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Research article

Grazing livestock move by Lévy walks: Implications for soil health and environment

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ABSTRACT

Grazing livestock plays an important role in the context of food security, agricultural sustainability and climate change. Understanding how livestock move and interact with their environment may offer new insights on how grazing practices impact soil and ecosystem functions at spatial and temporal scales where knowledge is currently limited. We characterized daily and seasonal grazing patterns using Global Positioning System (GPS) data from two grazing strategies: conventionally- and rotationally-grazed pastures. Livestock movement was consistent with the so-called Lévy walks, and could thus be simulated with Lévy-walk based probability density functions. Our newly introduced "Movement model" links grazing patterns with soil structure and related functions by coupling animal movement and soil structure dynamics models, allowing to predict spatially-explicit changes in key soil properties. Predicted post-grazing management-specific bulk densities were consistent with field measurements and confirmed that rotational grazing produced similar disturbance as conventional grazing despite hosting higher stock densities. Harnessing information on livestock movement and its impacts in soil structure within a modelling framework can help testing and optimizing grazing strategies for ameliorating their impact on soil health and environment.

1. Introduction

Behavior is a very complex animal trait that contributes to ecological functioning in all terrestrial surfaces across temporal and spatial scales (de Jager et al., 2011; Forester et al., 2007). Animal behavior is driven by various factors including social interactions, the search for resources and shelter from weather conditions and predators. Understanding how environment influences animal behavior and vice-versa is challenging. It requires us to identify and characterize the key factors driving these interactions. Animal movement is an aspect of animal behavior that can be easily isolated for study and is nowadays easy to monitor thanks to the development of positioning technologies (Rivero et al., 2021). Different techniques exist depending on the targeted species ranging from optical methods based on fluorescence for tracking

microorganisms (Ariel et al., 2015), to the more traditional usage of Global Positioning System (GPS) devices (e.g., collars with sensors) that have been used to track mammals and birds (Morales et al., 2010). Moreover, animal movement has been relatively well characterized for different animal species by using models based on random walks (Morales et al., 2004; Smouse et al., 2010). The so-called Lévy walk models are known to be accurate in representing animal movement from swarming bacteria (Ariel et al., 2015), to insects and large mammals (Benhamou, 2007; Sand et al., 2005). Harnessing information derived from such monitoring strategies may not only be useful for understanding animal movement, but is also a powerful tool to expand our understanding of the complex interactions between animals and their environment that has the potential to be used to predict changes in vegetation or in soil degradation produced by animals (de Jager et al.,

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2011).

The movement of grazing animals is predominantly studied for rangelands and less attention has been given to more intensively managed grazing systems (Rivero et al., 2021). Moreover, movement patterns are often analyzed to understand how they are influenced by management and field characteristics but little is known about how animal movement influences soil functioning and the environment in grazed lands (Rivero et al., 2021). Some applications have rather focused on using GPS data for tracking animals to identify injured animals that are less mobile than others (Schieltz et al., 2017). However, correlations between spatially explicit grazing patterns and environmental functions have not been fully explored (Schoenbaum et al., 2017; Stephenson and Bailey, 2017; Yamulki and Jarvis, 2002) but may importantly impacting GHG emissions (Graham et al., 2022; Merbold et al., 2021). Most studies quantified grazing-induced changes in soil structure and functioning as a function of time without considering any spatial variation induced by livestock behavior (Drewry et al., 2004; Gregory et al., 2009; Leitinger et al., 2010; Steinfeld et al., 2006). Large-scale soil degradation by animal treading is recognized as an environmental threat. Steinfeld et al. (2006) estimated that 20 % of the world's grasslands are degraded, mostly through overgrazing, compaction, or erosion caused by livestock treading. Soil compaction may be one of the major hazards of grazing (Hamza and Anderson, 2005); and often results in soil erosion (Nawaz et al., 2013), increased greenhouse gas (GHG) emissions (Oertel et al., 2016) and reduction of biomass productivity (Håkansson and Reeder, 1994) and carbon stocks (Brevik et al., 2002; Tubeileh et al., 2003), thereby impacting soil ecological services (Aitkenhead et al., 2016; Conrad, 1996; Foster et al., 2017) and economy (Graves et al., 2015).

Despite the potentially adverse environmental consequences, grazing livestock are increasingly considered an important component of regenerative agricultural systems (Spratt et al., 2021; Teague and Kreuter, 2020) and play a vital role in the circular bioeconomy by upcycling low-quality feed resources (e.g., by-products of the food industry) as well as producing high quality nutrition from grasslands (Wilkinson and Lee, 2018). It has been suggested that integrating grazing livestock into farm systems has the potential to increase biodiversity (Morris, 2021), may reduce GHG emissions (Dowhower et al., 2020), promote carbon sequestration (Stanley et al., 2018), and maintain sustainable production (Pinheiro Machado Filho et al., 2021). There are clear benefits and disbenefits associated with livestock systems and therefore a need to develop strategies for livestock-grassland management that tip the balance towards the benefits is critically needed. As a component of such a strategy, we need a better understanding and characterization of the movement of grazing animals. Such a characterization would help to predict compacted areas of the field (Romero-Ruiz et al., 2018) and dung and urine hotspots (van Groenigen et al., 2005). This in turn would facilitate the identification of compacted zones with reduced transport properties that could lead to sediment detachment, water runoff and soil erosion (Leitinger et al., 2010; Pulley et al., 2021), and enable us to predict field-scale GHG emissions from soil. The novel combination of animal movement models and models of soil structural dynamics and associated processes (Meurer et al., 2020; Romero-Ruiz et al., 2023) offers a promising approach for understanding the environmental impacts of managed grazing systems (Hu et al., 2021; Pulido-Moncada et al., 2022). In addition, integrated mechanistic models that include animal movement under different stocking strategies and their impact on key soil processes may offer a crucial first step towards developing a more complete understanding of grazing systems. Such approach may also provide information on how to mitigate adverse environmental and economic impacts of soil degradation under grassland-livestock systems, and to propose interventions that are animal-welfare friendly, to modify the typical/natural movements (e.g., portable shade, movable water troughs, environment enrichment) (Baveye et al., 2021; Vereecken et al., 2016).

Here we explored grazing livestock movement and the associated

impacts from two contrasting stocking methods on soil physical properties: conventional grazing (termed here as set stocking, SS) and cell-grazing (CG). Set stocking is defined as a method that allows a specific, non-variable number of animals on a specific, non-variable area of land (e.g., enclosed pastures) during the time when grazing is allowed (Allen et al., 2011), whereas cell-grazing (CG) is an approach where enclosed pastures are divided into smaller areas (i.e., cells) and livestock are moved frequently (e.g., daily) to graze all cells in a rotation (Allen et al., 2011). Cell grazing differs in practice from conventional grazing by virtue of its emphasis upon intensive management, stock rotation and the close monitoring of pastures (Richards and Lawrence, 2009). We demonstrated that daily and seasonal statistical patterns of the movement of grazing animals are consistent with Lévy walks. Such Lévy grazing characteristics were then used in combination with a soil compaction model to predict spatially explicit changes in soil bulk density due to grazing. We coupled a model of animal movement (for an arbitrary pasture) with a soil compaction model (based on soil rheology and soil physics models) to systematically calculate spatio-temporal changes in soil properties in response to a given grazing management. The modelling scheme developed here was used to reproduce field and movement data from a grazing experiment established in 2018, the "TechnoGrazing"® project, located at Rothamsted Research, North Wyke Devon, UK.

2. Field experiments at Devon, United Kingdom

2.1. Field monitoring of grazing patterns for livestock

Our experimental data were collected from the fourth year of the "TechnoGrazing" experiment which was set up had been running and at Rothamsted Research, North Wyke, Devon, UK (50°46'38.9"N 3°55'10.0"W) since April 2018 (Fig. 1). The pasture in this experimental land was a temperate permanent pasture. It was last reseeded in 2013 with a seed mix that was predominantly perennial ryegrass with 5% white clover. Enclosed pastures were setup in triplicate in 2018 with a fixed size of 1.75 ha for SS and 1.0 ha for CG, the latter of which was subdivided into 42 cells. For the year of our study (in April 2021), eighteen-month-old dairy beef steers were assigned to either SS or CG (based on liveweight and breed type) to achieve stocking rates of ca. 1.38 and 3.6 Livestock Unit (LU) ha⁻¹ for SS and CG, respectively (i.e., LU conversion factor was 0.6). The SS treatments were grazed with a daily stocking density of 2.3 animal ha⁻¹ (1.38 Livestock Units ha⁻¹, LU ha⁻¹; which equals the seasonal stocking rate) and 180 grazing days in a 1.75 ha pasture. The CG treatments were grazed with an average daily stocking density of 252 animal ha⁻¹ (151.2 LU), a seasonal stocking rate of 6 animal ha⁻¹ (3.63 LU ha⁻¹), daily rotation (depending on grass availability and animal feed demand during the grazing season.) in cells of an average area of 0.0238 ha and 180 grazing days.

