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Review of Livestock Walking Distances and Implications for the New Zealand Greenhouse Gas Inventory

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New Zealand Government

Review of livestock walking distances and implications for the New Zealand greenhouse gas inventory

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May 2019

Report for Ministry for Primary Industries

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1. Executive Summary

Energy expenditure associated with movement is a small but relatively ill-defined part of the current New Zealand national greenhouse gas (GHG) inventory calculations. It has been formed from world literature and provides a proxy for activity, based on slope and available pasture for grazing. There has been little data, in a New Zealand context, to calibrate the assumptions and their implications to the inventory calculations.

This project has investigated the potential to increase the accuracy of this calculation. This paper presents a summary of the methodology and potential outcomes of using data from Global Information Systems (GIS) and Global Positioning Systems (GPS).

GIS data were combined with physical databases (AgriBase) to determine the location of livestock in relation to the slope of the land they occupy, on a farm by farm basis. Using the Terrain parameter in the inventory, we have recalculated the energy expenditure and hence feed intake and methane output of sheep, beef and dairy animals. Current predictions use a Terrain parameter of 1 (flat) for dairy and 1.5 (25º slope) for sheep and beef. Finer slope increments (0-7º, 8-15º, 16-25º and >25º), coupled with average slope encountered by livestock were used to demonstrate that predicted dairy energy expenditure were similar under both current and potential new scenarios. However, energy expenditure by both sheep and beef using the current Terrain factor are much higher than those predicted using more precise slope data (overestimated by between 15 and 20%), indicating that the current approach may be overestimating energy expenditure by the same amount. With energy expenditure from walking being estimated as approximately 9% of the total energy expenditure, then potential emissions would decline by 1.8% in beef cattle and 1.35% in sheep. These calculations must be confirmed using the full inventory methodology.

Satellite imagery of Normalised Difference Vegetation Index (NDVI) can be calibrated to represent current pasture mass, but prediction is more problematic. We have produced an example of the potential impacts of using this more precise approach to estimating potential activity during grazing.

Finally, data were being collected using GPS collars on sheep, beef, dairy and deer to derive preliminary data on distance walked. While this data is relatively incomplete for inventory calculations, it has provided two insights to date. The first is to provide some validation of the current equations used. The second is to help clarify the walking distances of dairy cows to and from the milking parlour, as this is specifically not accounted for in the inventory.

Theoretical estimate would suggest that the average New Zealand dairy cow walks approximately 2.7km/d, to and from the milking parlour each day. Over the course of a standard 276 d lactation this equates to approximately 750km. This value is not currently calculated in the inventory and would equate to between 11.9 and 15.3 kt methane outputs and 230 to 300 t N_2O per annum, calculated for three years, 2008, 2013, and 2018. Under the assumption that approximately 50% of total energy intake is used for maintenance, and that the milking cow makes up 77% of the dairy cattle numbers, then transit distance to and from the milking parlour represent the addition of approximately 2-3% to the total dairy cattle emissions. These calculations must be confirmed using the full inventory methodology. The GPS data confirmed that theoretical data aligns closely with actual data for two farms.

GIS data, coupled with on the ground data bases provides an immediate opportunity to refine the inventory calculations regarding slope.

The potential of coupling GIS mapping with satellite imagery of NDVI needs to be explored.

2. Introduction

Ruminant livestock are a major source of the greenhouse gases (GHG) methane and nitrous oxide in New Zealand pastoral farming systems. One significant component that may vary with farming practice, feed availability and topography is the amount of energy used when grazing and walking.

The amount of energy an animal expends when grazing is an important component of their total energy requirements. Total energy requirements are used to calculate dry matter intake which can then be used to calculate emissions. The current inventory model calculates the metabolisable energy required for grazing (ME_{graze}) using a number of parameters including walking distance and terrain (as well as live weight and the availability of green forage).

This project used recent research and data to review the assumptions on walking distance and terrain encountered for dairy cattle, beef cattle, sheep and deer. The project provides recommendations as to whether the terrain and walking parameters should be updated to better reflect actual livestock walking distances.

Included in the report are:

- A compilation of recent research and data relating to grazing patterns for dairy cattle, beef cattle, sheep and deer
- The distance travelled by these animals while grazing
- The type of terrain encountered while grazing and the availability of forage
- A review and analysis of this research against the assumptions currently used to calculate metabolisable energy for dairy cattle, beef cattle, sheep and deer in the Inventory.
- Recommendations as to whether the terrain and walking parameters in the Inventory should be changed
- Recommendations for future research that would enable the ME_{graze} equation to be more accurately estimated in the future.
- Implications of changes in farm practices since 1990 on livestock walking distance.

