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Modelling to analyse the impacts of animal treading effects on soil infiltration

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Abstract:

Animal treading can change soil physical properties, and thus is an important factor in hydrological modelling. We investigated the impacts of animal treading on infiltration by using a series of rainfall simulation experiments at Whatawhata Research Center, Waikato, New Zealand. The study identified significant variables for estimating soil steady-state infiltration at a micro-site ($0{\cdot}5\ m^2$) and fitted the Green and Ampt equation by modifying or including variables for soil and water parameters and animal activities on grazing paddocks. A regression function for estimating steady-state infiltration rate was created for each of four scenarios: between tracks (inter-track), track, easy slope with ash soil, and easy slope with clay soil. Significant variables included the number of days after treading, antecedent soil moisture, field capacity, percentage of bare ground, bulk density, and the high degree of soil damage (damage not compacted). Regression models explained more than 71% of the variance in steady-state infiltration for three scenarios, but only 53% for the easy slope with clay soil. The remodified Green and Ampt equation provided satisfactory estimation of infiltration for all scenarios (accuracy >80%), and thus enables us to use the modified model for Waikato hill country pastures of different topography, soil physical condition, season and grazing management. Copyright © 2006 John Wiley & Sons, Ltd.

KEY WORDS animal treading; infiltration rate; soil compaction; surface runoff

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INTRODUCTION

Animal treading can change to soil physical conditions via compaction, pugging, surface cracking or the creation of animal tracks (Singleton *et al*., 2000; Taddese *et al*., 2002; Drewry *et al*., 2004). These changes also effect soil water infiltration and could potentially increase sediment and nutrient losses in surface runoff (Greenwood *et al*., 1998; Roering, *et al*., 1999; Mudd and Furbish, 2004). Therefore, understanding the impact of animal treading on soil water conductivity is an important first step in estimating sediment and nutrient flows in hillslopes.

Many previous field measurements have provided quantitative evidence on the loss of sediment and nutrients due to animal treading for flat dairy grasslands, hill-lands, and different soil types (Elliott *et al*., 2002; McDowell *et al*., 2003a,b, 2005; Smith and Monaghan, 2003). However, the effects of soil surface disturbance resulting from animal treading on water infiltration in rangeland soils are still poorly understood (Russell *et al*., 2001; Alados *et al*., 2004).

This study addresses this research gap by modelling the impacts of animal treading on soil water infiltration. By understanding the hydrological processes operating at a micro-scale ($1\ m \times 0{\cdot}5\ m$), it is hoped that results can be integrated for use at larger scales. Parameters within the model important to water infiltration (Sheath and Carlson, 1998; McDowell *et al*., 2003a,b; Elliott and Carlson, 2004) were fitted to data from a series of rainfall simulation experiments. The modelling processes aimed (1) to identify significant variables for estimating soil water infiltration and the subsequent recovery of soil properties at a micro-site and (2) to incorporate these variables in a modification of the Green and Ampt (1911) equation. Modelling of significant parameters was tested by rainfall simulation on a range of topography, soil physical condition, season and grazing management.

MATERIALS AND METHODS

Study area

The field trial was carried out at Whatawhata Research Center (37°48′S, 175°5′E, ~220 m a.s.l.), near Hamilton, New Zealand. The study site represented typical hill topography and grazing of the region. Vegetation at the site was predominantly ryegrass–clover pasture (*Lolium perenne* L. and *Trifolium repens* L.). The topography was dominated by steep slopes ranging from 10 to 35°, dissected by animal tracks in a terrace pattern that yielded track and between-track areas. Tracks have been formed through concentrated walking of sheep and cattle. Easy slopes (<10°) are located on ridges and in valley floors.

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The region has a maritime climate with a mean annual rainfall between 1200 and 1700 mm, depending on elevation. Rainfall in the winter is twice that in summer (December to February).