Daily area allocation in the CG pastures was determined by average pasture cover and estimated ad-lib feed demand (2.5% of animal liveweight). Animals were weighed at the beginning of the grazing season (April) and then ca. monthly thereafter. Average (±SEM) individual initial liveweight of the steers were 518 ± 10.7 (n = 12) and 489 ± 9.2 kg (n = 18) for SS and CG, respectively. Steers were removed from the enclosed pastures in early October, to allow for safe soil sampling, and measurement and their liveweights were recorded which were 657 ± 9.6 (n = 12) and 603 ± 6.0 (n = 18) for SS and CG, respectively. The mean liveweight averaged across the grazing season (April to October) were therefore 585 ± 9.0 (n = 12) and 540 ± 8.8 kg (n = 18) for SS and CG, respectively. The measured number of steps per animal, that was on average 1649 and 927 steps per day for SS and CG during the 2019 grazing season, respectively (Morgan et al., 2019).

Data on the movement of steers managed under SS and CG were collected using GPS enabled trackers (Yabby-Plus, Nortrak®, UK), mounted on collars worn by each animal (Fig. 1a and b). These data were collected from April to October 2021 and transmitted via 2G,

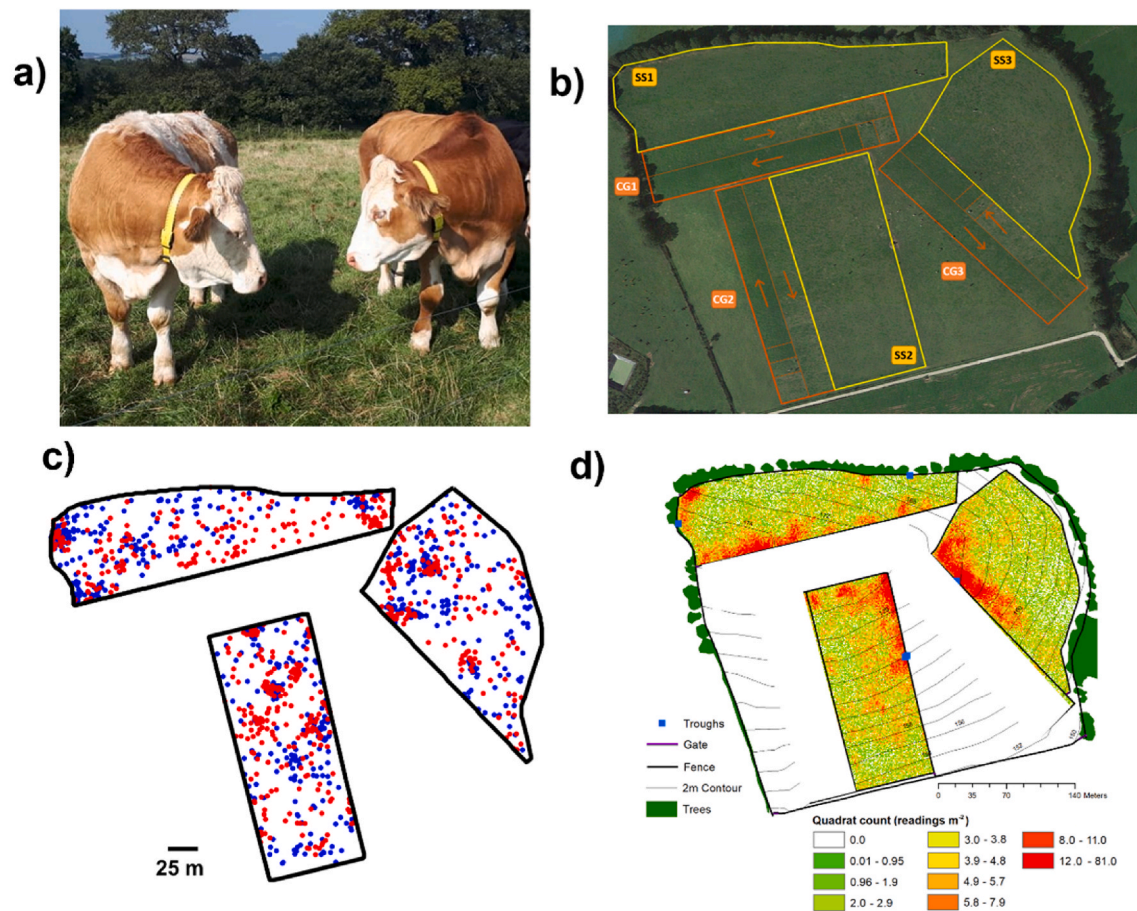


Fig. 1. (a) Picture of steers in a set stocking (SS) pasture fitted with collar-mounted GPS tracking devices; (b) Aerial image of the grazing experiment showing the layout of the replicated experimental pasture enclosures for SS (SS1, SS2 and SS3) and cell grazing (CG: CG1, CG2 and CG3) stocking methods; (c) Locations corresponding to two steers (red and blue points) in each of the SS experimental pastures after one day of grazing; (d) Heatmap of GPS grazing data in the SS pastures across the grazing season of 2021 showing that grazing animals covered a large proportion of the grazing area.

providing a location for each animal at intervals from 1 to 5 min. These data were then processed to obtain animal locations at constant intervals of 5 min (i.e., 288 locations per day). Some periods of data were not recorded due to technical issues related to the GPS collars. An average of 15% of the total possible data GPS data locations across the season were used for each collar in this study. This corresponds to approximately 44 days of data for each collar randomly distributed in the grazing season.

2.2. Collection of bulk density and penetrometer data

Soil mechanical properties were measured prior to the start of the grazing season (end of March) and when steers were removed (early October). Bulk density and penetration resistance were measured in both treatments (SS and CG) following stratified random sample designs. Soil samples for bulk density determination were collected from the top soil (0–10 cm, see below) from a total of 90 sampling points using the cylinder method (Blake and Hartge, 1986). Bulk density values are reported as dry soil mass divided by soil volume (cylinder volume). As designs have a random component, the sampling location coordinates for the autumn campaign were different to those for the spring campaign. Soil penetration resistance measurements were collected using a hand-held digital cone penetrometer (FieldScout SC 900, Spectrum Technologies Inc, Illinois, USA) fitted with a 2.54 cm diameter cone tip following manufacturer instructions. The target measurement depth was 45 cm, though it was not achieved in all the points due mainly to the presence of stones/rocks in the soil profile. In that case, additional

measurement attempts were carried out in the proximity of the original sampling point (within 30–50 cm). The deepest measurement achieved at each sampling location were then recorded and used for statistical analysis.

3. Modelling framework

3.1. Lévy walk models of animal movement

In order to have a spatially explicit representation of the expected locations in which animals visit, it is imperative to have an animal movement model that reproduces the main characteristics of animals in a confined space. Typically, animal movement (including unconfined mammals, bacteria and insects) can be characterized by models based on random walks or combination of random walks. In such implementations, animal movement is often described in polar coordinates that are characterized by rotation angle (θ) and the traveling distance (r) that indicate the direction to which animals will move and the Euclidean distance between the current and next locations, respectively. Animal movement patterns are then obtained by sequentially sampling from probability density functions (PDF) of each of θ and r .

In Lévy walk models of animal movement a uniform PDF is used to sample rotation angles from 0 to 2π and a heavy-tailed PDF is used to sample the traveling distance. In this study, r was sampled using the Weibull distribution given by:

$$p_w = f_w(x_w; a_w, b_w) = \begin{cases} \frac{b_w}{a_w} \left(\frac{x_w}{a_w}\right)^{b_w-1} e^{-\left(\frac{x_w}{a_w}\right)^{b_w}} & \text{if } x \geq 0, \\ 0 & \text{if } x < 0, \end{cases} \quad (1)$$

where p_w is the probability of the traveling distance x_w , and a_w and b_w are the Weibull parameters that are used to scale the traveling distance and highlight the distances with highest probability.

