that the form is not linear, the exponent parameter is not consistent across all studies, probably reflecting soil type responses to treading as well as the damage assessment method used. It is likely that structural vulnerability (and perhaps stock type) also affect the exponent. The method reported by Sheath & Boom (1997) was a visual damage method including multiple damage types on a Dunmore hill soil (allophanic), whereas Nie et al. (2001) used a visual method to score pugging damage on an Australian soil type (Brown Chromosol) similar to a New Zealand semi-arid soil order. Zegwaard (2006) used the “chain method” on a Te Kowhai silt loam (gley). If a similar functional form is fitted to each of these studies, the exponent values are as follows:

b = -0.00064 Dunmore hill soil (Sheath & Carlson, 1998)

b = -0.00025 Te Kowhai silt loam (Zegwaard, 2006)

However, there is also some evidence of variation in the damage-pressure relationship within the Zegwaard (2006) data, which included three separate damage events. The uppermost points from this study (i.e., within the orange group in Figure 1) relate to a treading damage event where the soil was at 89% of saturation, compared to 73% and 79% saturation levels in the other two events that contribute to this study data set. These results suggest that the exponent parameter should be able to be modified in the Damage module by the user.

3.2.2 Initial treading damage effects on soil properties

Direct animal damage on wet soils is known to affect the following soil characteristics:

1. Macroporosity – these are the large pores (typically >30 µm) that are usually air-filled when soils are below field capacity (variously defined as -10 kPa or -33 kPa) and only partially to fully water-filled for short periods when soil is between field capacity and saturation. Treading will compress these pores and reduce the macropore space as a proportion of total porosity. The relationship between damage extent and macroporosity appears to be linear (Figure 2) although there is clearly a lower theoretical limit of 0% macroporosity, when all macropores are eliminated.
2. Water-holding capacity (WHC) – water is held in various size pores, with potentially available water (PAW) for plant uptake generally regarded as being in mesopores with diameters between 0.1 – 30 µm. Where macropores are compressed into mesopores, it is therefore possible for PAW to increase in the short-term. There is some evidence of this in Drewry et al. (2022) where volumetric soil water content at field capacity (-10 kPa in that study) increased under cattle grazing compared to a control site.
3. Infiltration rate – the reduction in large pore space means that water is held more tightly to soil in smaller pores and drainage flow is reduced. A reduction in infiltration rate leads to greater ponding (on flat soils and where soil is pugged, thus creating small pools) or greater runoff (on sloping soils). The relationship between damage extent and infiltration rate can also be approximated by a linear equation (Figure 3), though this also has a theoretic limit of 0 mm/hr for a completely sealed soil surface.

In Figure 2, the data points from three separate studies that measured soil damage and macroporosity in two soil types are shown. Soil damage was defined as noted previously, i.e, the proportion of surface area affected by treading. The 2005 and 2006 studies were both on a Te Kowhai silt loam (Gley soil), while the 2002 study was on a Tokomaru silt loam (Pallic soil). The 2006 study with the most data across the range is fitted with a linear function of the form y = ax + b that reflects the apparent linear form (Eqn. 3).

$$\text{Macroporosity (\%)} = -16.77 \times \text{Damage} + 21.83 \qquad \text{(Equation 3)}$$

This relationship implies that some level of macroporosity is retained in the Gley soil, even with complete surface damage.

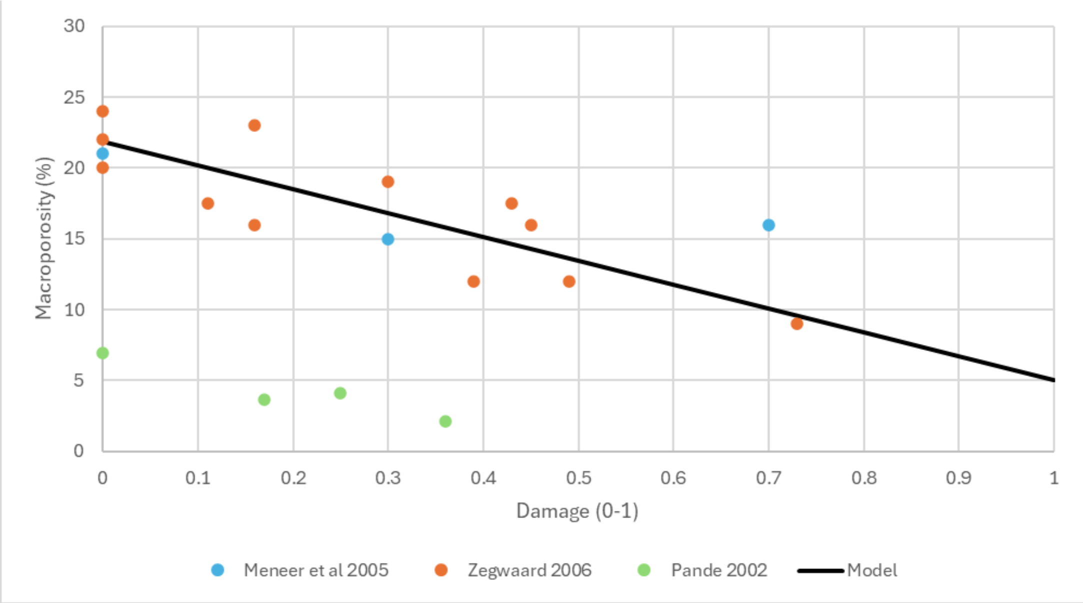


Figure 2: Effect of surface damage on macroporosity (% of total porosity) in a Tokomaru silt loam (Pallic soil; Pande 2002) and a Te Kowhai silt loam (Gley soil; Meneer et al 2005, Zegwaard 2006).

The “natural“ or undamaged levels of macroporosity differ between the two soil types (20-24% in the Gley vs. 7% in the Pallic soil) although the slope of the relationship appears similar. In the 2002 study on the Pallic soil, the slope coefficient of a similar linear fit is -12.51. This suggests that compete loss of macroporosity would occur at a damage level of ~0.53.

In Figure 3, the data points from two separate studies that measured soil damage and infiltration rate are shown. The 2006 study with the most data across the range is fitted with a linear function of the form y = ax + b that reflects the apparent linear form (Eqn. 4).

Infiltration rate (mm/hr) = -1563 × Damage + 1069 (Equation 4)

This relationship implies that in the Gley soil, no infiltration would occur at a damage level of ~0.68.

The “natural“ or undamaged levels of infiltration differ between the two soil types (1070 mm/hr in the Gley soil vs. 54 mm/hr in the Pallic soil) and the slope of the relationship is quite different (1563 mm/hr in the Gley soil vs. 127 in the Pallic soil).

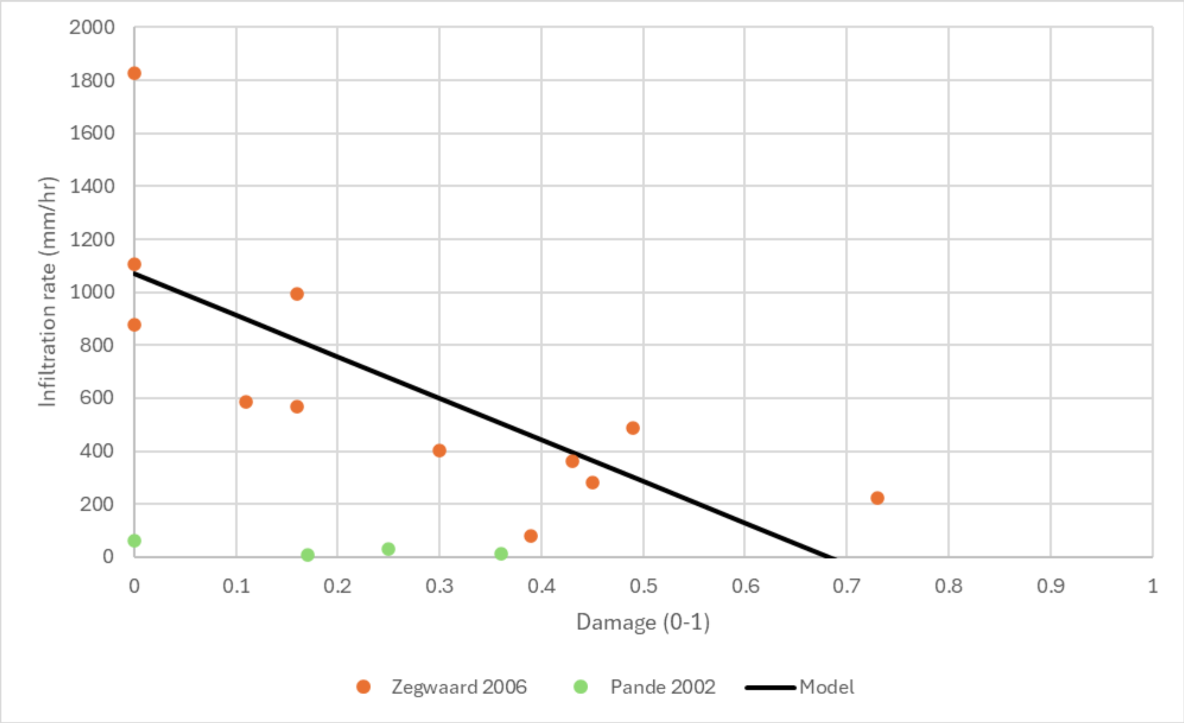
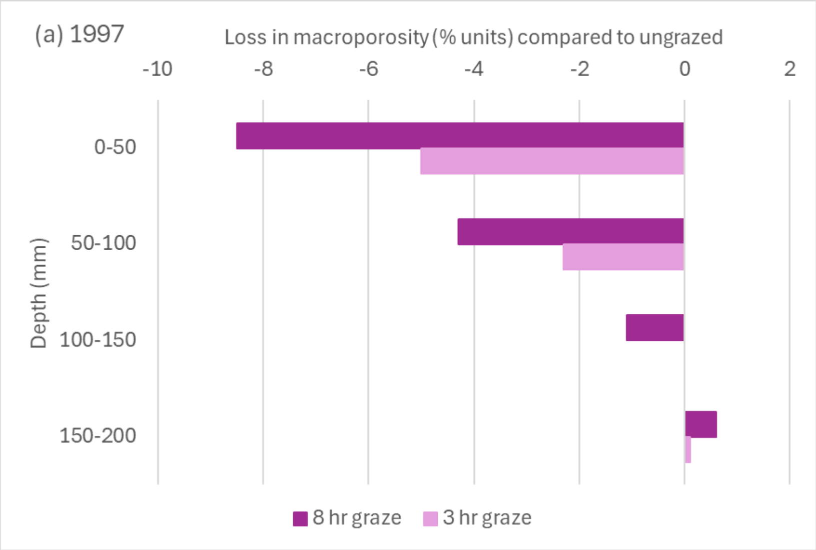


Figure 3: Effect of surface damage on infiltration rate (mm hr^{-1}) in a Tokomaru silt loam (a Pallic soil; Pande 2002) and a Te Kowhai silt loam (a Gley soil; Zegwaard 2006).

Tian et al. (1998) used field data on infiltration rates from two soil orders (Allophanic and Brown) on easy slopes in North Island hill country to develop functions for infiltration rate. The data were from artificial rainfall simulations following damage from one or two treading events in late winter, collected at 3, 5, 7 and 11 months after the damage event. The empirical functions for steady state infiltration rates were a function of soil organic matter (OM), soil moisture at the time of damage (SM), surface damage (D), bare ground (B), number of damage events (N), anion storage capacity (ASC) and time since damage (T). For any given soil, the combination of the intercept, OM and ASC terms establishes the initial value prior to damage. The second group of terms (SM, D, B, N) establishes the loss due to damage and the third group (T) establishes the recovery rate. Thus, for a single damage event on a given soil type, a general formulation relating the change in infiltration rate to the SM and D levels at the time of damage will be adequate.