AgResearch scientists in forage science, farm systems and environmental research were consulted to access relevant past reviews and unpublished reports related to pasture quality and the greenhouse gas inventory. Dr Ian Brookes (Massey University) was contracted to review the document.

3. Methods

A review of livestock walking distances and terrain encountered during grazing requires a significant inventory of data across dairy cattle, beef cattle, sheep and deer. AgResearch has accumulated a number of data sets relating to the behaviour and movement of sheep, beef, dairy, and deer in recent times as it uses GPS technology to understand animal behaviour and impacts. At the same time, we have developed data sets and GIS technologies that allow us to calibrate satellite imagery with pasture availability. The GIS technologies also assist in defining actual terrain covered, especially in sheep, beef and deer farming, much more rigorously than in the past. These data and techniques provide us with the opportunity to combine these attributes to help answer the question of walking distance.

Specifically, the review of livestock walking distances included the following steps.

Section 4: A description and analysis of current equations.

Section 5: A literature search.

Section 6: A compilation of experiments using global positioning system (GPS) data to estimate walking distances.

Section 7: The use of geographical Information systems (GIS) and physical database information to define the distribution and number of different livestock species in different terrains in New Zealand.

Section 8: The use of farm size data to estimate transit distance walking to and from the milking parlour for dairy cows.

Section 9: Comparison of the current contribution of walking distance/EGraze with those estimated by the GIS and GPS information.

Section 10: Recommendations

A detailed methodology is provided in each section.

4. Current equations and implications for animal walking distance

4.1 Calculation of energy use

The New Zealand government is required to report on its GHG emissions on an annual basis to comply with international agreements. Livestock-driven methane emissions from enteric fermentation and soil-mediated nitrous oxide emissions from animal excreta, fertiliser and effluents make up the vast majority of New Zealand's agricultural GHG emissions.

Emissions of methane and nitrous oxide are calculated from estimates of livestock dry matter intake (DMI), assuming pasture is the sole component of the diet (Ministry for Primary Industries, 2017). Livestock voluntary intake is determined by physiological demand for energy, feed supply, and ease of harvest. Currently the activity of the animal is estimated using the following equation.

The exception to this is deer. The activity of deer is assumed to be part of the general calculation for maintenance as actual activity data is not available.

GRAZE (MJ net energy/d) = ((C.DMI(0.9-DMD)) + (0.05T/(GF +3)))W

Where:

C = 0.05 (sheep, goats) or 0.006 cattle, and is a constant that represents the energy requirement of prehension, and the difference between sheep, goats and cattle represents mouth size and bite size relative to liveweight.

DMI (kg/d) = ME required (MJ ME/d) ⁄ ME value of pasture (MJ ME/kg DM)

DMD = dry matter digestibility.

T = 1.0 or 1.5 or 2.0

GF = availability of green forage (tonnes DM/ ha). Assumed to be 3.5 tonnes

W = live weight

The equation represents two parts of the foraging process.

The first, **(C * DMI * (0.9 − D))** represents the energy required in the eating process, and includes prehension, chewing and rumination.

The second, **(0.05 * T /(GF + 3))** represents the energy required for movement of the animal to harvest the forage. This is broadly a reflection of the walking distance of an animal.

Once net energy is calculated, this is converted to metabolisable energy using an efficiency of energy use equation, based on the energy content of the diet.

4.1.1 Variations in the parameters

The value for energy used for walking is a constant for each livestock class, as T and GF are assumed constant. and then multiplied by liveweight. For sheep and beef the constant, using a Terrain parameter of 1.5, becomes 0.011538 MJNE/kg LW/d. For dairy cattle, using a Terrain parameter of 1, it becomes 0.0.00769 MJNE/kg LW/d.

The amount of green forage (GF) is considered a constant at 3.5 t DM/ha. This is a near maximal amount of forage to be offered in New Zealand grazing situations. A reduction in the amount of forage available does impact on the walking distances significantly. For example, reducing the amount of forage available to 1000 kg DM/ha, which is often the case on New Zealand sheep and beef farms in spring, would increase the value to 0.01875 MJNE/kg LW/d, or an increase of 62%.

A sensitivity analysis of the potential variation in the value assigned to walking is depicted in Table 1. This shows the relative change in the value of the constant when available herbage mass (GF) and terrain (T) vary. At a green forage availability of 1 T/ha and a Terrain parameter of 2 then the value of the constant is 3.25 time greater than the current value for dairy cows (using T=1 and GF=3.5 T.ha).