3.2. Soil compaction model

The soil compaction model developed by Romero-Ruiz et al., 2023 is used to systematically calculate temporal dynamics of soil bulk density, macroporosity and saturated hydraulic conductivity in response to animal treading for a given management treatment (stock density, grazing days and soil moisture conditions). The model is based on a dual-domain conceptualization of the soil which is considered to be formed by: (1) a soil matrix that is represented as an assembly of soil aggregates and resulting intra-aggregate porosity and (2) a soil macroporous region that can be seen as inter-aggregate porosity. Compaction induced by animal treading is modelled considering that a walking animal produces a time dependent stress applied on the soil that can be represented by a half-sinus cycle (Scholefield and Hall, 1986). Such a transient load produces an elastic (temporary) and a viscous (permanent) deformation of the soil frame resulting in irreversible deformation given by ϵ_v . This deformation is modelled using the Bingham rheology theory (Vyalov, 2013) considering information about the initial (prior to compaction) strain ϵ_0 , the axial load and duration of stress application and the soil rheological properties as:

$$\epsilon_v(t) = [\epsilon_B^2 S_{sm}(t)^{N_v} (1 - \cos(\omega t)) + \epsilon_0^2]^{\frac{1}{2}}, \quad (2)$$

where t is the time, ω is the angular frequency, ϵ_B comprises information about the soil rheological properties and the characteristics of the compaction event (e.g., soil complex viscosity and weight of the animal), $S_{sm} = \theta/\varphi_{sm}$ is the water saturation of the soil matrix, θ is the water content and N_{nu} is an empirical exponent. The time dependent

function $S_{sm}(t)^{N_v}$ is used to modulate the compaction damage as controlled by the soil water content (Romero-Ruiz et al., 2023). The viscous strain ϵ_v can thus be used to model soil properties by using geometrical approximations as detailed by Romero-Ruiz et al., 2023.

In addition to soil compaction damage, the soil compaction model can estimate recovery of soil properties as a function of time once the compacting elements are removed. Soil macro, meso and microporosities change dynamically as a function of time and recovery is expected to be associated with biological activity, climatic cycles and management. Meurer et al. (2020) showed that macroporosity (w_{mac}) recovers at an exponential rate asymptotically to a maximum macroporosity (w_{mac0}). Similarly, soil structure recovery in the viscous strain can be modelled as:

$$\epsilon_v = \epsilon_0 - (\epsilon_0 - \epsilon_i) e^{-d_r/\lambda_r}, \quad (3)$$

where ϵ_{mac} is the soil strain, representing the strain resulting after the grazing season, d_r is the number of days after the last grazing season, and λ_r determines the recovery rate. In this modelling framework, recovery by wetting and drying cycles (Stewart et al., 2016) is not considered.

3.3. The Moovement model: coupled animal movement and soil compaction modelling

We developed a model to systematically evaluate grazing-induced spatio-temporal changes in soil properties. The ‘‘Moovement’’ model couples a model that simulates animal movement in a given arbitrary field (Section 3.1) and the soil compaction model (Section 3.2). A schematic representation of the Moovement model is shown in Fig. 2.

3.3.1. Initialization of the moovement model

The Moovement model requires soil properties to be initialized and a spatial distribution of soil properties needs to be provided for an initial time in order to predict changes associated with compaction and recovery. The initial distribution of a given soil property (e.g., bulk density) can be obtained by: (1) assuming homogeneity, (2) using

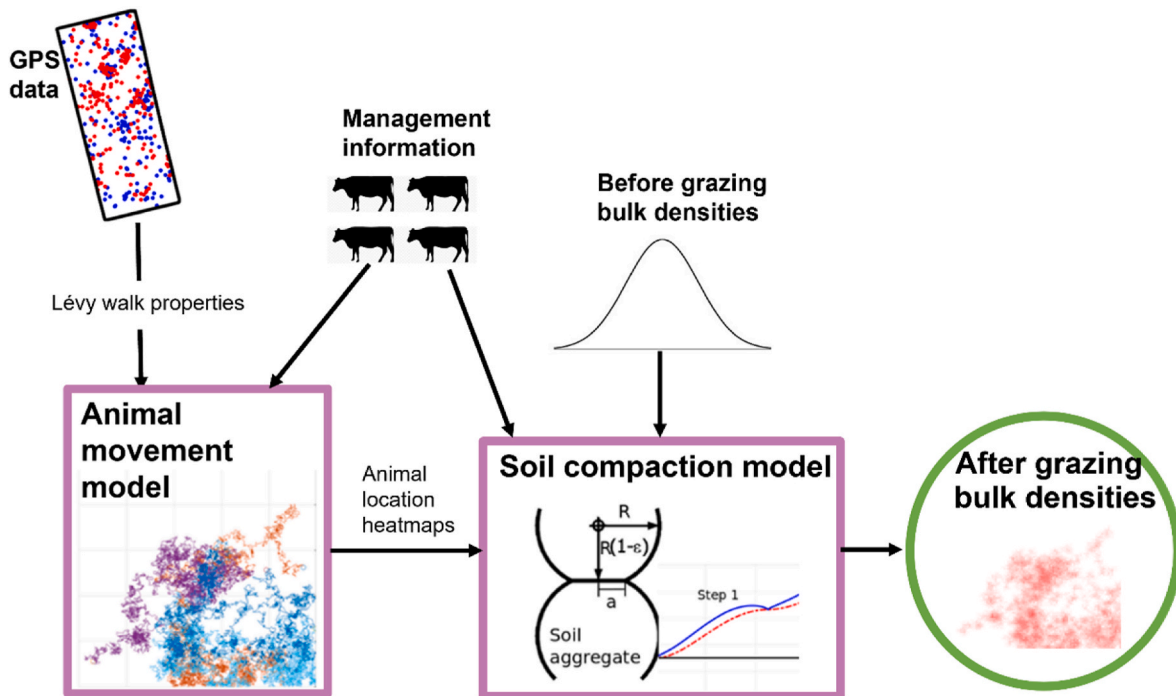


Fig. 2. Diagram illustrating the main elements of the Moovement model for coupled modelling of grazing animals and soil properties. Characteristics of grazing animals are fed into the model to predict spatial patterns of animal movement. Then these patterns are used in combination with initial soil physical properties for predicting changes as a function of time.

unconditional spatial simulation, and (3) using conditional spatial simulation. When homogeneity is assumed, a given unique value is assigned to all spatial locations, say on a grid. In unconditional simulation, the mean value (\bar{Y}_0) and standard deviation (σ_{Y_0}) of the given property are used together with a known variogram to simulate the property of interest on a given grid. In this method, the covariance matrix C for the property of interest for a given grid is generated by using a variogram model (e.g., spherical) fitted to a known data set. The Cholesky decomposition method (Webster and Oliver, 2007) is used to obtain the upper (U) and lower (L) matrices that satisfy $C = LU = LL^T$. The vector y of spatially located values for the given property is obtain by:

$$\begin{aligned} y &= Lg, \\ Y &= y\sigma_{Y_0} + \bar{Y}_0, \end{aligned} \quad (4)$$

where y is given in standard normal form and has the size of the number of points in the grid N , and g is the vector of length N sampled from a standard normal distribution. The conditional method simulates the property of interest in a given grid constrained to spatially T points located within the grid for which a value is given Z_T (i.e., the simulations are conditioned to known spatially-indexed measurements). Similarly, to the unconditional spatial simulation, a covariance matrix C can be obtained considering all grid points plus the locations corresponding to Z_T . Given that the dimension of C is $[N + T, N + T]$, it can be decomposed as:

$$\begin{bmatrix} C_{NN} & C_{NT} \\ C_{TN} & C_{TT} \end{bmatrix} = \begin{bmatrix} L_{NN} & 0 \\ L_{TN} & L_{TT} \end{bmatrix} \begin{bmatrix} U_{NN} & U_{NT} \\ 0 & U_{TT} \end{bmatrix}. \quad (5)$$

The vector of conditionally simulated values y can be obtained by:

$$\begin{aligned} y &= \begin{bmatrix} z_N \\ L_{TN}L_{NN}z_N + L_{TT}g \end{bmatrix}, \\ y &= y\sigma_{Y_0} + \bar{Y}_0. \end{aligned} \quad (6)$$

where z_N is Z_N given in its standard normal form.

3.3.2. Modelling animal movement and soil compaction patterns

The Movement model couples animal movement models based on Lévy walk with soil compaction models to predict changes in soil properties as a function of space and time (see Fig. 2). The model simulates daily animal movement patterns and calculates the resulting number of steps per square meter in the grazed pastures. Such grazing patterns are then fed into the soil compaction model in combination with information about the initial soil properties and the corresponding soil moisture conditions. The soil compaction model then predicts resulting change in soil properties as produced by animal treading that is used recursively as a new set of initial conditions. When grazing stops, the soil structure recovery model can be activated to simulate recovery of soil properties by bioturbation as described in Section 3.2.