3.2.3 Depth distribution of treading damage effects

The effects of wet soil treading damage on macroporosity and infiltration rate will occur to varying depths, depending on soil properties and the severity of the damage. Figure 4 shows these effects for macroporosity in a Te Kowhai silt loam following multiple late winter-early spring grazing events involving two intensities of grazing (an 8-hour and a 3-hour break), in comparison with non-damaging grazing events (Drewry, 2003). The less damaging 3-hour event resulted in a lesser overall decrease in macroporosity within each soil layer sampled, as well as the decrease being much less in the deeper layers of the profile.



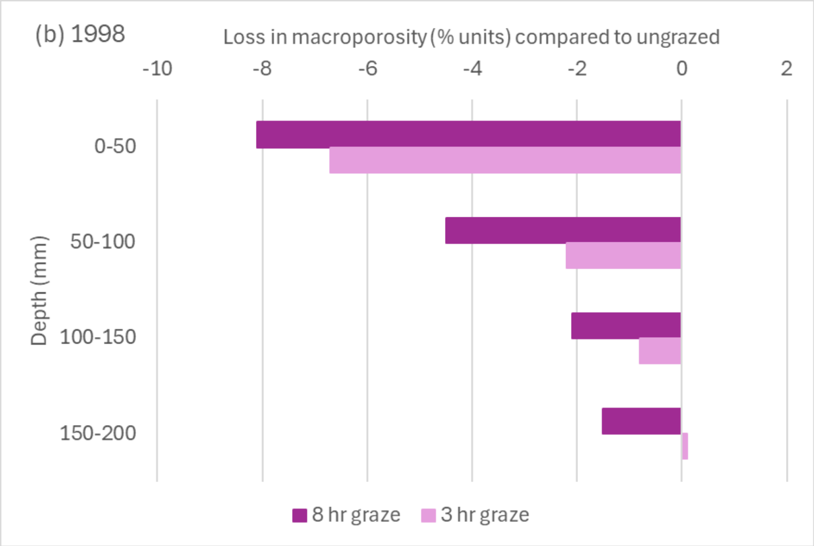


Figure 4: Reductions in macroporosity through the soil profile of two winter grazing strategies in comparison with a non-damaging grazing strategy, repeated in (a) 1997 and (b) 1998.

3.2.4 Recovery of soil effects

Recovery of soil properties over time since a damage event is mediated by biological activity (essentially a recovery of the air-filled pore space), including new root growth and turnover and macrofaunal burrowing, such as by earthworms Drewry (2006). Various studies have reported recovery rates for specific soil and pasture characteristics.

In terms of our characterisation of treading damage as visible soil surface effects, Zegwaard (2006) observed a range in recovery times of between 6 – 20 weeks. This was done in three experiments on Te Kowhai silt loam soil in the Waikato, but in different years and time during winter, and so with damage being inflicted at different levels of saturation. Using a similar surface roughness measurement, Pande (2002) observed persistent effects of heavy damage (Surface damage ~ 0.36) at 5 weeks on a Tokomaru silt loam in the Manawatū, but did not measure further. In a different experiment on a Taihape steepland soil, bare ground cover had recovered to levels similar to undamaged sites by 10 weeks. Betteridge et al. (2003) report an unspecified Waikato study where surface roughness took four months to recover after grazing damage.

In terms of soil properties, Pande (2002) observed that macroporosity had recovered by 10 weeks after an August damage event on a Taihape steepland soil in the southern Hawke's Bay, while infiltration rate had recovered within 4 weeks. In the Tokomaru silt loam study, infiltration rates were still significantly reduced at 7 weeks after damage. On a Te Kowhai silt loam in the Waikato macroporosity took 4-13 weeks to recover in the study of Zegwaard (2006), and 14-21 weeks to recover in the study of Drewry et al. (2003). In the same study, macroporosity was still reduced at 21 weeks on a Kereone loam soil, but all soils had recovered hydraulic conductivity after 6 weeks. The unspecified Waikato case study reported in Betteridge et al. (2003) notes a 3-4 month recovery period for macroporosity. All these studies involved single damage events, with the effects of multiple damage events known to take more than a year to recover.

The temporal pattern of recovery across these studies is quite variable, but in general recovery rates appear to be greater in the early stages of recovery. An example of this for hydraulic conductivity is shown in Figure 1b of Drewry et al. (2003).

3.3 Direct effects of treading on pasture plants

A number of studies have reported on the impacts of animal treading on pasture regrowth (Drewry, 2003; Meneer et al., 2005; Wilson et al., 2024) but this is assumed to be a combination of multiple soil and plant damage factors and not solely related to the effects of direct plant tissue damage alone.

Direct animal damage effects on plants include:

1. Tissue wastage – above-ground plant tissue is sheared off and contributes to plant litter either on the surface or buried in the soil from animal trampling. This results in an immediate reduction in leaf area and pasture herbage mass. At the same time, below-ground plant tissue is also abscised as the plant puts more energy into recovering photosynthetic tissue. This root turnover also effectively contributes to buried plant litter.
2. Tissue damage – growing points and leaves are subject to contusion, reducing tiller numbers and herbage accumulation via a reduction in leaf area index. Damage increases the susceptibility of the plant to microbial infection, thereby increasing on-going senescence.

These effects are over and above the grazing removal of standing herbage and loss of leaf area that is associated with the livestock grazing/treading event.

3.3.1 Plant tissue wastage

Sheath & Boom (1997) present two linear equations for the amount of herbage trodden into and below the soil surface, relating this to the amount of surface damage as follows:

Winter: $H = 4.23 \times D + 74$ ($R^2 = 0.33$) (Equation 5)

Spring: $H = 5.11 \times D + 78$ ($R^2 = 0.51$) (Equation 6)

Where H is the herbage trodden (kg DM/ha), D is the amount of surface damage (% of surface area, which directly relates to the Damage variable described in section 3.2.1).

Beukes et al. (2013) used a herbage loss modification to the Whole Farm Model derived from an unpublished report that related herbage wastage to field capacity. Wastage was nil up to 50% of field capacity, a linear function of water content between 50-100% of field capacity, up to 16% at field capacity, and 40% on rainy days when soil was already at field capacity. This wastage was applied equally to the available herbage (thus reducing cow intake) and the residual herbage (thus reducing residual herbage and transferring the wastage to surface organic matter).

3.3.2 Plant tissue damage

Pande (2002) measured basal pasture cover (defined as the percentage of vegetative cover at the soil surface, rather than at the canopy) which provides a good measure of the extent to which the regrowth potential of the sward might be reduced after treading damage. The relationship is linear and consistent with the theoretical maximum damage leading to a complete loss of plant basal cover (Figure 5). The data is fitted with a linear function of the form y = ax + b that reflects the apparent linear form (Eqn. 7).

Basal cover (%) = -47.68 × Damage + 46.05 (Equation 7)

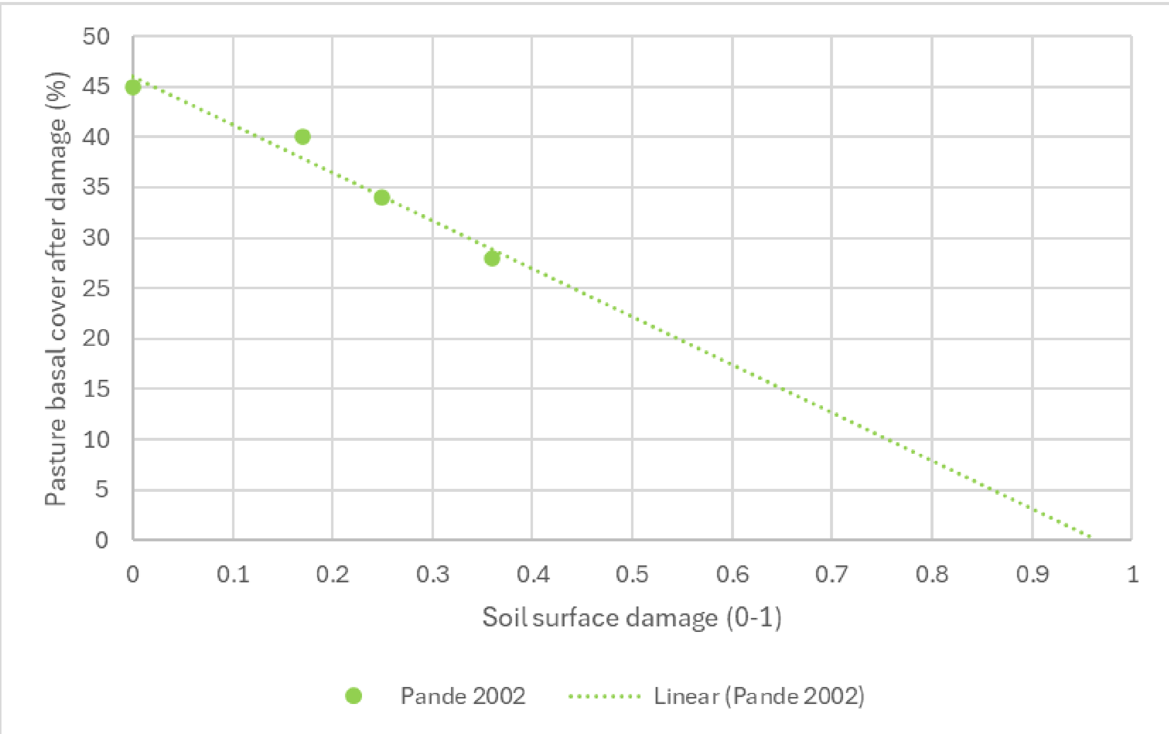


Figure 5: Relationship between pasture basal cover and surface damage after treading on a Tokomaru silt loam (extinction point inferred).

Other studies (Nie et al., 2001; Zegwaard, 2006) have measured tiller numbers as an indicator of sward condition in terms of regrowth potential, under a range of soil damage levels (Figure 6). The data from the two studies are fitted with a linear function of the form y = ax + b that reflects the apparent linear form (Eqns. 8 and 9).

Zegwaard (2006): Tiller density (tillers/m^2) = -2171 × Damage + 2087 (Equation 8)

Nie et al (2001): Tiller density (tillers/m^2) = -5734 × Damage + 3998 (Equation 9)

The different intercepts reflect expected differences in 'natural' tiller densities typical of pastures in cattle grazed systems under differing historic sward management. The relationship between tiller numbers and surface damage in the Waikato study of Zegwaard (2006) is consistent with the theoretical maximum damage (1.0) leading to a complete loss of growing points. In reality, a proportion of these will survive and new growing points will be initiated from plant crowns.