	Terrain factor						
Green Forage (tDM/ha)	**1**	**1.2**	**1.4**	**1.5**	**1.6**	**1.8**	**2**
1.0	1.63	1.95	2.28	2.44	2.60	2.93	3.25
1.5	1.44	1.73	2.02	2.17	2.31	2.60	2.89
2.0	1.30	1.56	1.82	1.95	2.08	2.34	2.60
2.5	1.18	1.42	1.65	1.77	1.89	2.13	2.36
3.0	1.08	1.30	1.52	1.63	1.73	1.95	2.17
3.5	1.00	1.20	1.40	1.50	1.60	1.80	2.00

Table 1: Changes in relativity of net energy expenditure for grazing when Terrain (T) and feed on offer (GF) change, compared with a Terrain factor of 1 and a GF of 3.5t DM/ha.

4.1.2 Interpreting the Terrain parameter

This study aims to test the current assumptions of the inventory against data collected by GIS and GPS methods. To do this, we need to understand where the current equation is derived from, as some underlying assumptions are embedded in the current equation.

The original equation was formulated by Freer et al. (1997) based on Australian data and conditions and used Emove as the activity of the animal related to walking distances, allowing for the horizontal and vertical movement of the grazing animal.

Emove (kJ/d) = LW* (1+ tan(S))/(0.02*B + 60)

Where S=slope in radians

B= weight of green herbage available

This was later rearranged to

Emove (kJ/d) = LW*0.0026*(1+ tan(S))/(0.000052*B + 0.16)

And finally simplified to reflect the movement in foraging, assuming that an animal would walk up to a maximum of 6.5km/d while foraging (Corbett et al., 1987). with Terrain, represented by (1+ tan(S)), simplified to the term T. While the terminology of flat, undulating and hill is used, the actual translation of these terms is as follows.

T = 1 = Flat= 0º slope

T = 1.5 = Undulating = 28º slope

T = 2 = Hilly = 45º slope

4.1.3 Direct estimates of energy use while walking

AFRC (1999) provides more details, but an assumption needs to be made about distance travelled. AFRC also included activities of standing and position change when lying. However, these functions are presumed to be included in the basal maintenance requirement in the Australian feeding standards used in the NZ Inventory (AIM). Thus, the pertinent part of the AFRC activity equation is simply the distances travelled in the horizontal and vertical planes while at pasture. These distances may be different to the grazing components expressed by Freer et al. (1997) in their Emove equation, as their equation considers all movement to be associated with grazing rather than any social activities. The AFRC equation is:

Net energy in walking (kJ) = A*H*LW + 0.028kJ*V*LW

Where A = 2.6 kJ for sheep and 2.0 kJ for cattle

H = horizontal distance in kilometres

V = vertical distance in metres

LW = live weight (kg).

This equation could be used to confirm the GRAZE component of the inventory calculations, using GPS and GIS data to source vertical and horizontal walking distances.

Animal walking distances to and from the milking parlour are not currently accounted for in the inventory. Changes in the distribution of farms throughout New Zealand, increasing farm size and increasing herd size may impact on walking distance, energy use and therefore feed intake and, indirectly, methane emissions.

4.2 Bown et al 2013 review

Bown et al. (2013) provided a full review of the energy equations used by the National Enteric Methane Inventory. They concluded that the equation currently in use for grazing and activity was at variance with modern models for predicting the additional energy requirements associated with grazing and activity. Specifically the following recommendations were made:

“a) **ME_{graze} in cattle and sheep.** The NEMI adopts an outdated equation from CSIRO (1990) which accounts for terrain (flat, undulating or steep) but does not account specifically for distance walked (or climbed) by livestock. It was recommended that the NEMI adopt the more recent equation of Nicol & Brookes (2007) for MEgraze + MEmove + MEactivity to assess more precisely the activity costs of grazing, including distance walked and the nature of the terrain.

b) **ME_{graze} Terrain assumptions in cattle and sheep.** The NEMI assumes all dairy cattle are farmed on flat terrain. This is not appropriate in today’s farming situation where dairy conversions are occurring increasingly on undulating terrain. Similarly, the NEMI assumes all beef cattle and sheep are farmed on undulating terrain. This may be inappropriate for high production beef finishing systems on flat land and high-country sheep farms. It was recommended that Terrain assumptions for dairy, beef and sheep should be reviewed and validated, especially if the NEMI develops into a regional or individual farm model.

c) **Deer ME_{graze}.** The NEMI equations do not consider separately the energy requirements of grazing or activity for deer as they are “assumed” to be included in the current NEMI calculation for MEm. The Bown et al., (2013) review recommended the adoption of the factorial approach of CSIRO (2007) and Nicol & Brookes (2007) to improve precision of calculating deer MEm requirements. Therefore, the additional energy requirements of grazing and activity of deer in addition to MEbasal would be need to be assessed separately. It was recommended that the NEMI adopts the Nicol & Brookes (2007) equations as for cattle and sheep. (Bown et al., 2013)

However, the requirements to update the inventory equations to account for the proposed changes were not available at the time of review. The information in this current report may provide a platform for developing a framework for change.