3.4. Application of the movement model to the TechnoGrazing experiment

Grazing management and soil bulk density data were used to test the ability of the Movement model for assessing impacts of grazing on soil structure. We aimed at predicting after grazing bulk densities assuming that the before grazing bulk densities were known for both SS2 and CG2. To do this, GPS data from SS2 and CG2 were analyzed to derive the properties of the uniform and Weibull PDFs that are characteristic of each strategy. Animal movement was then simulated by sampling r and θ from the treatment specific PDFs and using the management information (e.g., LU, stocking rate, stocking density and number of grazing days) and the geometry of pastures SS2 and CG2. For simplicity, the cells in pasture CG2 were represented using 42 cells of equal size. In order to initialize the bulk densities (i.e., calculate the before grazing bulk

densities) across the whole pasture area, we generated conditioned realizations based on the observed values as described in Section 3.3.2.

Daily updates of bulk densities were then obtained by feeding (1) the before grazing bulk densities, (2) the simulated heatmaps of animal locations (number of steps per square meter), and (3) soil moisture data to the soil compaction model. This process was repeated until the end of the grazing season for both SS2 and CG2 to obtain the after grazing bulk densities. In this study, the model was calibrated by fitting the mean of the simulated after grazing bulk densities to the mean of the measured bulk densities in SS2. In the compaction model (equation (2)), the model property ε_B (known to be related to soil texture and the compaction force) was used as a calibration property and obtained using a grid search. The property N_B was set to 3, as found by Romero-Ruiz et al. (2023).

4. Results

4.1. Observation of grazing patterns of grazing livestock: grazing animals move by lévy walks

Animals in the SS pastures move in a group and cover a large proportion of the grazing area on most days (see Supporting video 1). However, there are some areas where animals spend more of their time and these overlap with three main apparent attractors: (1) locations of water troughs, (2) locations of neighboring grazing pastures and (3) locations of trees. This can be observed when the daily locations and seasonal heatmap in Fig. 1c and d, respectively. Seasonal (for the entire grazing season) and daily r and θ of were obtained and compared for the two contrasting stocking methods: SS and CG (Figs. 3–5). In both SS and CG, animal movement is characterized by an exponentially distributed travel distance and a uniformly distributed rotation angle in both seasonal (Fig. 3) and daily (Figs. 4 and 5) scenarios. Together they constitute animal movement within the so-called Lévy walk.

4.1.1. Moving characteristics depend on the pasture size

The PDF corresponding to travel distance in the CG presented slight differences with that obtained for SS (Fig. 3a). In both SS and CG pastures, small travel distances have much higher probabilities, larger travel distances (e.g., >20 m) are much less likely to occur, especially within CG (where the largest distance possible was ~ 30 m), due to the more limited space in the grazing area. Rotation angles suggest there was no preferential angle for animal movement in any of the grazing treatments (Fig. 3c).

4.1.2. Livestock movement is consistent across days, individuals and fields

The distribution obtained from daily travel distance data were remarkably similar for different animals for both SS and CG (Figs. 4 and 5). This is expected for CG where space is limited but also indicates that individuals move similarly as a function of time despite changes in temperature and weather across the grazing season (see Figure S1 in Supporting Information, SI) in the SS treatment. The maximum normalized standard deviation of the travel distance and rotation angle were 0.47 and 0.45, respectively. Similarly, the PDFs of the travel distance and rotation angle within each pasture are similar for all individuals indicating that animals follow the same movement patterns when located in the same pasture. Finally, animals for different SS pastures present PDFs with similar characteristics which indicates that daily and seasonal grazing patterns can be represented using the same statistically properties the same for different pastures, independent of pasture shape, topography, and distracting elements (e.g., shelter, water troughs, animals in neighboring pastures). Similar results were obtained for CG pastures (Fig. 5) where a homogeneous behavior was expected due to the size of the pastures.

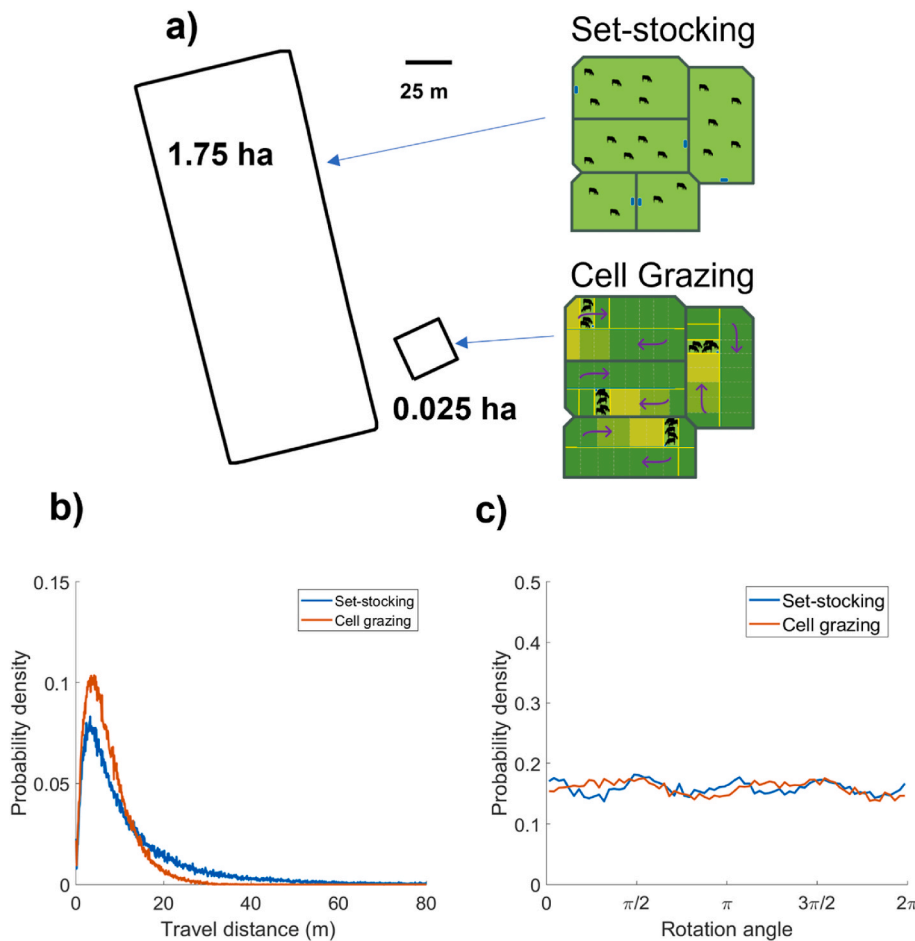


Fig. 3. (a) Comparison of perimeters of pastures corresponding to set stocking (SS, fixed area of 1.75 ha for the whole grazing season) and cell grazing CG (variable area of between ca. 0.02 ha to 0.05 per day), and the schematic representation of both grazing strategies. Probability density functions (PDF) characteristic of (b) traveling distance and (c) rotation angles of steers grazing in SS and CG methods. The PDFs presented in b) and c) consider data from the full grazing season, all pastures and all animals.

4.2. Lévy walk modelling for predicting grazing patterns

Statistical characteristics of animal movement (Fig. 3) were used to derive theoretical PDFs for the travel distance and rotation angle of SS and CG in order to replicate animal movement patterns observed in the field (Fig. 6a and d). The travel distances (Fig. 2b) are characterized by a Weibull PDF (WPDF) and the rotation angle by a uniform probability distribution (UPDF). The WPDF properties derived for SS are $a_w = 14$ and $b_w = 1$ (Fig. 6b), whereas the WPDF for CG are $a_w = 7$ and $b_w = 1$ (Fig. 6e). The rotation angle of both SS and CG (Fig. 2c) is characterized by a UPDF from 0 to 2π (Fig. 6b and e). By sampling from the Lévy walk PDFs, we simulated daily animal movement within a pasture (Fig. 4c and f, see Supporting video 2). As illustrated, these Lévy functions can be used to simulate realistic grazing patterns for any given grazing strategy, including pastures from arbitrary shapes, any desired number of steers and for any number of days.