Three soils dominate the study site: Waingaro, Dunmore, and Kaawa. The Waingaro clay loam (Umbric Dystrochrept, USDA Soil Taxonomy) occurs predominantly on the steep areas. Because of sensitivity to moisture (Sheath and Carlson, 1998), the Waingaro clay loam tends to crack in summer and swell in winter. The Dunmore silt loam (Entic Dystrandept) is derived from volcanic parent material including ash (Elliott *et al*., 2002). It has coarser texture and higher macroporosity (pores >30 μm) than the Waingaro clay loam (Sheath and Carlson, 1998), and occurs on easy slopes. It has less clay and is less sensitive to soil moisture fluctuations than the Waingaro clay loam (Sheath and Carlson, 1998). We refer to the Dunmore silt loam as the ash soil in this paper. The Kaawa hill soil (Ochreptic Hapludult) is developed from argillite but can also incorporate an overlain of volcanic ash. We refer to the Kaawa hill soil as clay (Bruce, 1978).

Field experiment

Data on soil infiltration associated with soil physical properties were obtained using simulated rainfall (Bowyer and Burt, 1989). The treading damage described in this paper was created by cattle (440 kg average liveweight) during winter (late July–early August). In the first part of the trial, cattle treading that formed track and between-track areas on steep hill land areas was examined. The second part of the experiment examined treading impacts on easy sloping areas with clay and ash soil types.

A full description of the trial design and soil chemical and physical analyses can be found in Sheath and Carlson (1998). Briefly, in June, variations in cattle density (40–70 ha^{-1}) as normalized livestock units and treading duration (2–3 days) were used to produce three levels of treading damage: low, medium and high, each with three replicate paddocks (Proffitt *et al*., 1995). Plots were selected within the paddocks as the grazing occurred (see Table I). For example, after day 1 the low-damage plots were selected and covered with protective cages to prevent further damage. After day 2, medium-damage plots were selected and after 3 days the high-damage plots were selected. It was the grazing duration rather than intensity that led to the different damage levels. On a total paddock basis, the mean level of soil surface disturbance was 43% (low tread), 53% (medium tread), and 72% (high tread) for the three damage treatments (Sheath and Carlson, 1998), whereas mean soil moistures (per cent gravimetric dry weight for 0–75 mm depth) at the time of treading were 86% for tracks, 82% for easy contoured ridges and gullies for both soil types, and 56% for steep areas between tracks (Li *et al*., 1995). The experiment also considered a double-treading scenario for easy slope areas in which a second treading occurred in early September. The average level of soil surface disturbance in double-treading plots was 20% higher than that in high-damage plots. The double-treading treatments were applied only to easy slope areas.

The impact of treading damage on hydrological processes was assessed using quadrate point estimates. Each quadrate consisted of a small bounded plot 1·0 m long by 0·5 m wide. These plots covered four scenarios: tracks, inter-tracks, easy slope area with ash soil, and easy slope area with clay soil. The treading arrangements for each scenario are listed in Table I. Owing to resource limitation, only 70 plots were selected for the above four scenarios. After the desired single (July–early August) or double (earlier September) treading had occurred, all the plots were caged to prevent further damage through the year (the plots were trimmed every 4 to 6 weeks after the second grazing event) (Wheeler *et al*., 2002). Rainfall simulation experiments were conducted following the treading treatment. For track and between-track areas, rainfall simulations were conducted in early August, October, December, February and June. For the easy slope areas, rainfall simulations were conducted in July, September, December, February and June. These repetitions aimed to determine the recovery of the infiltration rate following winter treading. The rainfall intensity used was 60 mm h^{-1}, but varied from 55 to 65 mm h^{-1}. The 30- and 60-min rainfall events with a return period of 1 year are 30 mm h^{-1} and 21 mm h^{-1} respectively. Although our chosen rainfall intensity is uncommon, it was used to ensure surface runoff occurred. The effects of high rainfall intensity on the corresponding infiltration rate are expected to be small within a rainfall event (Flenniken *et al*., 2001). In a few exceptional plots, where cracking was too severe to generate runoff, rainfall intensities up to 140 mm h^{-1} were used.

The antecedent soil moisture for each plot was measured by taking 10 core samples (0–75 mm depth) from

Table I. Details of treading management and measurements for different scenarios

Damage class	Tracks		Inter-tracks		Easy slope (10–20°)		
	Damage (%)	No. of plots	Damage (%)	No. of plots	Damage (%)	No. of ash plots	No. of clay plots
Controls	0–5	0	0–5	0	0–20	5	5
Moderate	50–60	10	30–40	10	20–40	5	5
High	90–100	5	50–60	5	40–60	5	5
Double	60–100	0	40–70	0	50–80	5	5
Total plots		15		15		20	20

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the adjacent area. Each rainfall simulation lasted at least 80 min and included 10 to 20 min of application after reaching the steady-state infiltration rate. The volume of surface runoff measured at the outlet of each plot was used to calculate the change in infiltration rate with time.