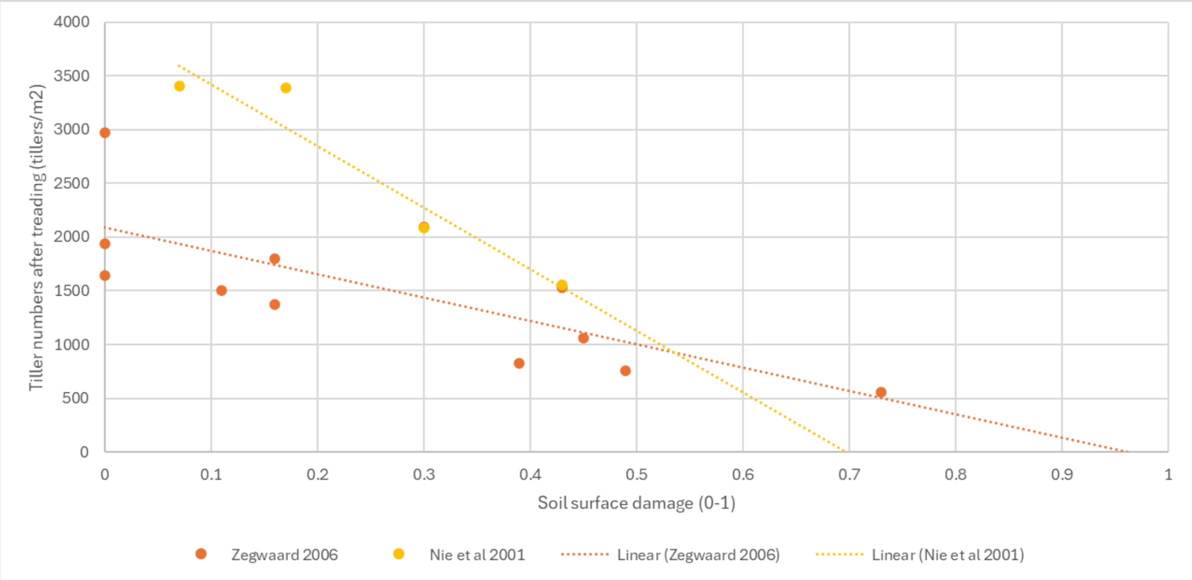


Figure 6: Relationship between perennial ryegrass tiller numbers and surface damage after treading on two soil types under differing historic climate and grazing management regimes (extinction point inferred by a linear fit).

3.3.3 Recovery of plant effects

Recovery of plant growth over the time scales relevant here (months) relies on both the normal post-defoliation regrowth from surviving tissue and new growing point initiation and expansion of plant basal area into the open soil surface spaces created by the treading damage. Total herbage accumulation, measured in several studies, is a combination of these factors. Here we confine the literature search to measures of pasture condition, such as basal area and tiller numbers, as these constrain pasture biomass regrowth in the period following damage, independent of damage to soil properties such as macroporosity, which will indirectly influence herbage accumulation rates.

Pande (2002) observed that tiller populations took 9 months to recover in the Taihape steepland soil in the southern Hawke's Bay, while in the parallel Tokomaru silt loam study, tiller numbers were still significantly reduced at 7 weeks after damage. In the lowland study, basal cover returned to pre-damage levels within 7 weeks under 'low' and 'medium' damage conditions but was still only about 66% of pre-damage cover in the 'high' damage areas (Figure 7). Meanwhile, basal areas in the undamaged areas had increased by ~75%, so a much longer period would have been required for all the damaged areas to be restored to the basal cover levels of undamaged swards.

It is worth noting that, at this site, tiller numbers in all the damaged areas increased to greater levels than in undamaged areas over the 7-week recovery period measured. This is likely a function of greater light and Red:Far Red light ratios persisting at the base of the slowly recovering sward, conditions which will favour new tiller initiation (Korte et al., 1982). Hence, dynamic tiller populations are not necessarily a good indication of recovery rates.

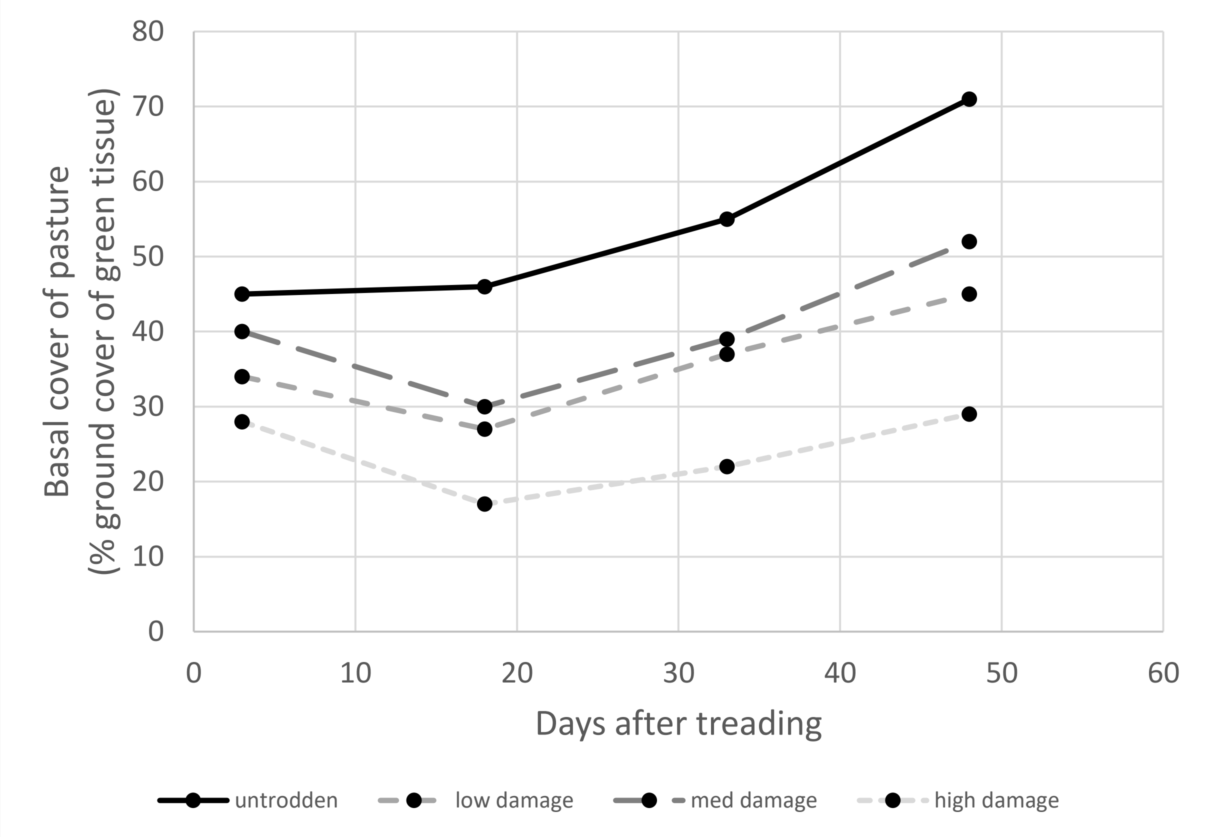


Figure 7: Recovery of pasture basal cover over time since varying levels of treading damage on a Manawatū lowland Tokomaru silt loam soil.

Nie et al. (2001) noted no significant interaction between pugging effects on reducing perennial ryegrass tiller numbers and time. By this it is inferred that the loss in tiller numbers persisted until at least 13 weeks after the treading damage imposed in that study – their last measurement date.

Wilson (2024) observed no significant effect of treading damage on perennial ryegrass tiller populations in a treading study on the Tokomaru silt loam, under measurement frequencies of c. 3 months, so it may be assumed that any effects were ameliorated within that time frame.

Betteridge et al. (2003) reported in one unidentified case study that tiller density and bare ground took 5 months to recover.

3.4 Overall treading effects on pasture growth

A small number of studies have measured pasture growth rate responses to treading events which represent the combined outcome of direct damage to plants and indirect effects on plant growth from damage to soils. These data sets can be used to validate the model outputs, driven by the component effect relationships implemented in APSIM (see Section 4.2). However, this validation step was out of scope in the context of the current contract.

3.4.1 Damage effects

Betteridge et al. (2003) have summarised a number of such studies to create a "Ready Reckoner" that relates the loss in subsequent pasture productivity to animal pressure (stocking rate and grazing duration). These curves can be summarised in a single relationship that relates proportional loss in productivity to animal pressure (Figure 8).

The data from this reckoner are fitted with a power function of the form $y = ax^b$ that reflects the apparent diminishing marginal effects form (Eqn. 10). This is consistent with the observation that herbage accumulation is not completely eliminated, and that recovery occurs.

Pasture yield reduction (%) = $0.5314 \times (\text{Damage})^{0.6496}$ (Equation 10)

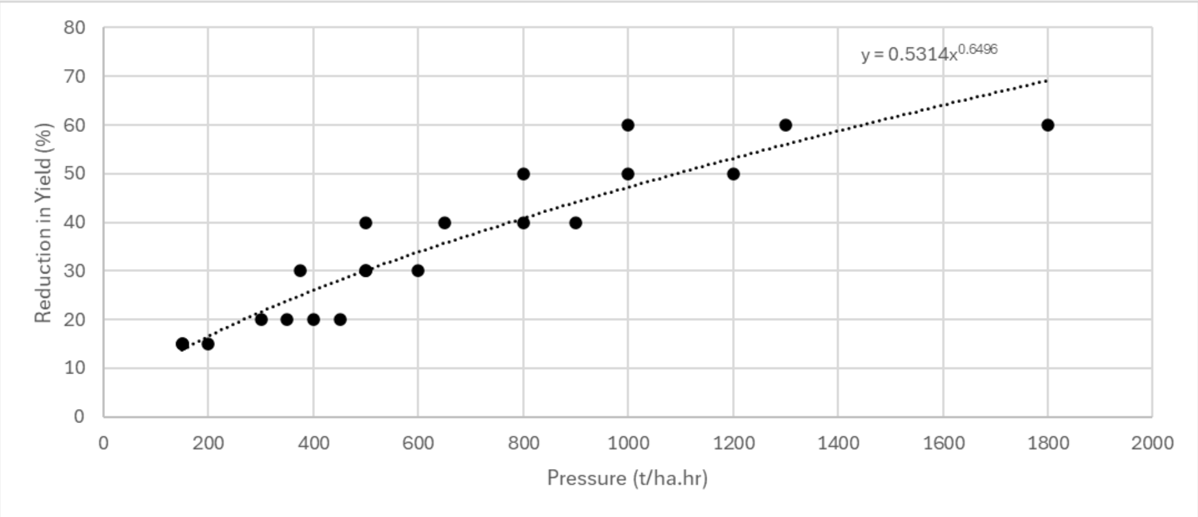


Figure 8: Relationship between pasture productivity loss (%) and animal pressure derived from the ready reckoner of Betteridge et al (2003) that incorporates data from a number of pasture production studies.

3.4.2 Recovery period

In terms of the recovery time for pasture growth, Pande (2002) observed no significant loss in herbage accumulation from 28 weeks after an August damage event on a Taihape steepland soil in the southern Hawke's Bay. In the Tokomaru silt loam study, pasture growth was still significantly reduced at 7 weeks after damage. Herbage accumulation rates in the Waikato study of Zegwaard (2006) took 14-23 weeks to recover. On the same soil type, pasture growth had recovered by 16 weeks (Drewry et al., 2003), with recovery more rapid in their study on the Kereone loam (7 weeks).

In the study of Zegwaard (2006), several relationships between pasture growth rate recovery time and damage indictors were proposed, such as:

$$RT = -93.59 + 1.63HR - 0.04HR^2 + 2.2GSM - 0.012\,GSM^2 \quad (r^2 = 0.72) \qquad \text{(Equation 11)}$$

$$RT = -5.94 + 0.31BG \quad (r^2 = 0.60) \qquad \text{(Equation 12)}$$

$$RT = -3095 + 1.22SR \quad (r^2 = 0.70) \qquad \text{(Equation 13)}$$

Where RT is recovery time (weeks), HR is the treading duration (hours), GSM is the Gravimetric Soil Moisture content (%) prior to treading, BG is the proportion of bare ground (%) after treading, and SR is the soil surface roughness index (%) after treading.