4.3. Animal movement models provide insights of management-specific grazing patterns and related soil health indicators

The statistical information about Lévy animal movement characteristic of daily animal movement were combined with information about grazing variables (e.g., stocking rate s_r , number of grazing days N_g , pasture shapes) in order to predict the expected grazing patterns after a full grazing season (Fig. 7a), and thus help model and compare grazing patterns between the conventionally grazed SS and the intensively grazed CG methods (see also Supporting video 3). The management information described in Section 2 was used to derive seasonal heatmaps (count per m^2) of grazing areas in SS and CG (Fig. 7a). Both SS and CG reproduced a similar and relatively homogeneous grazing pattern in the

pasture after the grazing season, but the number of steps per square meter is likely to be higher in the CG treatment. The predicted mean number of steps per square meter after the season was approximately 300 and 250 for CG and SS, respectively (Fig. 7b).

A more intensively grazed pasture, such as that for CG, would be expected to have a higher number of steps per square meter after the grazing season, and as a consequence should induce more soil compaction and impact on soil properties. However, each grazed cell has a recovery period of around 21–42 days depending on the length of the rotation. Soil bulk density (BD) and penetration resistance (PR) are two common soil compaction indicators that are known to respond to grazing and are affected by SS and CG stocking methods (Fig. 7c and d). In both stocking methods, we observed an increase in bulk density and penetration resistance indicating soil compaction (Fig. 7c and d). The before grazing mean bulk densities were 0.66 g/cm^3 and 0.68 g/cm^3 for SS2 and CG2 (see also data presented by Pulley et al. (2021)), respectively, while their respective after grazing mean bulk densities were 0.82 g/cm^3 for both treatments. Similarly, the before grazing average PR from 0 to 10 cm depth (PR10) were 343 Pa and 351 Pa for SS2 and CG2, respectively, while their respective after grazing mean PR10 were 649 Pa and 816 Pa. We observed an increase in bulk density of 20 and 24% due to grazing for SS2 and CG2, respectively and an increase in PR10 of 90 and 130% for SS2 and CG2. The resulting increase in bulk densities and penetration resistance is consistent with the grazing intensity and the modelled grazing patterns using Lévy walks. The increase in such indicators of compaction in both SS and CG agreed with simulations for the seasonal number of steps modelled for SS and CG. In the heatmap surfaces, the predicted mean number of steps per square meter were 20% higher in CG.

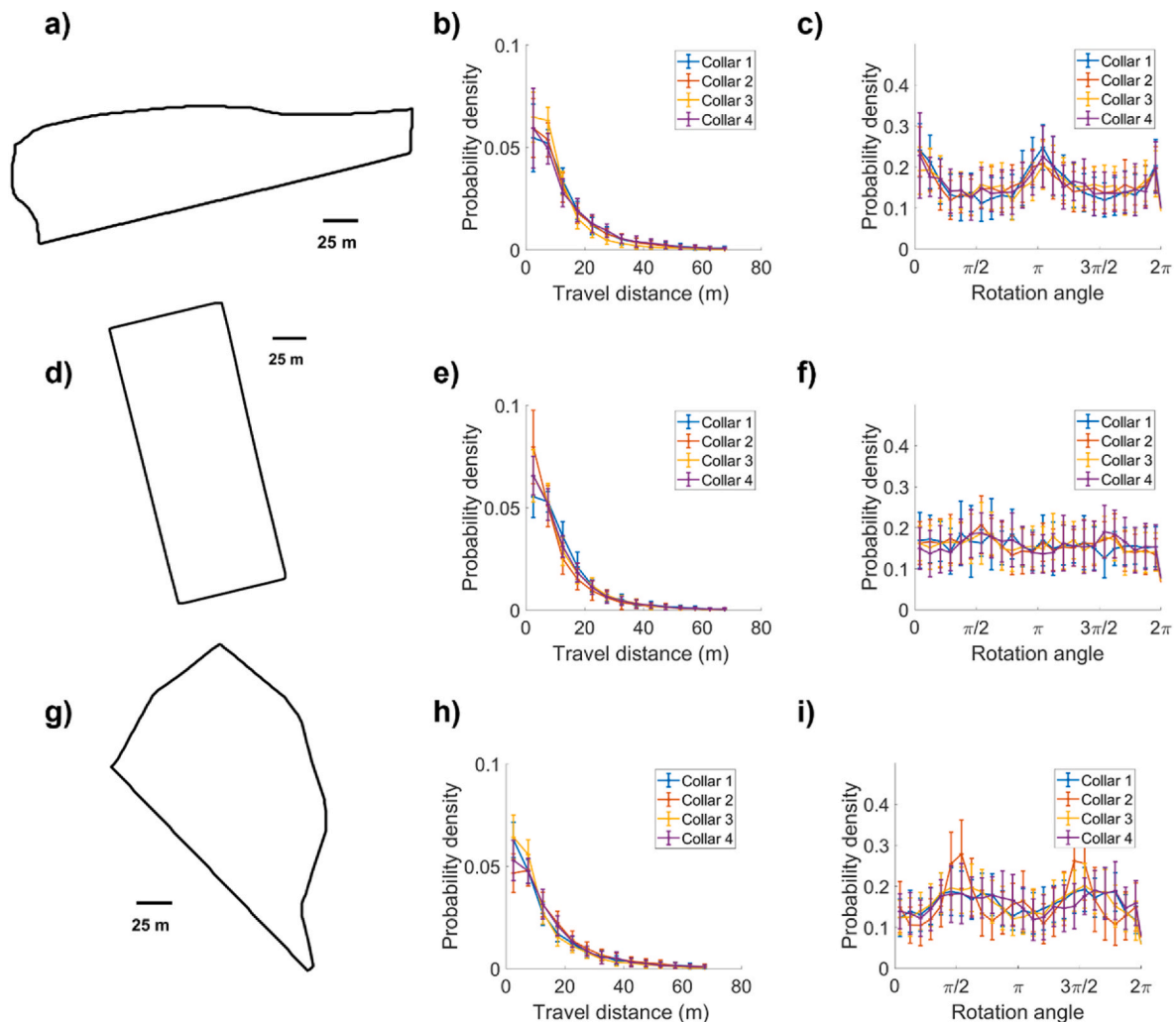


Fig. 4. Perimeters and orientation of experimental set-stocking (SS) pastures (a) SS1, (d) SS2 and (g) SS3. Daily averaged probability density function of GPS-derived travel distance for pasture (b) SS1, (e) SS2, and (h) SS3. Daily averaged probability density function of GPS-derived rotation angle for experimental pasture (c) SS1, (f) SS2, and (j) SS3. The error bars correspond to the standard deviation of the calculated daily probability densities. Each collar corresponds to a different steer.

4.4. Spatio-temporal impacts of grazing: the movement model

We estimated spatially explicit bulk densities in pastures SS2 and CG2 after grazing by using the seasonal treading patterns derived for SS and CG (Fig. 7) as inputs for a soil compaction model as illustrated in Fig. 2. The model was initialized with the help of bulk densities measured before to the start of grazing (Figs. 8 and 9). In order to initialize bulk densities across the whole pasture area, we generated realistic realizations based on the observed values and their spatial autocorrelation as shown in Fig. 8b and 9b. The before grazing spatially simulated bulk densities are more heterogeneous for SS than CG (Fig. 8d and 9d). The model properties were fitted using the SS post-grazing bulk density data and, thus, the mean of the modelled post grazing bulk densities presented in Fig. 6 is equal to the mean of the measured bulk densities of 0.83 g/cm^3 (Fig. 8d and e). The model predicted a mean post-grazing bulk density of 1.05 g/cm^3 for the CG treatment, which was higher than the measured mean of 0.87 g/cm^3 (Fig. 9d and e). Similarly to bulk densities observed before grazing, the after grazing bulk densities show more variability for SS than for CG (Fig. 8d and 9d). The spatial patterns of bulk densities in SS (Fig. 8b) are predicted to be conserved after grazing (Fig. 8c).