Steady-state infiltration rate model development

Changes in soil water content and conductivity are governed by soil physical and topographical conditions. Since evapotranspiration during a rainfall event was not significant (Torri *et al*., 1999), the total water received by a plot during a rainfall event can be divided between surface runoff and infiltration. When simulated rainfall is applied to soil, surface runoff does not occur immediately because the soil is unsaturated. As the soil water content approaches saturation, the rate of infiltration decreases until steady-state infiltration is reached. It has been reported that the modified Green and Ampt model can be used to model the infiltration rate when rainfall intensity is medium or high (Yu, 1999). Initial modelling of the simulation data suggested that the modified Green and Ampt equation provided a better fit to the observed data than the other two infiltration equations tested, namely the Philip equation and the Kostiakov equation (Tian *et al*., 1998). Therefore, we expanded the parameters of the modified Green and Ampt equation to include parameters relevant to infiltration on pastures with animal treading damage.

The original model proposed by Green and Ampt (1911) determined the volume of water infiltrating into the soil during a rainfall event. Mein and Larson (1973) introduced a modified Green and Ampt equation:

$$I = A + \frac{B}{t} \tag{1}$$

where I (mm h^{-1}) represented infiltration rate, t (min) elapsed time, and A and B parameters relevant respectively to the steady-state infiltration and the filling rate of soil water storage before surface runoff occurs.

The steady-state infiltration rate A affects the quantity of infiltrated water with time, especially in a long (>60 min) rainfall event. At our chosen rainfall intensity, steady-state infiltration occurred as early as 40 min from the beginning of rainfall simulation. Therefore, the mean value of the infiltration rate from 60 min to the end of simulation was used to estimate the steady-state infiltration rate. The filling rate B controls the time to the start of runoff. This parameter determines the slope of the infiltration curve from the beginning of a rainfall event to steady state. Through plotting the infiltration curves, a constant value of 100 for parameter B provided a good fitting with the infiltration filling rate (Tian *et al*., 1998).

Stepwise multiple linear regression was performed using the SPSS statistical software to determine significant soil and water parameters pertinent to the steady-state infiltration rate A. Four regression models were developed for each of four scenarios (Table I). Ten variables were considered in the study: season, antecedent soil moisture, percentages of bare ground, percentages of damage, damaged without compaction, field capacity, bulk density, treading, slope, organic matter, and soil type. The results of regression analysis were evaluated against the field measurement using root-mean-squared error (RMSE).

RESULTS AND DISCUSSION

Significant variables for estimating steady-state infiltration rate

Significant and insignificant variables affecting A for each of the four scenarios are summarized in Table II. Three variables were significant ($P < 0{\cdot}05$) for the between-track scenario: the number of days after treading, antecedent soil moisture, and soil field capacity. Three additional variables were significant for the track scenario: percentage of bare ground, bulk density and the degree of treading damage. These additional variables reflected the greater degree of animal hoof activity than the between-track scenario. The repeated walking of animals along the same route enhances the proportion of ground that was bare and increases soil bulk density (Sheath and Carlson, 1998). In contrast, decreased animal movement on inter-track areas meant that fewer soil physical properties were affected. For the easy slope scenarios, only three variables were significant ($P < 0{\cdot}05$). Two common significant variables for both ash and clay soils were the percentage of bare ground and the degree of treading. Although these two variables were possibly correlated, the stepwise regression identified that bare ground accounted for more variability in A than the degree of treading (Table II).

Field capacity was included in the steep (track and between-track) scenarios, but not for the easy sloping scenarios, whereas the opposite was true of organic matter. Soils with abundant organic matter tend to be resistant to compaction and surface crusting, which acts to aid water infiltration into the soil. In the easy sloping areas, organic matter will have accumulated via upslope erosion of fine particles and from plant residues and animal returns in dung. Areas of sediment deposition tend to be variable and organic matter affects infiltration rate (Lado *et al*., 2004) through continually breaking down and releasing finer, more-decomposed particles that aid in. The spatial distribution of organic matter is mainly driven by surface runoff and vegetation productivity.