Wilson (2024) observed a significant effect of treading on reduced pasture growth rates only within the first two months after treading damage in a perennial ryegrass-plantain sward on the Tokomaru silt loam in the Manawatū.

4. Development of the Damage and Recovery Model

Section 3 summarised the relevant literature addressing treading damage and recovery of soil and pasture properties. This section describes how that information was synthesised and implemented in the Damage and Recovery model for use within APSIM.

4.1 Treading damage module structure

Figure 9 shows the generalised structure of the Damage and Recovery model. Animal pressure at the grazing event is calculated from stocking rate, liveweight and grazing duration (3.2.1). A new variable soil damage is calculated as a function of animal pressure (3.2.2), dependent upon the status of soil water content relative to field capacity. Soil and pasture properties are modified as a function of soil damage (3.2.2, 3.3). The model then simulates pasture growth under those conditions. Recovery of those soil and pasture properties occurs over time to restore them to original values (3.2.4, 3.3.3).

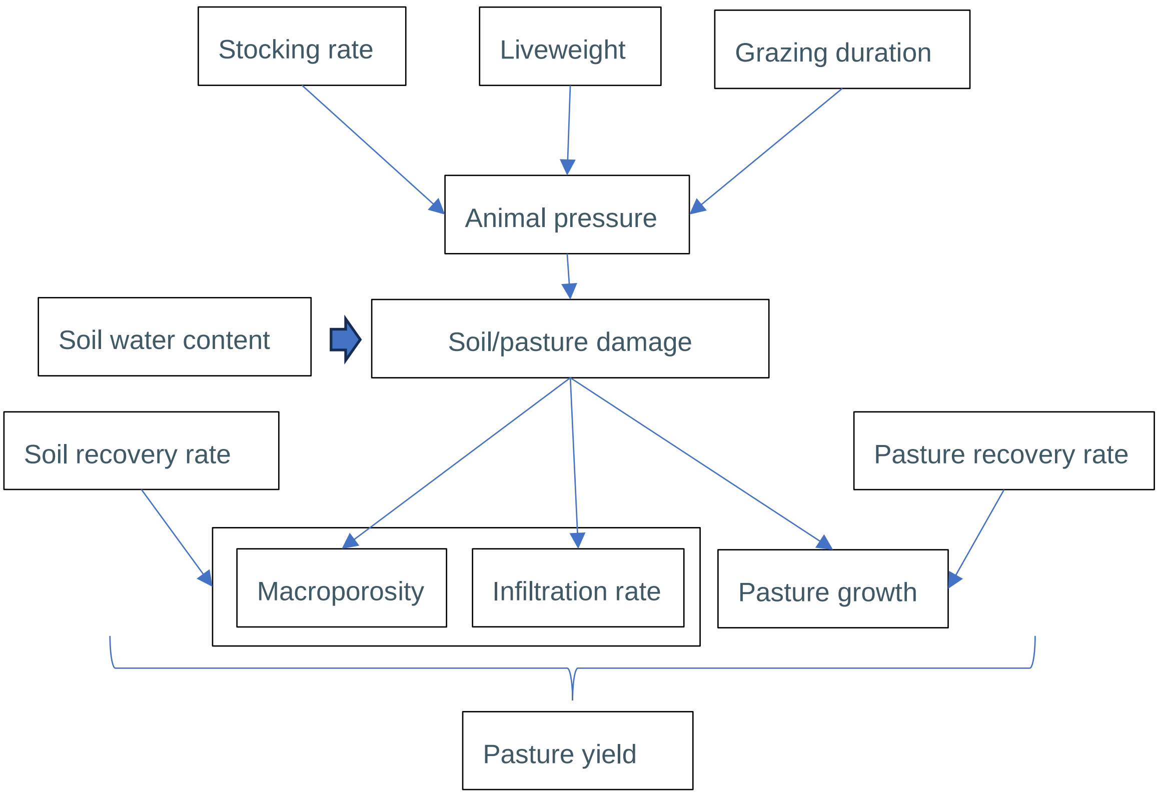


Figure 9: Conceptual model of how damage and recovery effects were modelled.

4.2 Implementation in APSIM

The effects of treading damage are coded into a new APSIM manager "*Damage*", which will interact with the "*SimpleGrazing*" module currently used to control pasture harvesting, and with the "Soil physical" module that describes the relevant properties of the soil profile (macroporosity, drained upper limit and infiltration rate).

Within this module, parameters that are available in the user interface include livestock numbers, liveweights, grazing duration (all of which contribute to the calculation of grazing pressure), and damage recovery rates for soils and pastures (specifically both the perennial ryegrass and white clover modules).

4.2.1 Effect of animal pressure on soil damage

Animal numbers, liveweights and grazing times are not explicitly modelled in *AgPasture*. Thus, a treading pressure value for each grazing event is calculated within the "Damage" module.

$$TP = SR * LW * GD / 1000 \quad \text{(Equation 14)}$$

Where TP is the grazing pressure value (t LW/ha.hr), SR is the instantaneous stocking rate (animals per hectare), LW is the average mass of animals (kg) and GD is the length of the grazing period (hours).

A new variable 'SoilDamage' is created that has a daily value. This value can be increased by treading events on any given day or decreased as a result of natural recovery processes.

From the treading pressure value, the soil damage associated with that event is calculated (as in Figure 1 and Equation 2) and added to the value of 'SoilDamage' on a daily time step.

$$SD_i = SD_{i-1} + 1 - e^{(-0.000639471 \times TP)} \quad \text{(Equation 15)}$$

Where grazing events span multiple days (GD > 24 hr), the change in value of soil damage is pro-rated between the number of days.

4.2.2 Macroporosity

Macroporosity is defined in APSIM as the volume between saturation (θ_{SAT}) and drained upper limit (θ_{DUL}, at -33 kPa), both of which thresholds can be modified dynamically in the course of a simulation. In terms of the macroporosity % values noted in Figure 2, this would be represented in APSIM as macroporosity divided by total water holding capacity at saturation:

$$\text{Macroporosity (\%)} = (\theta_{SAT} - \theta_{DUL}) \times 100 / \theta_{SAT} \quad \text{(Equation 16)}$$

Plant available water is defined in APSIM as the volume between drained upper limit and lower limit (θ_{LL}, at -1500 kPa), both of which thresholds can also be modified dynamically. Given the dynamics indicated above, the effect of damage should be implemented in the model by altering θ_{DUL}. Thus, increased damage will increase θ_{DUL}, leading to a reduction in macroporosity (θ_{SAT} - θ_{DUL}) and an increase in plant available water (θ_{DUL} - θ_{LL}).

The reduction in macroporosity is implemented as a modification to DUL, assuming a linear relationship with the level of damage.

$$DUL = DUL_{init} + SD \times (Macroporosity_{init} - 0.02) \quad \text{(Equation 17)}$$

Where DUL_{init} is the initial (undamaged) drained upper limit and $Macroporosity_{init}$ is the initial macroporosity (see Eqn. 16). The effect of Eqn. 17 is that as the level of soil damage increases, DUL is forced closer to soil saturation leaving a macroporosity of 0.02 at the most severe level of damage.

4.2.3 Infiltration rate

Infiltration rate is defined in APSIM as the saturated hydraulic conductivity of each soil layer (K_S, mm/day), that can be modified dynamically during the course of a simulation to reflect temporary damage and recovery effects caused by treading events.

The reduction in infiltration rate associated with damage is implemented as a modification to saturated hydraulic conductivity assuming a linear relationship with the level of damage:

$$K_S = SD \times (K_{S\_init} - 2 \times K_{DUL}) \qquad \text{(Equation 18)}$$

Where K_{S_init} is the initial undamaged K_s and K_{DUL} is the hydraulic conductivity at DUL.

With regard to the Tian et al. (1998) infiltration rate modelling study, for our purposes, we could ignore slope (assuming all relevant sites are effectively flat) and treatment (assuming only one treading event). APSIM does account for soil organic matter (OM) and soil moisture (SM) content but does not currently account for bare ground cover or anion storage capacity (ASC). Thus, it would be necessary to re-model the functions with the original data, restricting the independent variables to OM, SM and Damage. However, that data was not available.

4.2.4 Depth distribution of soil impacts

To capture the reduction in severity of treading damage with increasing depth in the soil, a stepped decay function was applied as:

$$SD(z) = exp\left(-4\ Ł\left(1 - \frac{z_0 - z}{z_0 - z_{max}}\right)\right) \qquad \text{(Equation 19)}$$

where SD (0-1) is the shape of the damage function with depth, z (mm) in the soil, z_{max} and z_0 (mm) are the depths in the soil where the damage first starts to reduce from the maximum value and the depth at which there is largely no damage. The operator Ł stands for bounding between 0 and 1. Values of $SD_z < 0.02$ were set to 0. See Figure 10 for an illustration of the function.

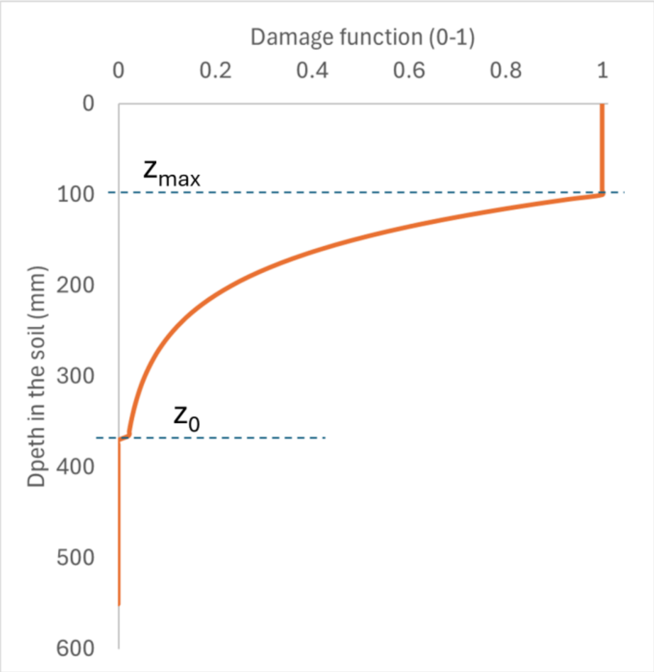


Figure 10. Shape of the damage function in the soil where z_{max} is set to 100 mm and z_0 to 375 mm.

4.2.5 Recovery of soil and pasture properties

To represent soil recovery, a fixed proportion of the prior value of 'SoilDamage' (SD) is subtracted from the daily value, producing a first-order decay function for the value of SD. This fixed proportion is derived from observations of the length of time taken for differential soil surface damage in treading trials to disappear (Section 3.2.4). The full equation allows for repeated damage events on the current day, which are added to the damage value from the previous day. No recovery occurs on the days where soil damage increases.

$$SD = \max[1, SD_i - (SD_i \times RR_{soil}), SD_i + SD_i] \quad \text{(Equation 20)}$$

where 'SD' is the soil damage value, 'i' is the day and 'RR_{soil}' is the recovery coefficient specific to a given soil type.

Note that because the function is a first order decay, the value of SD will never reach 0 (complete recovery), and thus a recovery threshold SD value is applied when it is considered that effective recovery has occurred. This value is set at SD = 0.05 (Figure 11).