5. Discussion

Animal movement in grazing systems is characterized by Lévy walks and statistical differences in characteristics of animal movement (i.e., travel distance and rotation angle) were directly linked to the size of the grazing area that animals are limited to move in. Despite depending on the size of the pasture, the characteristic parameters of the Lévy walks held without large variations in the PDFs of travel distance and with little or no difference in rotation angle when comparing SS with grazing areas about 70 times larger than those for CG. Daily patterns of livestock movement are similar for different individuals, in different pastures independently of seasonal variations of weather conditions in both CG and SS. Daily Lévy movement implies that animals cover the entire grazed surface in a relatively short period (e.g., a few days). For this reason, soil compaction due to grazing is expected to occur relatively evenly across the field during a full grazing season. However, spatial patterns of soil degradation (e.g., bare ground, overgrazing) can still be associated with distracting elements that attract/cluster animals, such as water troughs or other animals in neighboring pastures, and to elements that occur more at random such as weather variations that make soil vulnerable to compaction (Hamza and Anderson, 2005) in certain areas of the enclosed pastures. For simplicity, such elements were not considered when modelling animal movement in this study. The after grazing bulk densities and their variability were reasonably reproduced

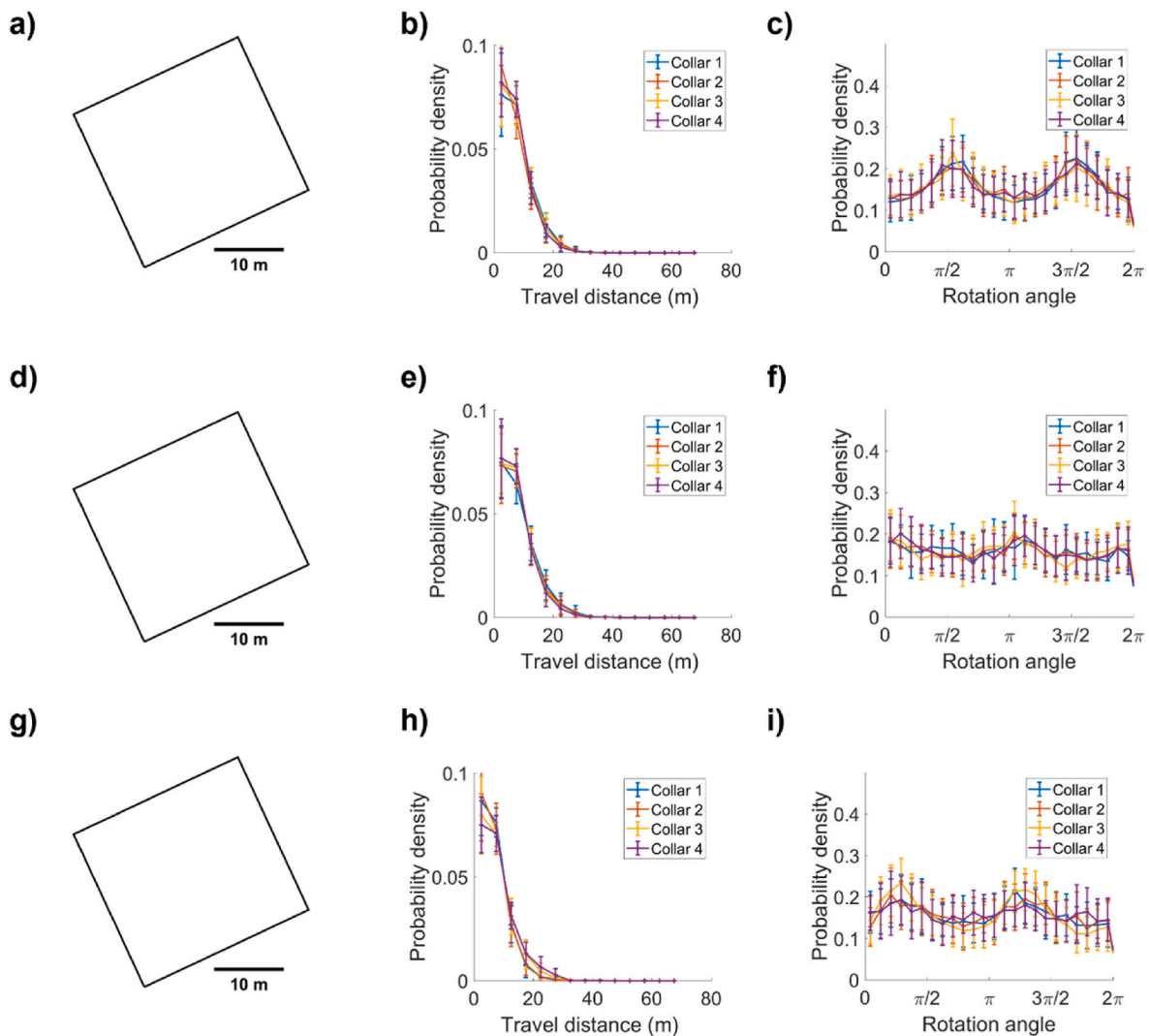


Fig. 5. Example of the perimeter of one cell of experimental cell grazing (CG) pastures (a) CG1, (d) CG2 and (g) CG3. Daily averaged probability density function of GPS-derived travel distance for pasture (b) CG1, (e) CG2, and (h) CG3. Daily averaged probability density function of GPS-derived rotation angle for experimental pastures (c) CG1, (f) CG2, and (j) CG3. The error bars correspond to the standard deviation of the calculated daily probability densities. Each collar corresponds to a different steer.

by our modelling approach. This suggest that incorporating these elements may not be essential in these grazing systems. However, this may be highly relevant for grazing systems where distracting or clustering elements are more intensively used (e.g., livestock enclosures in African rangelands; [Graham et al., 2022](#); [Vrieling et al., 2022](#)).

Our results from the SS pastures suggest that for pastures of different shapes, orientations (i.e., and potentially different shading), topography and distracting elements, animals will graze using the same Lévy walk movement properties provided that the grazing area is the same. The movement of animals has been suggested to be driven by a search for resources ([Benhamou, 2007](#)) around the entire fields. However, this was not supported by weekly monitored NDVI (Normalized Difference Vegetation Index) data collected in our experiment (see [Figure S2](#) in the SI), showing poor correlation between areas with high NDVI numbers and areas more frequently visited by the animals for a given week. This may be explained by the fact that the grass abounded during the entire season across the pastures and the animals did not need to search for resources. This could be as well linked to the botanical composition of grass in the pastures. Over the years, animals in the SS pastures have preferentially grazed the most palatable species (even overgrazing them) since they are not restricted in their movement and capacity of selection (unlike animals in the CG pastures) leading to a decrease of

these species and the increase of less preferred species. Therefore, even though the abundance of the less palatable species was high, animals might not be interested in consuming them. The animal movement was also driven by social interactions, search of shading spots and water troughs rather than by the search of grassier locations around the field and still consistent with Lévy movement. This has been demonstrated to describe movement of various other animals in different ecosystems and scales ([Binkley et al., 2003](#); [Forester et al., 2007](#); [Morales et al., 2004](#); [Sand et al., 2005](#); [Schieltz et al., 2017](#); [Schoenbaum et al., 2017](#); [Stephenson and Bailey, 2017](#)).

Soil compaction effects of grazing were expected to be affected by the stocking, and therefore grazing intensity corresponding to the CG and SS methods. The pre-grazing values of bulk density and penetration resistance were similar for both methods, which suggests quick soil structure recovery for the CG during the winter. Coupled modelling of animal movement and soil structure dynamics allows to derive grazing patterns using an animal movement model based on Lévy walks provided realistic probability density function for a field pixel (1 square meter in this study) to be affected by grazing. By introducing the management characteristics of grazing for CG and SS such as number of animals, LU, stocking rate and daily stocking densities, it was possible to gain insights about the expected grazing-induced soil structural changes. The