Linear regression models for steady-state infiltration

The analysis of the steady-state infiltration rate benefits the understanding of the hydrological process resulting from animal treading activities. Different models were created for each of the four scenarios.

For the inter-track scenario, the following linear function includes six variables for estimating the steady-state infiltration rate i:

$$i = 0{\cdot}05\chi - 0{\cdot}261\theta + 0{\cdot}592K_{\mathrm{f}} - 0{\cdot}111\beta + 2{\cdot}529T_{\mathrm{r}} - 0{\cdot}059D_{\mathrm{a}} + 13{\cdot}46 \tag{2}$$

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Table II. Significant variables identified for each of four scenarios by using stepwise linear regression analysis

Variable	Inter-track plot		Track plot		Easy ash		Easy clay	
	Coef.	P	Coef.	P	Coef.	P	Coef.	P
No. days after treading event in July χ	0·050	0·000	0·081	0·000	0·032	0·070	0·017	0·224
Soil moisture θ(v v^{-1} × 100)	−0·261	0·000	−0·445	0·000	−0·416	0·001	−0·148	0·294
Organic matter O_m(g kg^{-1})	—	—	—	—	0·755	0·104	0·703	0·105
Damage not compacted[a] (%)	—	—	—	—	—	—	0·295	0·000
Field capacity K_f(v v^{-1} × 100)	0·59	0·004	1·372	0·000	—	—	—	—
Bare ground over plot area β (%)	−0·111	0·371	−0·052	0·000	−0·456	0·000	−0·539	0·023
Treatment	2·529	0·144	—	—	5·718	0·017	11·766	0·002
Bulk density (g cm^{-3})	—	—	66·33	0·002	—	—	—	—
Anion storage capacity A_s (%)	—	—	0·277	0·086	—	—	0·303	0·123
Slope class B_d	—	—	—	—	0·418	0·299	—	—
Area of treading damage D_a (%)	−0·059	0·511	0·371	0·000	—	—	−0·177	0·174
Constant	13·460	0·242	−115·910	0·086	11·770	0·008	−5·284	0·582
R^2	0·710	—	0·720	—	0·725	—	0·538	—

[a] Heavily damaged plot area ρ.

where χ is the number of days after the treading event in July, θ is the soil moisture level (per cent gravimetric dry weight), K_f is field capacity, i.e. the percentage of water volume in the soil, β is the percentage bare ground over the plot area, T_r is the treading treatment, which was given a number (zero or one). The zero stands for a single-treaded plot and the one for a double-treaded plot. This binomial dummy indicator was analysed as a categorical variable. D_a is the percentage area with treading damage. The regression accounted for 71% of the variance in predicting steady-state infiltration. Overall, the values of i ranged from 19·40 to 66·20, 2 to 79·6, 12·4 to 74·4, and 11 to 83·1 respectively for the inter-track, track, easy slope ash and easy slope clay scenarios. The mean and range of each variable are listed in Table III.

The positive coefficient of χ indicated that steady-state infiltration rate increased with time since treading and reflected the recovery of soil macropores with time