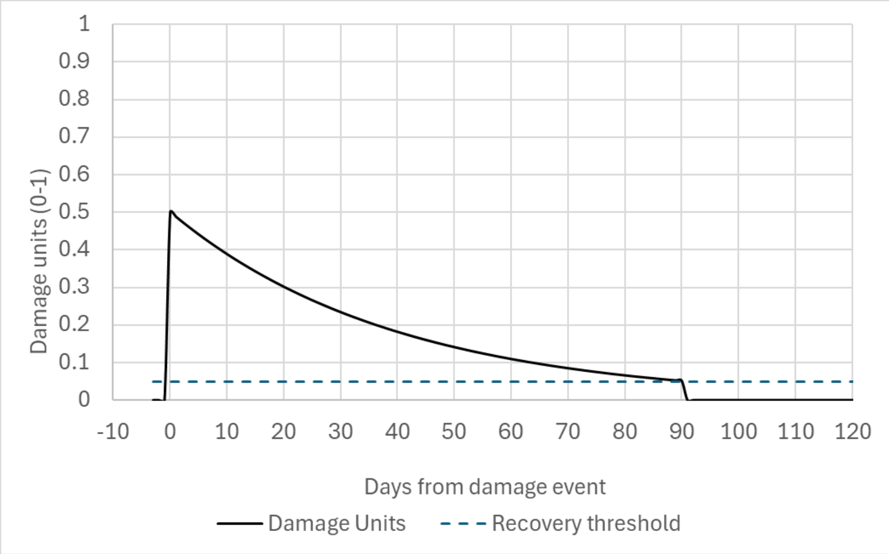


Figure 11: Effective recovery of the 'SoilDamage' parameter over a three-month period, assuming a single damage event and an RR_{soil} value of 0.013.

4.2.6 Effect of damage on sward properties

The loss of herbage mass associated with grazing is already incorporated in the *SimpleGrazing* module of the *AgPasture* model that implements a biomass removal. The module allows the user to specify a residual pasture mass amount.

A new variable 'PlantDamage' has been created, that will have a daily value. This value can be increased by treading events on any given day or decreased as a result of natural recovery processes.

4.2.7 Herbage wastage

In an operational dairy farm, grazing wet soils will normally lead to increased wastage of herbage. This is often referred to as 'poaching' and the effects can be minimised by careful grazing management. Given that these simulations are intended to reflect the effect of excellent management, poaching effects were ignored in these simulations.

4.2.8 Tissue damage

Waterlogging effects on plant growth (which apply even in the absence of grazing) are already incorporated into the *AgPasture* module of APSIM. They are assumed to operate through a reduction in soil aeration and root gas exchange associated with a reduction in air-filled pore space as water takes up a larger proportion of that pore space. In *AgPasture*, growth is limited if the soil water content is above a given threshold, the minimum water free porosity (θ_{mp}). This is calculated in Eqn. 21, where θ_{SAT} is the water content at saturation and p_{min} is the fraction of total porosity that has to be free of water to avoid any impediment to growth.

$$\theta_{mp}=\theta_{SAT}(1-p_{min}) \quad \text{(Equation 21)}$$

When the water content is greater than θ_{mp}, growth will be limited. The growth limiting factor (ε_A) is a scalar applied to daily growth rate, calculated using two factors (Eqn. 22): the ratio of current air-filled pore space to non-limiting pore space; and the maximum possible species-specific reduction in plant growth when the soil is saturated (S_L). Perennial ryegrass has a default value of 0.1 for S_L (thus daily $\varepsilon_A > 0.9$).

$$\varepsilon_A=1-S_L(\theta-\theta_{mp} / \theta_{SAT}-\theta_{mp}) \qquad \text{(Equation 22)}$$

The waterlogging limitation is based on cumulative waterlogging, which means that growth limitation is more severe if waterlogging conditions are persistent. The maximum increment in one day is the same as the soil water saturation factor (S_L) and cannot be greater than one. The recovery from waterlogging happens every day when water content is below full saturation and is proportional to the water-free porosity. The maximum daily recovery rate from waterlogging has a default value of 0.25.

4.2.9 Recovery of plant damage

Growing point processes are not explicitly modelled in APSIM, so, as was the approach for soil recovery, a plant recovery function is implemented that modifies the level of damage impacting sward properties. The user can specify a daily recovery rate. A fixed proportion of the value of 'PlantDamage' is subtracted from the current day value, producing a first-order decay function. This value is derived from observations of the length of time taken for differential pasture growth rate effects in treading trials to disappear (Section 3.3.3).

$$PD = \max[1, PD_i - (PD_i \times RR_{plant}), SD_i + SD_i] \qquad \text{(Equation 23)}$$

Where 'i' is the day and 'RR_{plant}' is the coefficient specific to a given plant species. At this stage we have insufficient data to specify different RR_{plant} values for the main plant species in *AgPasture*.

As is the case for the soil recovery equation, because the function is a first order decay, the value of PD will never reach 0 (complete recovery), and thus a threshold PD value is applied when it is considered that effective recovery has occurred (sensu Figure 11Figure 11). This value is set at PD = 0.05.

5. Simulation Methods

5.1 APSIM structure

APSIM (Holzworth et al., 2018) is a process-based simulation model that consists of a set of interchangeable modules built around a core engine that enables the user to simulate desired combinations of climate, soil types, crops and management at a daily time step. APSIM revision 2025.02.7659.0 was used for the simulations reported here.

The climate module consists of a daily weather file spanning multiple years that includes minimum and maximum daily temperatures, rainfall, potential evapotranspiration, radiation, vapour pressure, relative humidity and wind run. This file can be constructed from weather station records but is commonly imported from the Virtual Climate Station Network (VCSN), a spline interpolation model that outputs the necessary data on a 5 km × 5 km grid for any location in New Zealand (Tait & Woods, 2007). The model has been evaluated by Cichota et al. (2008).

The soil module consists of a soil profile physical description defined as a series of layers with the characteristics of texture (sand, silt and clay proportions), bulk density, volumetric soil moisture contents at various matric potentials that relate to plant growth (air dry, -3000 kPa; lower limit, -1500 kPa, drained upper limit, -33 kPa; saturation, 0 kPa) and saturated hydraulic conductivity. Layers are also described in terms of soil organic matter and its various fractions, mineral nitrogen content, pH and cation exchange capacity. Below-ground crop parameters include effective rooting depth by species and crop-specific lower limit values (i.e. the volumetric soil moisture content below which the crop can no longer extract water). Soil water dynamics are controlled by a range of hydraulic parameters (e.g., diffusivity, evaporation rates, runoff). Soil nutrient dynamics are controlled by a range of biogeochemical parameters (e.g., mineralisation and immobilisation).

Within the suite of crop models, the *AgPasture* model represents an established pasture (i.e., no sowing management) that incorporates a range of pasture species that can be simulated individually or in combination to represent mixed swards. These species modules incorporate growth, carbon allocation, nitrogen response functions, senescence rates, and tissue nutritive value parameters.

Management modules include irrigation (rates and timing of water), fertiliser application (rates and timing of nitrogen), and harvesting/grazing. The grazing module *SimpleGrazing* includes options for rotational grazing of pasture at specific times and to specific levels of pasture mass without specifying the nature of the animal, which will be required for implementing treading damage functionality. This is where the new treading damage module logically sits within the APSIM framework. For the purpose of this project, we have built a new module, which could in time be assimilated into *SimpleGrazing*.

With respect to the scope of this study the perennial ryegrass and white clover *AgPasture* modules (Li et al., 2011) are used to represent the high producing dairy pastures typical of lowland coastal areas. These modules already incorporate a response of plants to waterlogged soils that is outlined in detail in Section 4.

5.2 Simulation sites

During discussions with NIWA and Kōmanawa Solutions Limited, six regions in New Zealand were selected for this study. Within each region, the Fundamental Soil Layers map (https://soils.landcareresearch.co.nz/tools/fsl/maps-fsl) was combined with the NZDEM (https://lris.scinfo.org.nz/layer/48131-nzdem-north-island-25-metre/) and clipped to identify areas within 20 m of sea level. The areas were further clipped to find areas with a >50% probability of the water table depth being within 2 m of the land surface based on shapefiles provided by NIWA to Kōmanawa. The soil information was summarised and supplied to AgResearch by Kōmanawa (P. Durney, *unpublished data, 2024*).

The six regional locations were chosen to represent coastal lowland areas susceptible to waterlogging as a result of future water table rise, and where intensive pastoral systems are common. These were:

1. Dargaville, Northland
2. Hauraki, Waikato
3. Maketū, Bay of Plenty
4. Himatangi, Manawatū
5. Kaiapoi, Canterbury
6. Invercargill, Southland

For each region, a weather file for a 52-year period (1972-2024) was generated for a central geographic location from the Virtual Climate Station Network. Geographic coordinate locations and mean annual temperature and rainfall statistics for the regions are shown in Table 1.

Table 1 Climate characteristics of six regional locations. Latitude and longitude are in decimal degrees; T_{mean_annual} – mean annual temperature in ºC; R_{mean_annual} – mean annual rainfall in mm/yr.

Region	Location	Latitude	Longitude	T_{mean_annual}	R_{mean_annual}
Northland	Dargaville	-35.978	173.880	15.5	1176
Waikato	Pipiroa	-37.223	175.522	15.0	1106
Bay of Plenty	Maketū	-37.774	176.461	14.8	1404
Manawatū	Himatangi	-40.335	175.241	13.5	902
Canterbury	Sefton	-43.247	172.683	12.2	633
Southland	Otaitai	-46.328	168.120	10.2	1059

Within these “at risk” areas, all soil orders comprising over 12.5% of the area within any region were selected. This identified six soil orders (of a possible 13), i.e. Gley, Recent, Organic, Pumice, Pallic and Ultic. The latter three were only substantive in three regions, i.e. Pumice in the Bay of Plenty, Pallic in Canterbury, and Ultic in Northland, but including them meant that all regions had >70% of their “at risk” area directly represented, and most had >80% representation (Table 2). The soils that did not meet the 12.5% threshold in any region (Table 3) were not modelled in APSIM but were assigned proxy soil orders based on the expert opinion of the authors.

Table 2. Percentage representation of soil orders across “at risk” areas of the six regions showing only the soils that had a contribution greater than 12.5% to any region.

Region	Gley	Organic	Pallic	Pumice	Recent	Ultic	Total
Northland	37	11	0	0	20	13	80
Waikato	42	22	0	0	6	2	71
Bay of Plenty	20	21	0	26	18	0	84
Manawatū	61	50	3	0	20	0	89
Canterbury	46	1	20	0	27	0	94
Southland	10	63	0	0	24	0	98

Table 3. Percentage representation of soil orders across "at risk" areas of the six regions that contributed less than 12.5% to any region.

Region	Allophanic	Brown	Granular	Melanic	Oxidic	Podzol	Raw
Northland		5	4	2	1	9	
Waikato	11	11	7				
Bay of Plenty	11	3				1	2
Manawatū		11					
Canterbury		3					3
Southland		2				1	

The New Zealand soils contained in the APSOIL database (https://www.apsim.info/apsim-model/apsoil/) were selected and, where possible, aligned to the New Zealand Soil orders resulted in 32 soils across five of the six required soil orders. Some soil orders were well represented (e.g., nine Gley, eleven Pallic, and seven Recent soils) but there were only three Pumice soils, two Ultic and no Organic soils identified in the database. Within each soil order, the outlier soils were discarded (e.g., atypical rock content or topsoil texture) and then a typical soil with a mid-range plant-available water content was selected to represent the soil order in the simulations. A new Organic soil was developed based on the Andrews_12a.1 S-map sibling. Data was drawn from the S-map orders (https://smap.landcareresearch.co.nz/), the New Zealand National Soils Database factsheet (Wilde, 2003) and the accumulated knowledge/experience of the authors to characterise this soil. Key soil properties are given in Table 4.