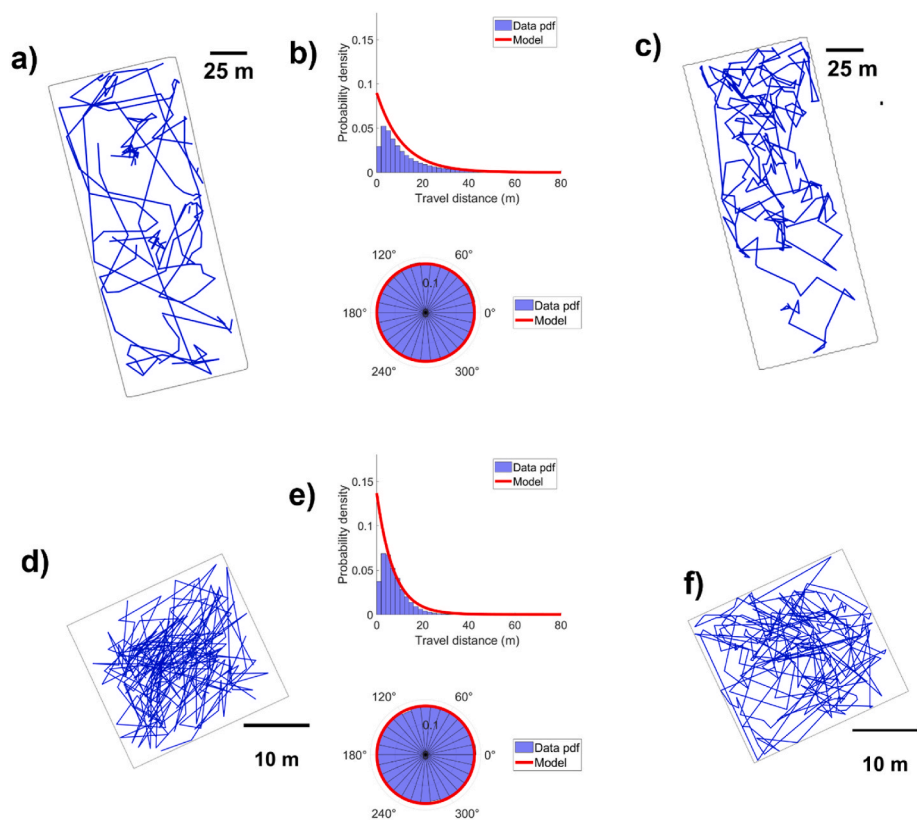


Fig. 6. (a) Example of actual GPS data derived grazing pattern for a single steer across a 24 h period in a set-stocking (SS) pasture (SS2). (b) Weibull probability density function adjusted to travel distance data and rotation angle from all experimental data in the season for SS. (c) Example of a simulated trajectory corresponding to a single steer for one day in pasture SS2. (d) Example of actual GPS data derived grazing pattern for a single steer across a 24 h period in a cell grazing (CG) pasture (CG2). (e) Weibull probability density function adjusted to travel distance data and rotation angle from all experimental data in the season for CG. (f) Example of a simulated trajectory corresponding to a single steer for one day in pasture CG2.

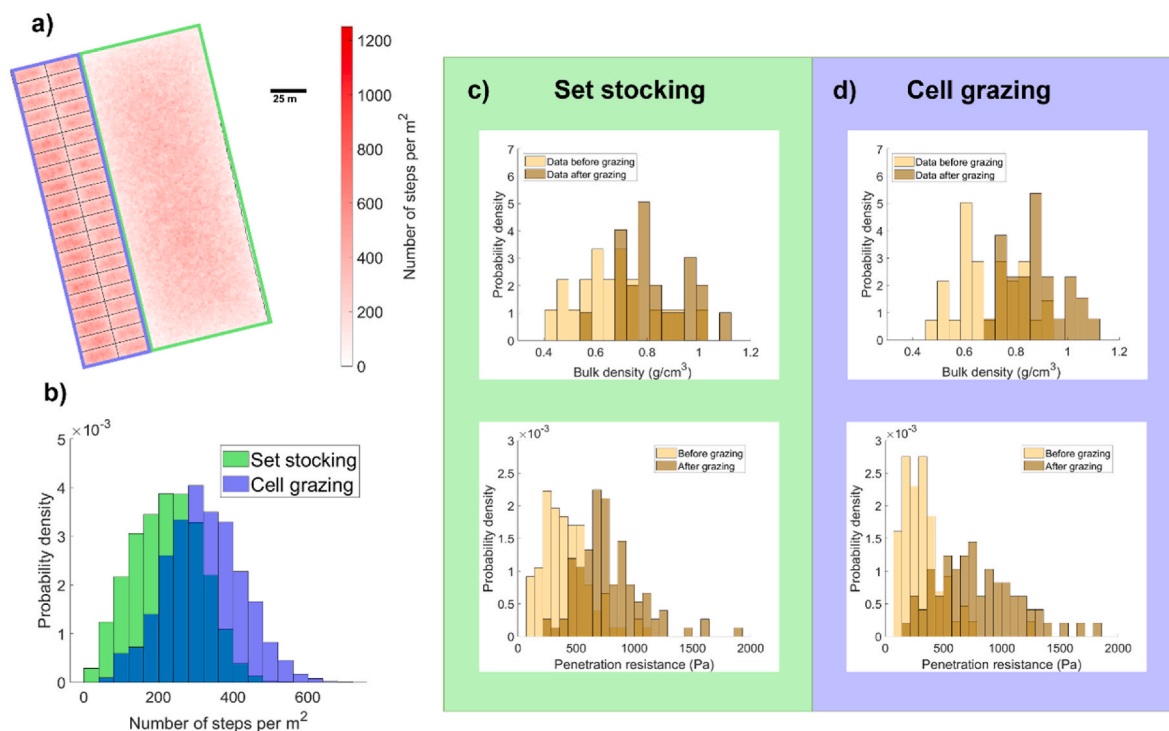


Fig. 7. (a) Heatmaps of treading patterns for the SS2 1.75 ha rectangular pasture and the adjacent CG2 pasture obtained by simulating Lévy walks during the full grazing season from April 9th 2021 to October 6th 2021. (b) Histograms showing the probability density function (PDF) of modelled number of steps per square meter during a grazing season for set stocking (SS) and cell grazing (CG). (c) Histogram of before and after grazing bulk density data at 10 cm depth, and mean penetration resistance in the top 10 cm for the SS method. (d) Histogram of before and after grazing bulk density data at 10 cm depth, and mean penetration resistance in the top 10 cm for the CG method.

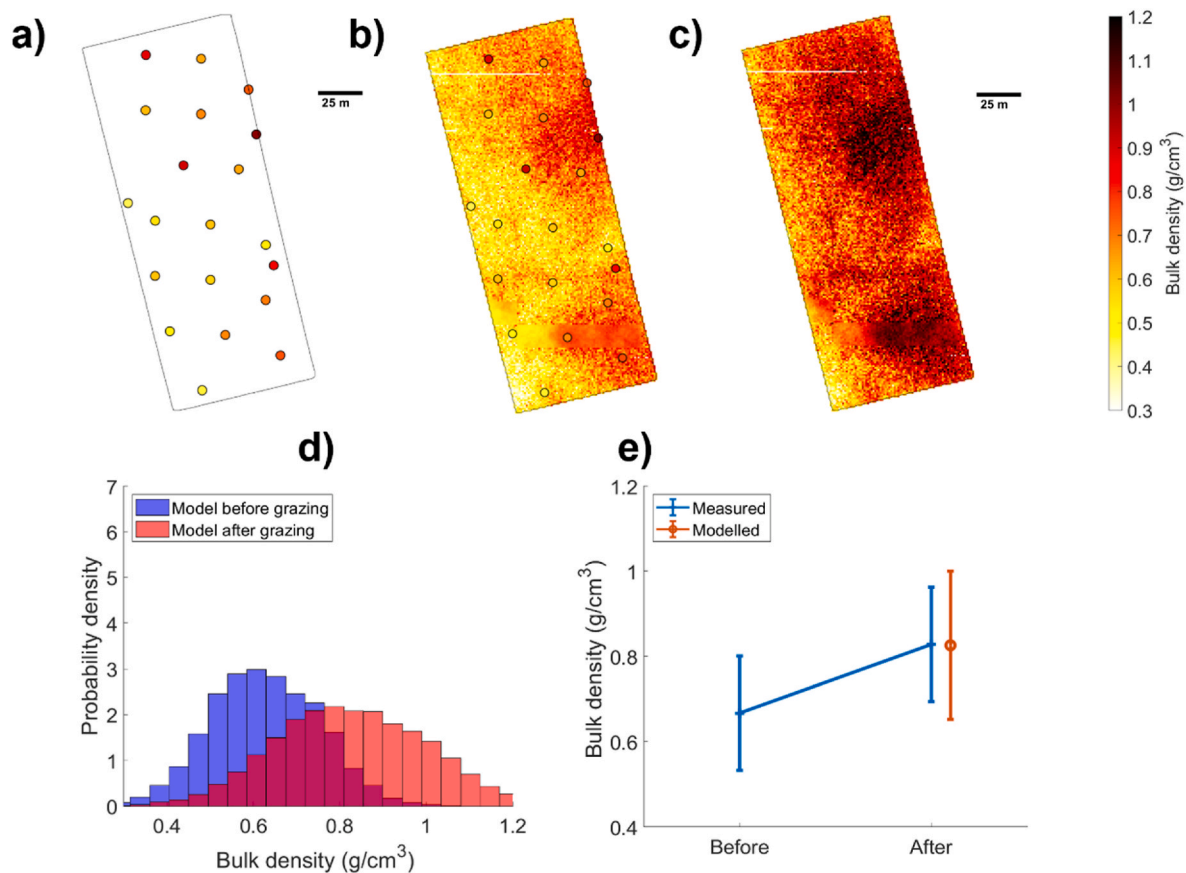


Fig. 8. (a) Spatially distributed grazing bulk densities (measured) prior to grazing for the set stocking pasture SS2; (b) Spatially simulated before grazing bulk densities conditioned to measured data shown in (a); (c) After grazing bulk densities obtained with the soil compaction model. (d) Before and after grazing histograms of modelled bulk densities shown in (b) and (c). (e) Comparison of modelled vs measured bulk densities after grazing.

modelled probability distribution of grazing steps per square meter predicted the CG pastures to be slightly more affected. This was consistent with the observed changes in mechanical properties such as bulk density and penetration resistance, for which post-grazing effects were slightly larger in the CG (higher stocking density) treatment.