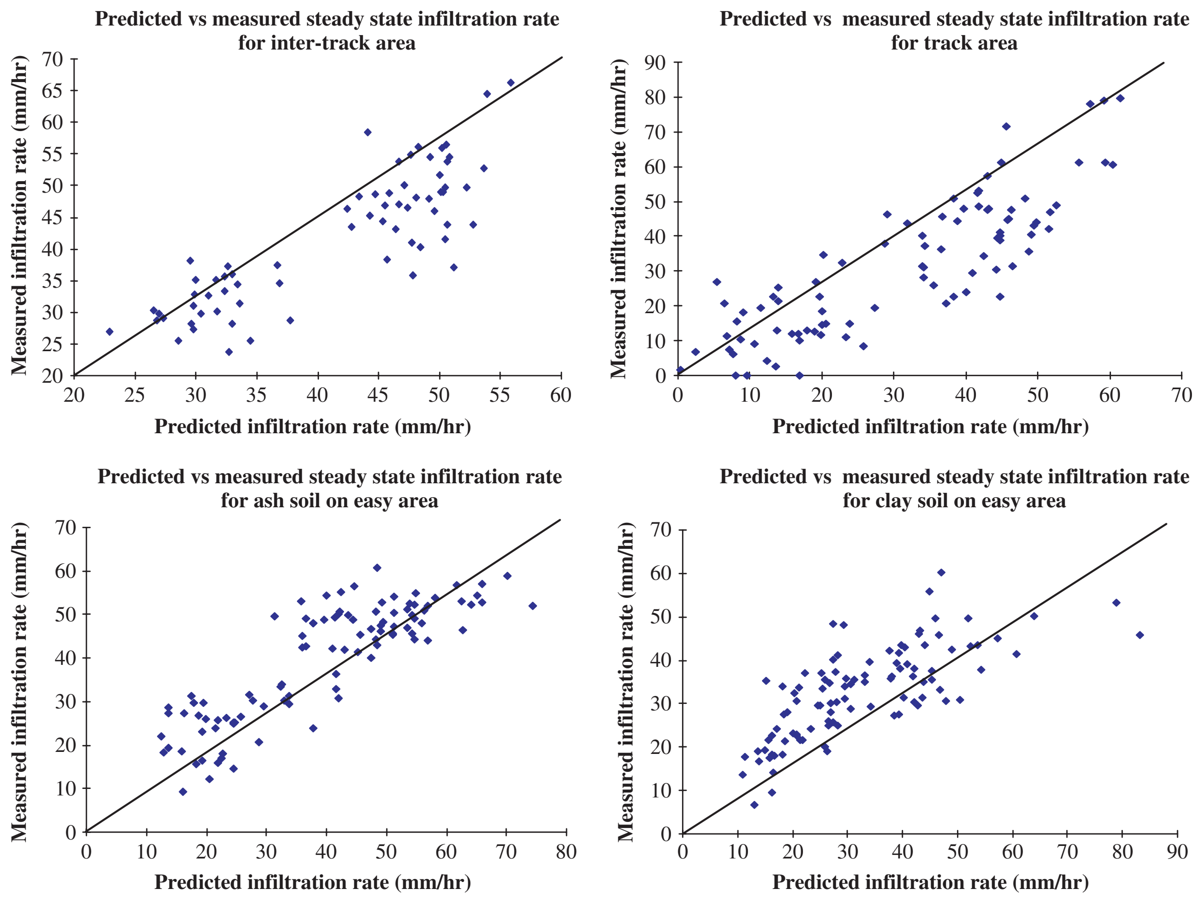

Figure 1. Comparison of predicted and measured steady-state infiltration rates

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Table III. Mean values for each variable and their range

Plot type	S_l (°)		O_m (%)		A_s (%)		K_f(v v^{-1}%)		B_d(g cm^{-3})		θ (%)		β (%)		D_a (%)		ρ (%)	
	Mean	Range	Mean	Range	Mean	Range	Mean	Range	Mean	Range	Mean	Range	Mean	Range	Mean	Range	Mean	Range
Ash	16·00	12–21	26·42	20·3–32·6	85·70	62·9–97·4	65·46	57–73	0·75	0·46–1·00	59·3	26–100	13·24	1·3–37	31·7	0–93	47	0–82
Clay	15·45	11–19	25·52	18·8–38·7	50·17	38·9–80·2	71·16	63–74	0·85	0·57–1·14	49·62	30–83	12·32	0·7–46·7	30·8	0–95	44·87	0–88·7
IH	32·29	28–35	20·17	18·2–21·7	60·80	51·4–67·8	56·27	48–59	0·97	0·89–1·04	50·95	24–70	15·5	1–36	36·87	3–68	—	—
IM	34·39	29–41	16·99	14–19.6	56·44	41–81.5	54·99	49–60	0·99	0·92–1·04	48·16	21–73	16·52	2·5–35·5	37·71	15·5–66·5	—	—
TH	2·91	0–7	18·24	15·6–21·4	65·23	59·5–71·2	51·50	48–55	0·96	0·87–1·04	55·85	24–82	20·09	2·9–61·4	41·36	7–98	—	—
TM	3·24	1–8	18·02	16·2–21·2	60·57	51·1–78·3	50·64	44–55	0·98	0·84–1·09	50·63	24–76	16·79	2·1–71	36·15	2·9–80·7	—	—
TP	2·62	1–4	17·96	14·6–22·7	67·28	56·4–77·3	61·99	48–68	0·90	0·86–1·00	56·21	30–74	32·1	4·3–82·1	47·06	7·9–100	—	—

(Drewry *et al.*, 2004; Drewry and Paton, 2005). The negative coefficient with θ suggested that infiltration rate was inversely related to soil moisture content, reflecting that wetter soil took less time to saturate. The equation also indicated that infiltration had a positive relationship with field capacity and a negative relationship with D_a (Malet *et al.*, 2003).