Table 4. Key soil properties of the topsoil layer of the representative soils. The data items and units are: ρ_b – bulk density in Mg /m^3; θ_{SAT} – saturated water content in m^3 /m^3; θ_{DUL} – drained upper limit in m^3 /m^3; K_s – saturated hydraulic conductivity in mm /day; and OC – organic carbon in %.

Region	Gley	Organic	Pallic	Pumice	Recent	Ultic
ρ_b	1.03	0.40	1.22	0.91	1.23	0.68
θ_{SAT}	0.53	0.84	0.48	0.56	0.49	0.66
θ_{DUL}	0.41	0.74	0.41	0.40	0.34	0.61
K_s	3186	1000	798	20963	2342	7354
OC	3.6	45.0	3.0	5.4	2.9	8.0
Local name	Taho	Andrews	Templeton	Ōropi	Waimakariri	Wharekohe

5.3 Basic APSIM simulation setup

A common simulation setup was used for all locations and soils. All sites were assumed to have no slope or aspect, being predominantly flat coastal lowlands. Pastures comprised perennial ryegrass and white clover plant modules within *AgPasture,* with maximum rooting depths of 600 mm for ryegrass and 300 mm for white clover. It is worth noting that higher water table conditions will likely further constrain rooting depth (Waddington & Zimmerman, 1972). The APSIM soil model was *SWIM3* (Huth et al., 2012) with a set potential lower boundary condition used to simulate the water table depth (see further detail below).

Fertiliser rates were assigned to be representative of intensive dairy systems (Gray et al., 2023) and avoided winter applications of fertiliser. The rates and dates varied across regions as shown in Table 5. There were no other soil chemical fertility limitations in the model.

Table 5. Fertiliser application dates and rates in kg N /ha used in the simulations. All applications were on the 15th of the month except for April, which was on the 25th.

Region	Mar	Apr	Aug	Sep	Oct	Nov	Dec	Total
Northland		33	33		33			99
Other North Island		33	33	33	33			132
Canterbury	27	27	27	27	27	27	27	189
Southland	34		34	34	34		34	170

Simulations for the Manawatū and Canterbury sites were irrigated assuming a well-designed and maintained centre pivot system. All other sites were unirrigated.

Pasture was harvested (with an assumption of no damage to the soil; see Section 4.2.1 for how the damage function was implemented) with the *SimpleGrazing* model using a target pre-grazing biomass rule with additional constraints to prevent intervals that were too long or too short between grazing events. The details are presented in Table 6. Excreta from grazed biomass was returned evenly (i.e., not in patches) to the soil. Urine N returns were assumed to be 42% of that contained in the grazed biomass, dung N was 28% and the remaining 30% was assumed to be removed from the soil-pasture into nearby lanes or into cow body mass or product. Urine N was distributed evenly into the soil to a depth of 200 mm.

Table 6. Key parameters controlling grazing timings, for all regions and soil types.

Month	Units	Jul	Aug	Sep	Oct-Apr	May	Jun
Pre-grazing biomass	kg DM /ha	2800					
Post-grazing biomass	kg DM /ha	1000	1250	1500	1500	1250	1000
Max. rotation length	days	90	70	50	50	60	60
Min. rotation length	days	21					

Simulations were cycled twice through the available weather data, i.e., from 1972 to 2023, resulting in a total simulation length of 104 years. Outputs from the first cycle of 52 years were discarded to allow the soil nutrient and water conditions to adapt to the local environment.

The primary output of concern here was the amount of pasture harvested (grazed) resulting from the rules above. The other outputs collected were related to the soil water and pasture/soil damage conditions. These were aggregated (sum, average, maximum) to monthly totals for output as appropriate for the output within the simulation. The outputs were further aggregated to annual values before further statistical analysis.

The simulation factors (and number of options) were: *Region* (6); *Soil* (6); *Day* of damage (3); *Month* of damage (12); and *Mean* water table depth (10); resulting in 12,920 simulations with italics emphasising the short label for the factor. See further below (Sections 5.5 and 5.6) for how the effects of the higher water tables and damage to the soil/pasture were implemented.

5.4 Water table scenarios

Data on the mean depth to the water table (all values of which in this report are expressed as depth below the soil surface) and the intra-annual annual variation were obtained from Durney et al. (2024) by Kōmanawa. The data were binned according to mean depth categories and then the mean amplitude of the intra-annual annual variation was calculated by category. The ratio of the amplitude to the mean varied by water table depth category

(Figure 12). Following discussions (NIWA, Kōmanawa), it was thought likely that the low ratios in the 1250 and 1750 mean depth categories were due to limited data in those categories. Given these considerations, a constant ratio of 0.45 was used in the simulation scenarios.

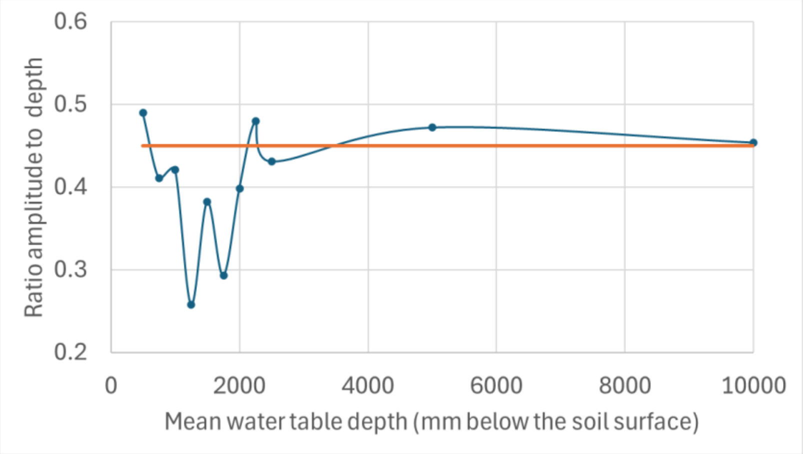


Figure 12. Ratio of the amplitude (deviation of the maximum or minimum water table depth from the mean depth) in intra-annual annual variation of the water table to the mean water table depth plotted against the mean depth. Blue line and symbols are taken from the categorised data as described in the text. The orange line is the ratio used in the simulations.

Across all the regions and soils, simulations were run for 10 mean water table depths of 500, 750, 1000, 1250, 1500, 1750, 2000, 2500, 5000 and 10000 mm below the surface[2]. Figure 13 shows two examples of the inter-annual variation in water table depth.

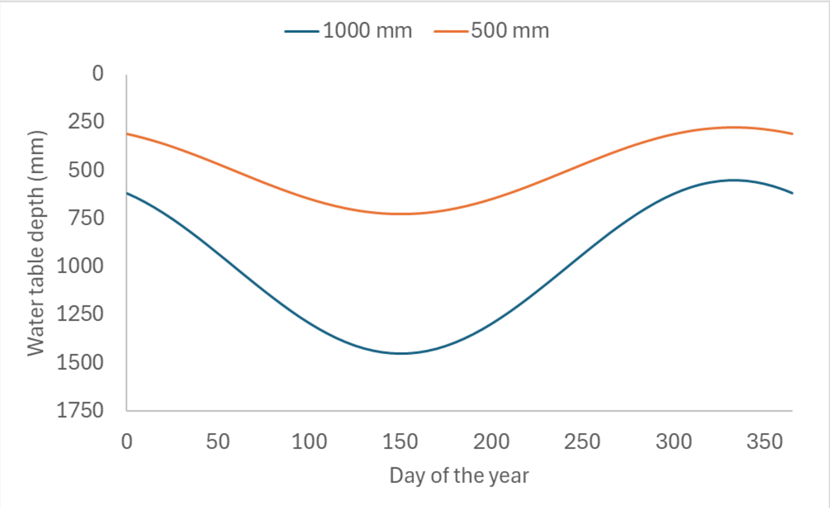


Figure 13. Examples of intra-annual water table depth variations used in the simulations. Data is shown for water tables at mean depths of 500 and 1000 mm below the soil surface.

[2] While simulations were also run for a mean water table depth of 2250 mm, there was an error in the set up and those data have therefore been excluded from this report.

5.5 Effect of Anaerobicity on Pasture Growth

The immediate consequence of a greater water content in the soil is that there is little space available for air. Therefore, there is limited O_2 available for root respiration processes and that limits the ability of the plant to extract water from the soil. APSIM does not directly model the changes in O_2 in the soil but rather uses the soil water content relative to the drained upper limit (DUL) and saturation (SAT) as a proxy. Following Johnson (2008), the anaerobicity effect is calculated from the relative water content in the root zone between DUL and SAT where the effects are cumulative over time. A value of 1.0 causes a full reduction in growth. There is no effect below DUL, while full soil water saturation for 10 days will cause a complete suppression of growth. Recovery from anaerobic conditions begins once the water content falls below SAT, with the recovery rate reaching a maximum of 0.25 /day once the water content falls below DUL. Figure 14 shows a diagram of this as an example for a hypothetical soil where the soil is first below DUL, then at SAT for 12 days, followed by some drainage and evaporation and then by a further short wetting event.

Anaerobicity is calculated and applied to the pasture growth each simulated day, with the water content evolving from a combination of soil, plant, weather and water table conditions.

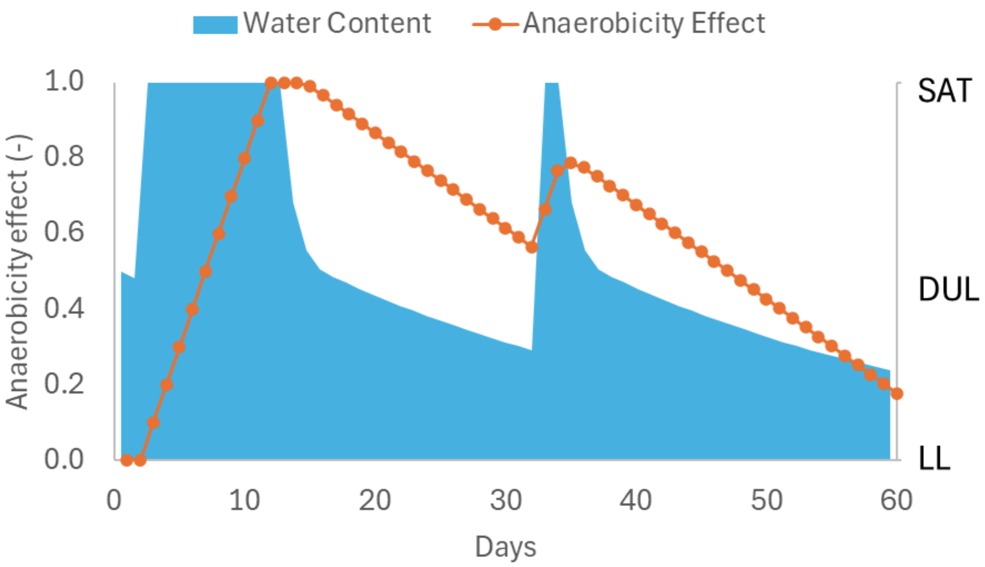


Figure 14. Example of the dependency of anaerobicity effect on both present day and historical soil water content (see the text for details). The shaded area shows the water content between the soil lower limit (LL), drained upper limit (DUL) and saturation (SAT). The orange line shows the anaerobicity effect that is applied to the daily pasture growth.

5.6 Treading Pressure and Damage Functions

Section 4 describes the relationship between soil conditions and damage to the soil and pasture. These effects were implemented using an APSIM script (Moore et al., 2014).

Under normal conditions, there is some damage to the soil and pasture whenever it is grazed but this damage is highly episodic, particularly under intermediate water table conditions, such that a 52-year simulation could not be relied upon to represent the effects across the various paddocks on the farm. Therefore, the pasture removal part of grazing (see Section 5.3) was isolated from the treading damage aspects. The equations in Section 4 were implemented such that the grazing pressure could be imposed at a given date which was independent of the herbage removal schedule.