Spatially explicit impacts of specific grazing strategies were derived by coupling an animal movement model with a soil compaction model. By doing this, we were able to derive daily realistic maps of bulk density from the grazed pastures. The soil compaction models require the management-specific grazing heatmaps as an input, as well as the soil moisture (that is known to control how prone a soil is to compaction). It also implicitly considers the soil texture and the weight of the grazing animals. Using this modelling framework, we were able to calibrate the model properties to accurately predict post grazing changes in the bulk density for the SS2. When using such calibrated properties in the CG2 pasture, the model, predicted a post-grazing bulk densities that were higher than the observed ones. This can be because, for simplicity, we assumed in the model that the weight of all animals was the same for all animals and grazing treatments and constant across the grazing season. Yet, the pre and post grazing season weight of the animals was slightly lower for CG compared to SS. In addition, the model did not consider soil structure recovery after grazing (Drewry, 2006) that could be a major factor impacting soil properties in the CG. By doing rotational grazing, non-grazed cells are undisturbed for a duration of up to 42 days before they are grazed again, which may promote soil structure recovery.

As well as changes in soil mechanical properties, grazing activity produces field-scale changes in soil hydraulic and retention properties that largely control soil water dynamics. These variations in soil properties and soil compaction that occurs at the field scale (Romero-Ruiz et al., 2022), have strong effects on soil functioning (Green et al., 2019)

and are difficult to characterize using traditional monitoring techniques that rely on point measurements. Information is sparse or fragmentary in space and time (Or et al., 2021; Romero-Ruiz et al., 2018). Utilizing information of animal movement characteristics can make it possible to fill in the gaps in this information by using simulations to predict changes in soil properties in space and time which is currently lacking. Such information can be used to better understand observations in order to mitigate environmental risks such as water runoff and soil erosion (Leitinger et al., 2010). Mechanistically derived maps of variations in soil properties may be utilized to improve our monitoring techniques by suggesting locations and times when sampling is optimal. It can as well help interpreting spatially resolved data collected with non-invasive measuring techniques such as proximal sensing methods (e.g., electromagnetic induction methods, EMI; and ground penetrating radar, GPR) and so improve monitoring (Garré et al., 2021).

Animal movement models can be used to predict areas for dung and urine deposition that can be linked with variations in vegetation (Metcalfe et al., 2019) and increased number of microbial communities that may represent hot-spots of increased GHG emissions (de Klein et al., 2001; Ebrahimi and Or, 2016; Zhu et al., 2021). Having the possibility to systematically obtain compaction related statistics at the field scale would allow analysts to derive regional soil compaction risk maps for grazing systems that consider different management strategies (e.g., grazing type and days, stocking densities, type of livestock, climate, soil texture) (Kuhwald et al., 2018). This may lead to realistic large scale prediction of grazing impacts on, for example, GHG emissions and carbon cycling under different scenarios using agroecosystem modelling (Coleman et al., 2017; Dondini et al., 2016; Nendel, 2014) that are currently lacking for all climates (Graham et al., 2022), and more generally in Earth-systems simulations (Faticchi et al., 2020).

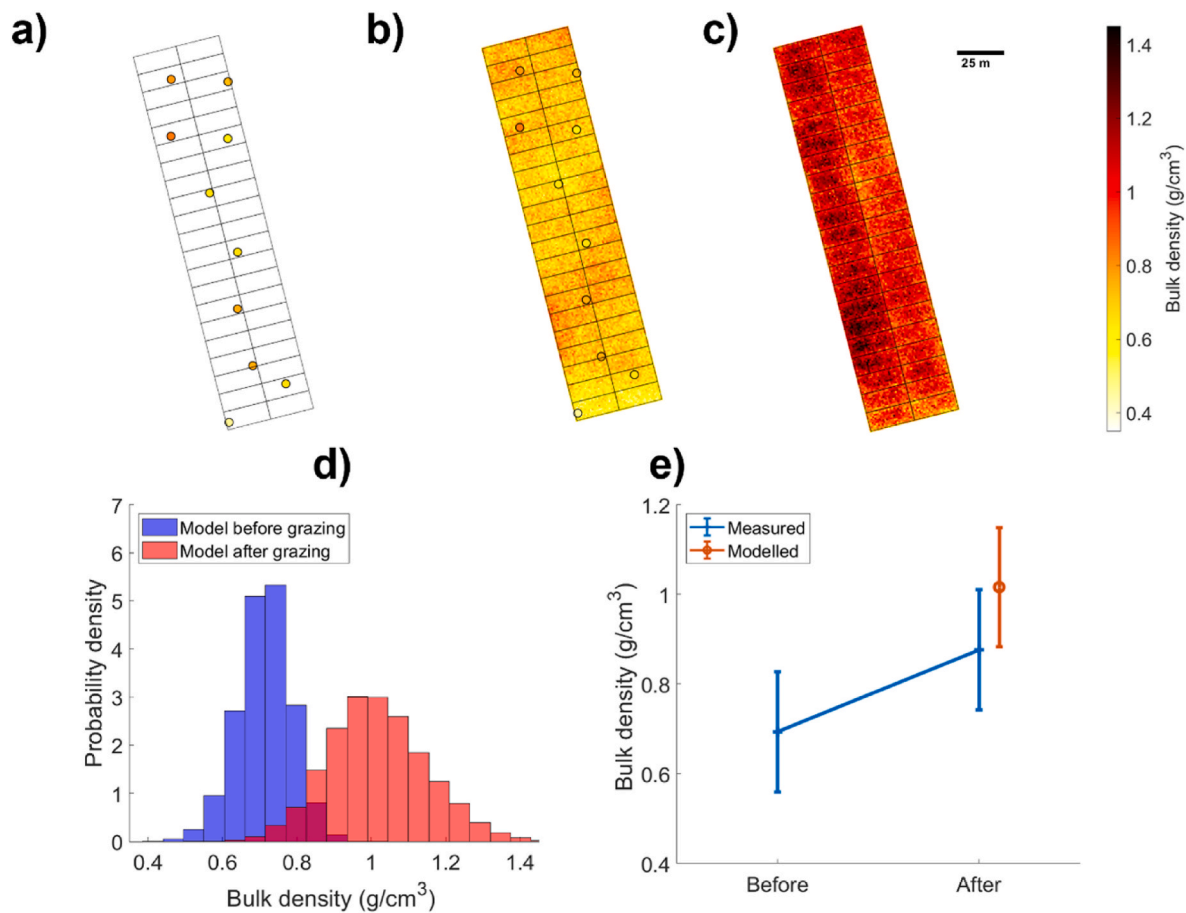


Fig. 9. (a) Spatially distributed grazing bulk densities (measured) prior to grazing for the cell grazing pasture CG2; (b) Spatially simulated prior to grazing bulk densities conditioned to measured data shown in (a); (c) Post grazing bulk densities obtained with the soil compaction model. (d) Before and after grazing histograms of modelled bulk densities shown in (b) and (c). (e) Comparison of modelled vs measured bulk densities after grazing. The error bars correspond to the standard deviation of the measured and modelled bulk densities.

Incorporating the modelling framework presented here may help to infer ecological function of soil directly from grazing strategies (Ver-eecken et al., 2022).

6. Conclusions

Grazing livestock move consistently in a pattern well-described by a Lévy walk and the Lévy properties depend on the dimensions of the grazing pastures. Animal (grazing steers) movement characteristics are independent of pasture shapes, orientations, topography and distracting elements; and rather depend on the area of the grazing pasture. Soil compaction reflected in higher bulk densities and soil penetration resistance due to grazing was shown to be similar for set-stocking and cell-grazing systems but slightly higher for cell-grazing which is consistent with Lévy walk grazing patterns modelling. When combined with a physically based model of soil structure, Lévy walk models can be used to help understand field scale effects of soil compaction due to grazing, for interpreting proximal sensing data, and for changes in vegetation and biodiversity. Similarly, the combination of an animal movement model and a soil compaction model allows predicting treatment-specific soil environmental functions when integrated in agroecosystem modelling.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence

the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.jenvman.2023.118835>.

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