For the track scenario, the regression accounted for 72% of the variance in predicting steady-state infiltration. Equation (3) has seven variables: five out of the seven variables are common to those in Equation (2). However, the variable T_r in Equation (2) is missing from Equation (3). This missing variable shows that single or double treading makes no significant impact on infiltration over a track area. This could be because tracked areas are already heavily damaged and the second treading adds little damage. Two additional variables in Equation (3), not found in Equation (2), are anion storage capacity or phosphorus retention A_s and bulk density B_d.

$$i = 0{\cdot}08\chi - 0{\cdot}445\theta + 1{\cdot}372K_f - 0{\cdot}052\beta + 66{\cdot}33B_d + 0{\cdot}277A_s + 0{\cdot}371D_a - 115{\cdot}9 \quad (3)$$

The coefficient for the variable D_a in Equation (3) is positive and may reflect the correlation between pore space and bulk density (McDowell *et al.*, 2003b). Similarly, anion storage capacity measures the proportion of aluminium and iron hydrous oxides active in phosphorus sorption, but also prevalent in ash soils; ash soils also tend to be porous (Singleton and Addison, 1999).

For the scenario of easy slope with ash soil, Equation (4) includes two different variables from that in steep hill country (Equation (5)), i.e. organic matter O_m and the slope S_l in degrees:

$$i = 0{\cdot}032\chi - 0{\cdot}416\theta + 0{\cdot}755O_m - 0{\cdot}456\beta + 5{\cdot}718T_r + 0{\cdot}418S_l + 11{\cdot}77 \quad (4)$$

Organic matter concentration ranged between 200 and 320 g kg^{-1}. As with anion storage capacity, those soils with more organic matter also tend to have good infiltration due to good aggregate stability (Singleton *et al.*, 2000). Slope ranged from 12 to 21°. This model explained 72·5% of the field steady-state infiltration rate.

For the scenario of the easy slope with clay soil, Equation (5) shares two variables with Equation (4), β and T_r, and one uncommon to all previous equations, namely ρ, which is the score for an area that has been damaged but not compacted. This was generated by placing a quadrat with 200 squares over the paddock and putting a point down in the centre of the square. If the point touched an area with visible damage, then it was counted as damaged.

$$i = 0{\cdot}017\chi - 0{\cdot}148\theta + 0{\cdot}703O_m + 0{\cdot}295\rho - 0{\cdot}539\beta + 11{\cdot}76T_r + 0{\cdot}303A_s - 0{\cdot}177D_a - 5{\cdot}284 \quad (5)$$

The empirical model explains only 53% of variance in steady-state infiltration. The predicted steady-state infiltration rate was plotted against that from the field measurement (Figure 1). The two clusters in the top left are due to time gaps between measurements. The data clustered with values less than 40 were from August and October. The rest were measured from December to June of the following year.

Results from assessing the infiltration recovery rate

Data on steady-state infiltration rates during the year indicated the rate of recovery after treading. For easy sloping land with ash soil this is displayed in Figure 2(a). The curves represent the mean values of field-measured