Testing of the damage function showed that the soil and pasture had always recovered to pre-damage conditions well within 12 months of the damage event. Given this, the simulations were set up such that there was a damage event on the same month and day in each year within the same simulation. The assumptions and range of conditions on the damage events were:

- 450 kg LW cows
- Grazing duration of 24 hours (which could represent a whole paddock or a break)
- Stocking density of 100 cows/ha from August to April and 300 cows/ha from May to July
- The exponent on the relationship between grazing pressure and damage function was -0.6395 × 10^{-3}
- The recovery rate parameter was set to 0.015 /day for both pasture species and soil damage
- The depth of uniform damage was set to 100 mm and the practical maximum depth of damage was 250 mm

5.7 Statistical analysis of the model outputs

The aim was to predict the expected value of the yearly harvest $E(harv)$ for any region and soil via a nonlinear function with three estimable parameters, adopting an assumed gamma distribution for the error. The data supplied came from the modelled monthly grazeable pasture harvested from six regions × six soil type simulations × 10 annual average water table levels under cattle grazing.

We adopted the following nonlinear relationship between the expected value of the harvest and the water table depth (WT):

$$E(harv + \epsilon) = P_m \left(1 - exp\left[\frac{wt_0 - WT}{\alpha}\right]\right); \qquad WT > wt_0. \qquad \text{(Equation 24)}$$

Here ϵ is a small constant (currently 0.1) added to the yearly harvest values to ensure that all are strictly positive. This is necessary because the gamma distribution never produces values equal to zero, despite the probability density function possibly becoming unbounded as zero is approached. The constant P_m determines the maximum expected harvest as $WT \to \infty$; α is a scaling constant sharing units with WT; and wt_0 is the water table depth where the expected harvest drops to zero (and can no longer be modelled by a gamma distribution). The parameter α might be described by saying that it determines how much the exponential curve shape is stretched horizontally: higher α means more stretch, and smaller curve slopes (everything else being held constant). Let wt_{min} be the minimum WT for the current region/soil/month: we need $wt_0 < wt_{min}$ so that the expected value of the harvest is positive at wt_{min}. Typically $wt_{min} = 500$.

Fitting a more complex functional form for the expected harvest (with lower overall fitting error) was considered inappropriate in the current setting where simplicity, interpretability, and avoidance of overfitting are more desirable. Model diagnostics at times indicated violations of two model assumptions: constant dispersion, and gamma distributed errors. Again, these issues were considered not worth pursuing in the current setting.

As a baseline the value of P_m was set to be equal to the mean harvest at WT = 10000 for each region and soil. This leaves two parameters, α and wt_0, that are chosen to maximise the likelihood function according to a gamma distribution.

For Ultic soils there were convergence problems due to missing data. These problems were resolved by constraining the potential range of α and wt_0 to be approximately equal to the respective ranges of these fitted parameters for the other 5 soil groups.

The one fixed parameter (P_m) and two fitted parameters (α and wt_0) are plotted according to region and soil in Figure 15a-f below. These are violin plots that show both the values of parameters as points, and a smooth approximate probability distribution based on the set of points of each x-axis category. As noted previously, P_m is strongly dependent on region and less so on soil type. The α parameter is influenced strongly by both region and soil type, while wt_0 depends strongly on soil type and less so on region.

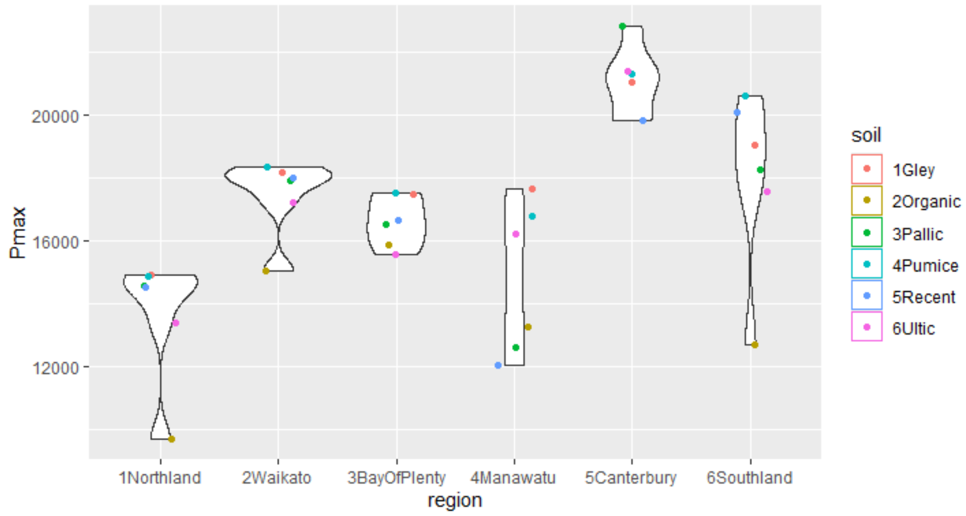


Figure 15a. P_m distribution by region.