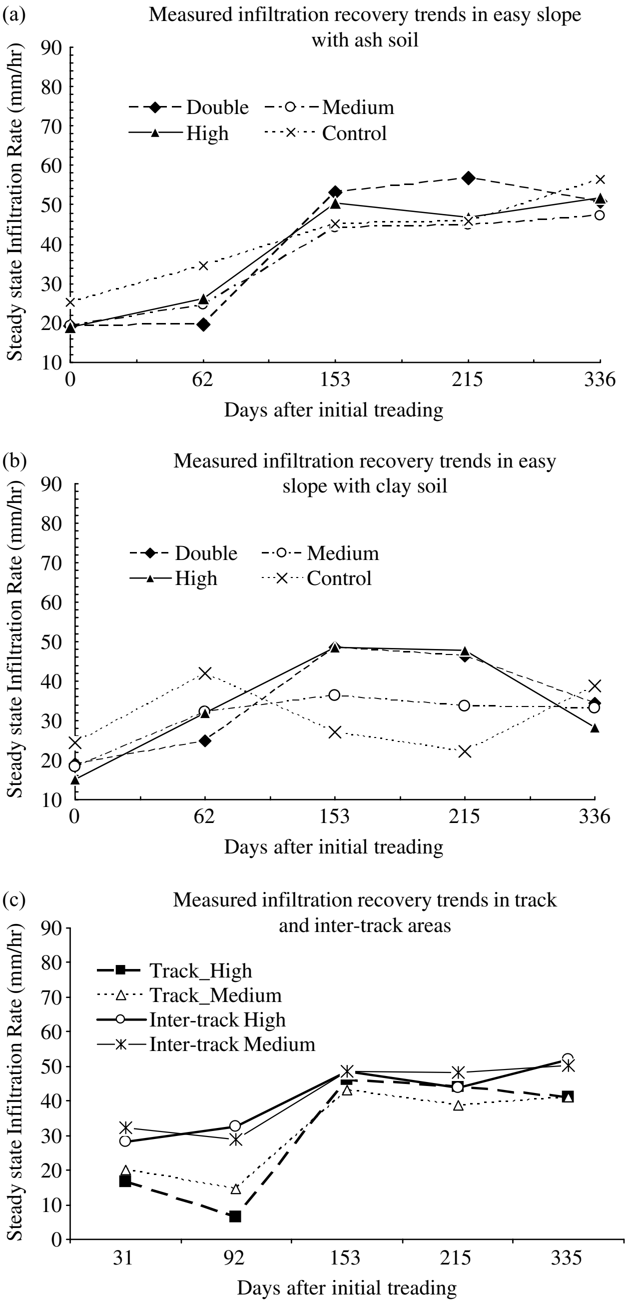

Figure 2. Infiltration recovery pattern following initial treading damage for all scenarios

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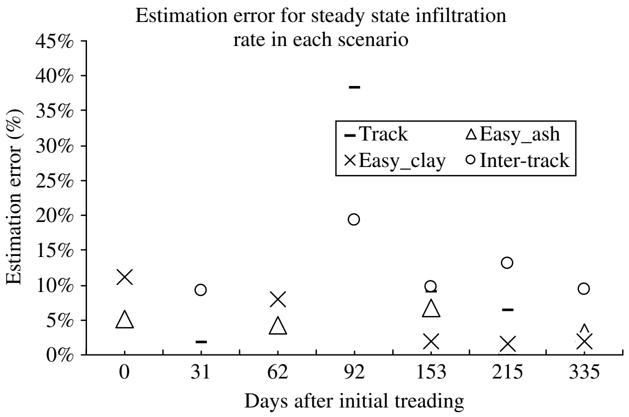

Figure 3. Accuracy assessment of the model-predicted steady-state infiltration rate in each scenario

steady-state infiltration rate for each treading treatment: i.e. low, medium and high damage. The recovery pattern for all treading treatments in the ash soil was linearly related with time since treading ($P < 0{\cdot}05$), whereas no clear relationship was evident in the clay soil ($P < 0{\cdot}2$). This could be because soils dominated by a clay texture tend to contain fewer macropores than ash soils (Singleton *et al.*, 2000).

Figure 2a and b shows that infiltration rate was lower in the double-treading scenario than others. This indicates that the second treading in September did impose further damage on steady-state infiltration rate. However, infiltration on double-treaded areas had a rapid recovery rate regardless of soil type. The recovery rate was slower in the high-damage area than in the medium-damage areas.

Figure 2c shows that the infiltration rate on a tracks plot was consistently less than that on a between-tracks plot. However, infiltration rates had recovered to the same degree in both the track and inter-track scenarios by the third simulation.

Model estimation of steady-state infiltration rate was evaluated using the mean absolute per cent error (Figure 3). The accuracy of the model estimations were more than 70% for all four scenarios, except one case in September in the track scenario. The field steady-state infiltration rate was consistently low for all track areas (high- and medium-damaged plots) in September. In general, the prediction errors might be partially due to the influences of inter-structural cracks and root channels.