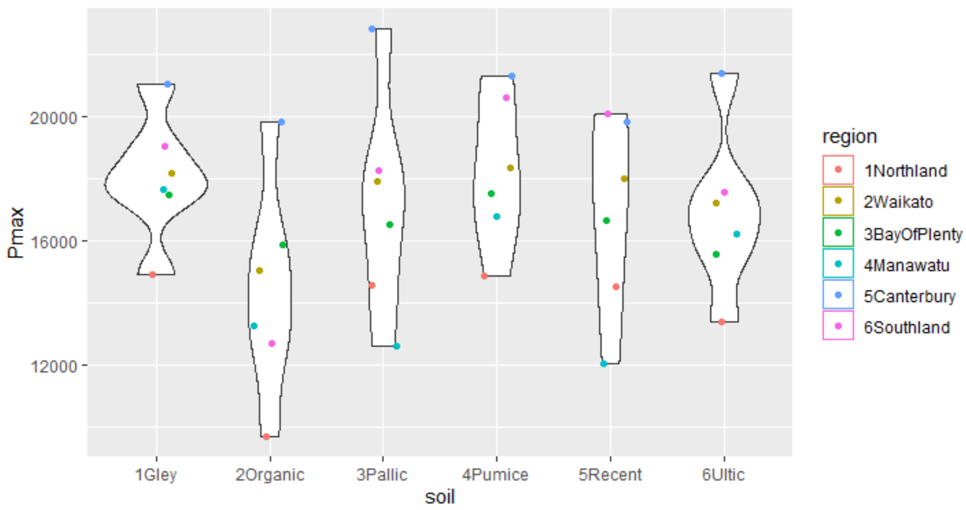


Figure 15b. P_m distribution by soil order

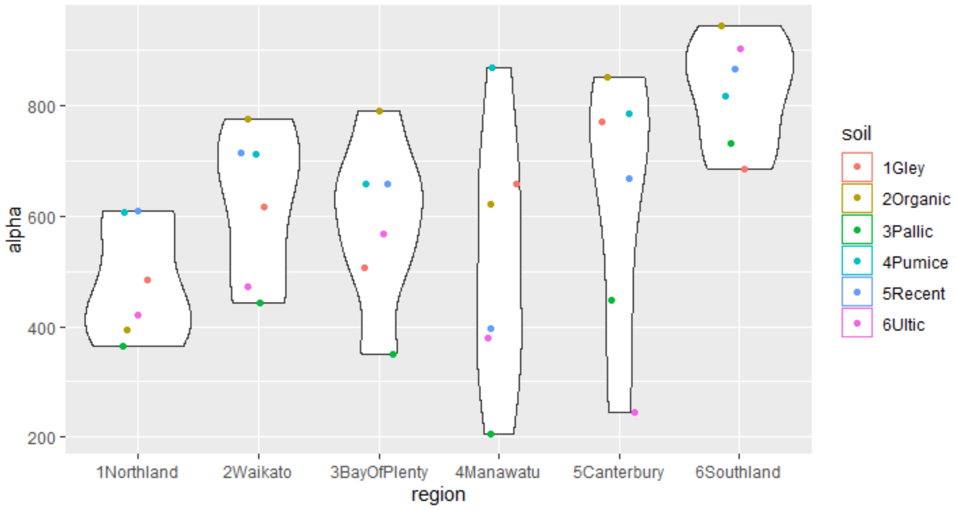


Figure 15c. α distribution by region

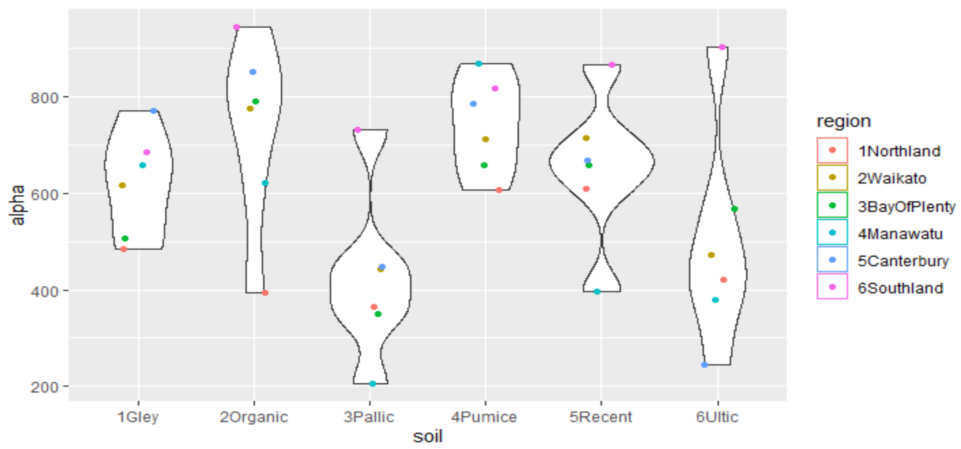


Figure 15d. α distribution by soil order

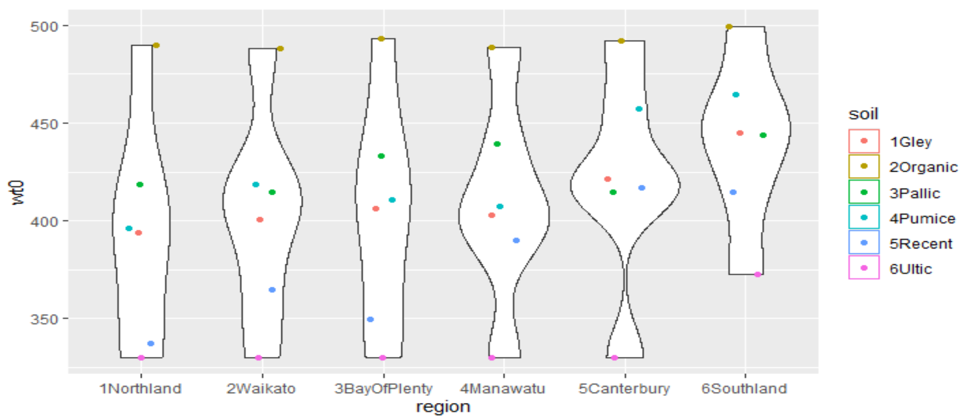


Figure 15e. wt_0 distribution by region

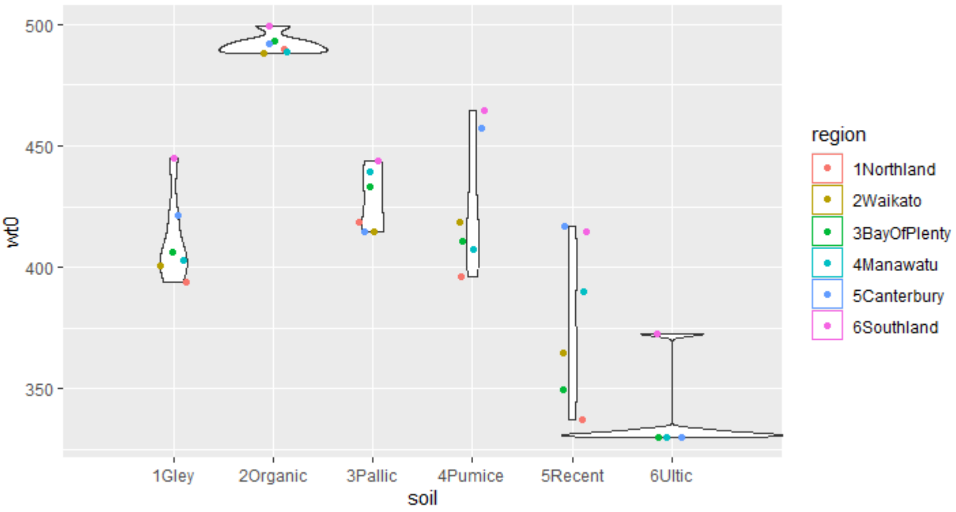


Figure 15f. wt_0 distribution by soil order

6. Simulation Results

6.1 Pasture production by region and soil

The simulated annual grazable pasture production outcomes under deep (wt_0 = 10 m) water table conditions (effectively non-limiting) are shown in Table 7. Mean annual pasture production was lowest in Northland and highest in Canterbury, resulting from a combination of the regional climatic conditions and the associated management assumptions (i.e., irrigation and fertiliser). The standard deviation of annual production ranged between 1.4 (Pumice soil in Southland) and 3.4 (Organic soil in Waikato) t DM /ha /year but across all soil orders was lowest in Canterbury. This is probably also because of the combination of high nitrogen fertiliser usage with irrigation.

The soil order also affected production. The lowest pasture production was on the Organic soil and this was likely due to nitrogen limitations (noting that fertiliser applications were tailored to region but not soil order). Examination of the time series of pasture growth rate in the Organic soil showed a high response to N fertiliser applications.

Table 7. Annual average grazeable pasture production (t DM/ha/year) under the 10 m mean water table depth across all the region and soil order combinations. The standard deviation is shown in parentheses.*

	Soil order					
Region	**Gley**	**Organic**	**Pallic**	**Pumice**	**Recent**	**Ultic**
	Annual average grazeable pasture production (t DM/ha/year)					
Northland	14.9 (2.3)	9.7 (2.5)	14.6 (2.3)*	14.9 (2.3)*	14.5 (2.2)	13.4 (2.1)
Waikato	18.1 (2.2)	15.0 (3.4)	17.9 (2.2)*	18.3 (2.2)*	18.0 (2.1)	17.2 (2.3)
Bay of Plenty	17.5 (2.3)	15.9 (2.6)	16.5 (2.6)*	17.5 (2.5)	16.6 (2.4)	15.6 (2.4)*
Manawatū	17.6 (2.8)	13.3 (3.3)	12.6 (2.9)	16.8 (3.3)*	12.0 (2.5)	16.2 (3.3)*
Canterbury	21.0 (1.7)	19.8 (1.9)	22.8 (1.6)	21.3 (1.7)*	19.8 (1.9)	21.4 (1.7)*
Southland	19.0 (1.8)	12.7 (1.9)	18.2 (3.0)*	20.6 (1.4)*	20.1 (1.5)	17.6 (3.1)*

*NB. Some region × soil combinations are non-existent (e.g., Pallic soils in the upper North Island regions, Pumice and Ultic soils in the South Island regions, see Table 2) but were simulated as part of the factorial simulation structure.

The effect of reducing the water table depth generally resulted in a reduction in mean annual grazeable pasture production. Two region and soil order combinations are shown in Figure 16, with the other 34 combinations following a broadly similar pattern (omitted for brevity). This reduction in pasture yield was from a combination of the effect of reduced aeration from the greater frequency of wetter root-zone soil layers at higher water tables and the greater likelihood of treading damage on the wetter soils. The fitted equations (refer Eqn. 24, Section 5.7) shown in Figure 16 for each region and soil order combination use the 52 individual years of data generated by the long-term simulations for each scenario.

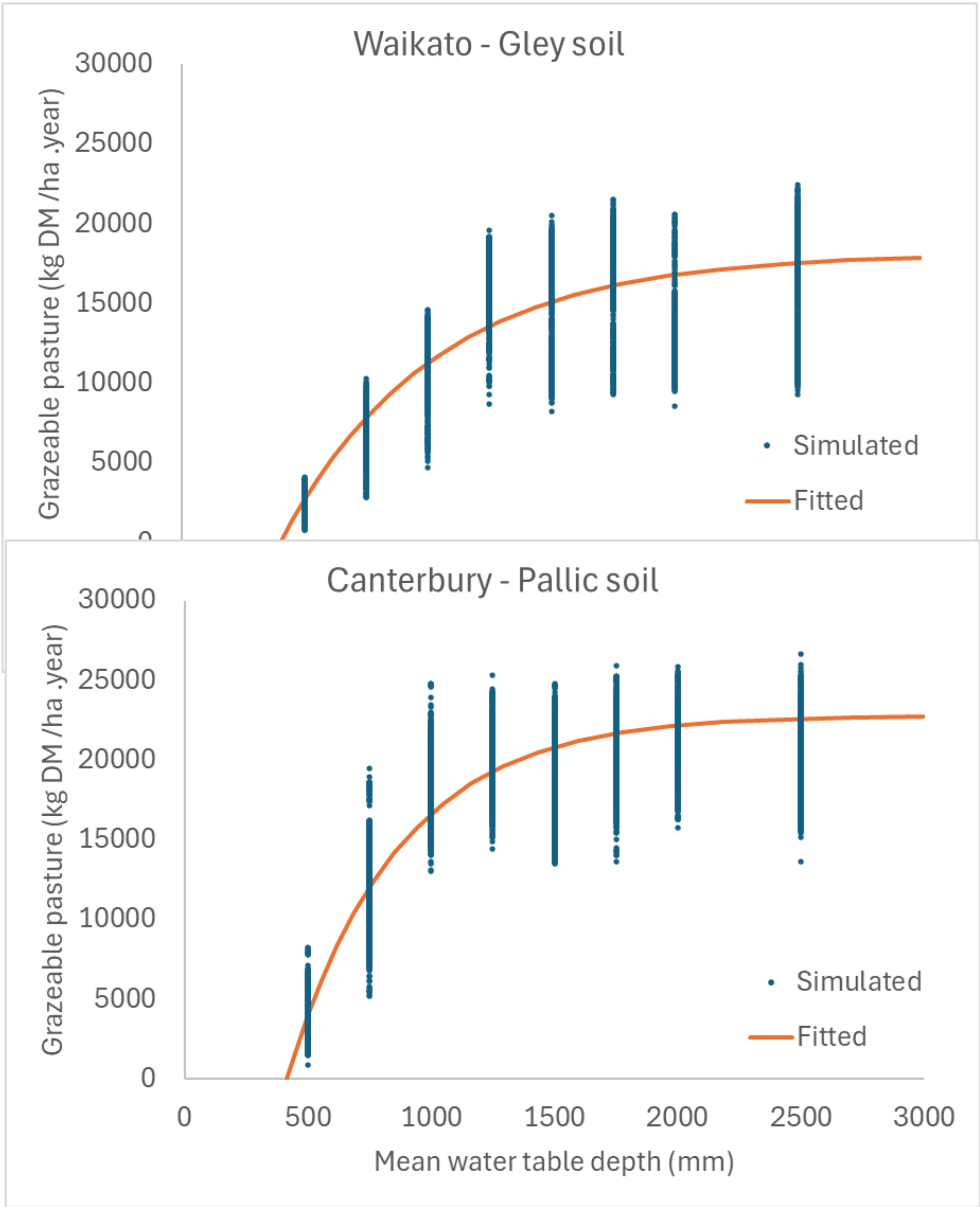


Figure 16. Simulated annual grazeable pasture (blue symbols) and fitted production functions as affected by mean water table depth for two region-soil combinations: a) Waikato-Gley and b) Canterbury-Pallic. The range in the symbols shows the year-to-year variation. The plots are truncated along the x-axis at a water table depth of 3 m in order to show the effects of rising water table depths closer to the soil surface. Production at the deepest (10 m) water table depth was 1.5% higher than at 3 m depth for the Waikato-Gley scenario and 0.3% higher for the Canterbury-Pallic scenario.

Table 8 reports the individual curve parameters for each of the region and soil order combinations.

Table 8. Key curve-fitted parameters describing the relationship between annual average grazeable pasture production and water table depth, for the 36 regional climate and soil order combinations. α is the slope of the non-linear curve (horizontal stretch) and wt_0 is the water table depth where the expected grazeable pasture production drops to zero.*

	Soil Order					
Region	**Gley**	**Organic**	**Pallic**	**Pumice**	**Recent**	**Ultic**
	α (mm)					
Northland	485	394	364	606	608	420
Waikato	616	776	442	711	714	471
Bay of Plenty	507	789	350	659	658	567
Manawatū	657	621	206	868	397	380
Canterbury	770	851	448	784	668	246
Southland	685	944	730	817	865	902
	wt_0 (mm)					
Northland	394	490	419	396	337	330
Waikato	401	488	415	419	365	330
Bay of Plenty	406	493	433	411	349	330
Manawatū	403	489	439	407	390	330
Canterbury	421	492	414	457	417	330
Southland	445	499	444	464	414	373

*NB. Some region × soil combinations are non-existent (e.g., Pallic soils in the upper North Island regions, Pumice and Ultic soils in the South Island regions, see Table 2) but were simulated as part of the factorial simulation structure.

6.2 Proxies for non-modelled soils

Any soil order contributing less than 12.5% of the area in any region was not formally modelled (see Section 5.2). Therefore, those soils would require proxies for the purpose of completing the regional-scale risk mapping. Using a combination of information on the soil orders (https://soils.landcareresearch.co.nz/topics/soil-classification/nzsc/soil-orders) and the expert knowledge of the authors, proxies are supplied as given in Table 9.

Table 9. Proxy soils suggested for the unmodelled soil orders.

Unmodelled Soil Order	Proxy Soil Order
Allophanic	Pumice
Brown	Pallic
Granular	Pumice
Melanic	Pallic
Oxidic	Pumice
Podzol	Pallic
Raw	Recent

6.3 Limitations and Cautions

The simulation outputs presented here assume:

- ideal grazing management with no grazing of already-damaged pastures (which would include off-paddock feeding options to avoid further damaging pastures);
- no grazing to the point that the pasture is so damaged that it requires re-grassing;
- no pests, diseases, or weeds (noting that a damaged pasture is often more susceptible to all of these);
- no ‘clustering’ of stock so the effects of damage around concentration points (e.g., gateways, troughs) is not considered; and
- a maximum grazing pressure of 3,240 t LW / ha.hr, being typical for on-pasture wintering. In some intensive wintering systems (such as in Southland) the intensity may be 2-3 times this.

Two precautionary comments should also be noted:

- There has been no background testing of APSIM in simulating Organic soils and so there is a greater uncertainty for: soil properties; simulation of the water balance; simulation of carbon and nitrogen dynamics; all of these will affect the simulation of pasture growth. Nevertheless, there does not seem to be anything obviously untoward from the simulation outputs.
- For some soil-climate combinations we observed systematic changes with time - these remain to be fully investigated.

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