Model performance for the infiltration in an entire rainfall event

Given satisfactory estimation of steady-state infiltration rate A, infiltration rate can also be affected by the filling rate B in Equation (1) at the beginning of a rainfall

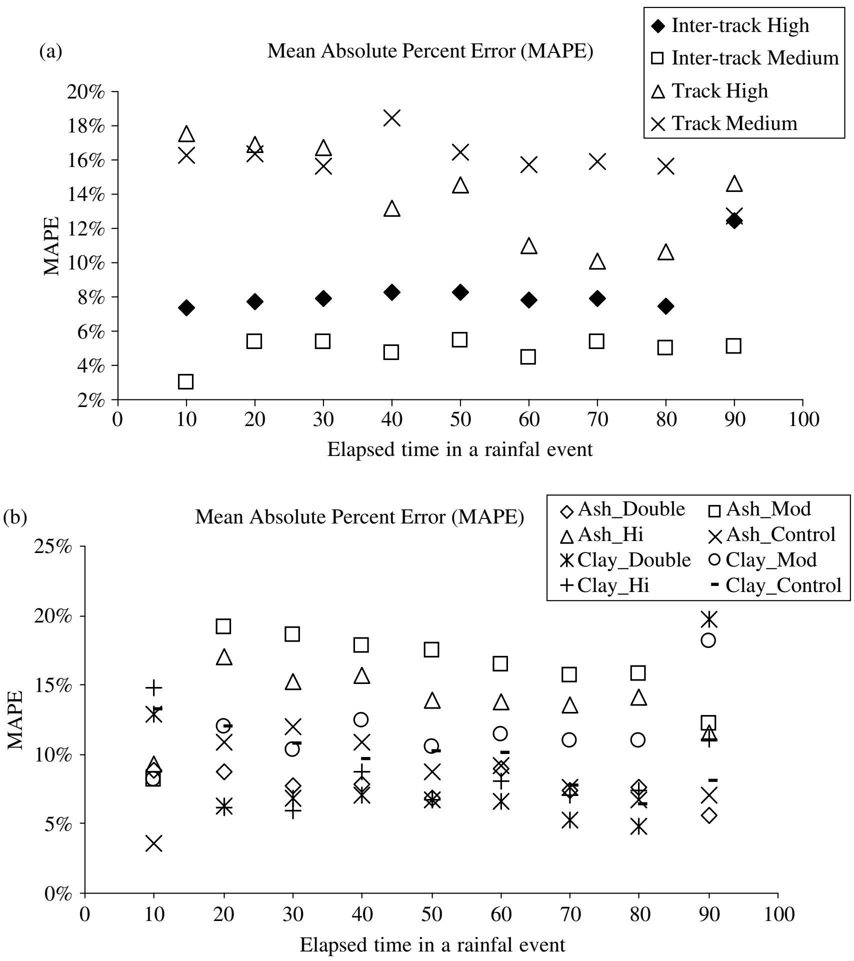

Figure 4. Predicted error analysis for infiltration rate change with elapsed rainfall time

event. Earlier work by Tian *et al.* (1998) showed that a constant infiltration rate was obtained by using $B = 100$. The error was analysed and is displayed in Figure 4. The estimation errors for all scenarios were less than 20%. However, estimation errors for each scenario show non-random trends with time. This non-random error distribution suggests that using one constant value for all scenarios to control infiltration filling can be significantly improved. To improve model estimation would require more data and additional information to identify those factors that better describe the variations of filling rate between scenarios.

SUMMARY AND CONCLUSION

We evaluated the widespread problem of decreased infiltration due to disturbed soils from animal treading. Analysis of a large number of rainfall simulation measurements over four seasons confirmed that the animal treading had significant impacts on infiltration processes in grazed pastures. Data indicated that, at our site, decreased infiltration was recovered after about a year except in a clay soil, which showed no obvious trend.

The positive and negative influences on infiltration rate met our perceptions of the function of measured soil physical and hydrological variables in four scenarios (easy slope areas with ash and clay soils, track and inter-track areas). In so doing, these models now enable us to predict infiltration in Waikato hill country with different topography, soil physical condition, season and grazing management.

An important impact of the model at micro-scale on catchment management is the improved understanding of the hydrological properties. The model predictions can be used for up-scaling water flow specifications in field size (large scale) with complex physical and geomorphologic conditions. Such an up-scaled hydrological model should be useful for studying erosion and chemical losses for evaluating water quality and quantity (Kozak and Ahuja, 2005).

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