5. Literature search

5.1 Literature review

A review of livestock walking distances and terrain encountered during grazing was conducted. Drivers of animal walking distances, including feed on offer, were searched for.

5.1.1 Literature search methods

The scholarly journal databases BIOSIS, CAB Abstracts and SCOPUS were searched using a variety of related keywords by an experienced knowledge advisor. Further searches were conducted through the New Zealand Grassland Association and New Zealand Society of Animal Production publications and the DairyNZ website.

Recent research and data were compiled, relating to:

- Grazing patterns for dairy cattle, beef cattle, sheep and deer
- The distance travelled by these animals while grazing
- The type of terrain encountered while grazing and the availability of forage

Details of the search and the resultant summary of the literature can be found in Appendix 1. An Endnote library is provided to support this.

5.1.2 Search results

Table 2 provides details of the extent of the search and the availability of papers mentioning grazing patterns, walking distances and terrain. Of the 233 texts available, 145 referenced domestic livestock. Only 37 had a direct quantification of walking distance or energy expenditure while foraging. These are reported in Appendix 1.

Table 2. Number of papers retrieved representing information associated with factors influencing foraging and potential walking distances of livestock.

Topic	Animal species				Livestock (general)
	Beef cattle	Dairy cattle	Sheep	Deer	
Grazing patterns	22	26	27	15	14
Walking distances	11	16	18	4	-
Terrain					27
Reviews					23
Modelling					12
Recording technology					17

Papers describing grazing patterns mainly presented data on preferences and patch grazing. These provided little insight of potential movement or changes in movement when diet choices were changed.

Papers describing terrain generally investigate the role of terrain in choice of grazing site. Generally, this confirms the idea that animals graze parts of the paddock that are less steep (e.g. Martin et al., 2015), resulting in lower energy expenditure than the average slope of the paddock would infer.

Reviews were relatively broad with no new information to inform calculations of energy expenditure during foraging.

Modelling papers generally used a range of current equations.

Papers describing recording technologies were associated with the technical aspects of each technology, rather than direct estimates or comparisons of walking distance or energy expenditure during grazing.

A summary of the 37 papers of direct relevance (Appendix 2) demonstrates that while some efforts have been made to refine the contribution of foraging to total energy intake, these efforts continue to confirm the general principles captured by current equations. Generally, new information provides further calibration for those equations rather than replacing them. Gaps in the types of data collected mean that detailed analysis of, for example, the role of forage availability on foraging behaviours is not possible at this time as suitable data sets are not available.

Table 3. A summary of direct measurement of walking distance during foraging from papers reporting herd or situational data.

	Number of records	Distance walked (km/d)		Feed on offer (kg DM/ha)
		Average	Range	
Dairy	2 (2)[1]	4.75	4.7-4.8	3460
Beef	17 (2)	3.73	1.96-9.42	1430
Sheep and Goats	4 (0)	3.01	2.85-3.17	485
Deer	2 (2)	3.6	1.2-6.0	No data

[1]Number of papers from Australia or New Zealand

Nine papers provided a direct measurement of distance walked (Table 3) and included measurements of 25 different herds or situations. The majority of these (17) were for beef cattle. Only two beef papers described vertical walking distances (Marco and Aello, 1998; Martin et al., 2015).

Dairy walking distance estimates included transit to the milking parlour, and were estimates of experimental herds (Clark et al., 2010), which must be viewed with caution due to farm size and layout being atypical of commercial farms.

The research published did not have sufficient data on available feed supply to test or develop relationships between feed offered and walking distance. No direct relationships between the amount of feed on offer and walking distance were able to be made, mostly due to the sparse amount of information describing the available feed.

Most papers used published equations to calculate energy expenditure from grazing and walking distance records.

One paper (McGavin et al., 2018) summarised several experiments in Australia to provide significant insight into the potential impact of paddock size, rather than feed availability, though the two may be related. Walking distance in paddocks less than 1 ha was approximately 2.8 km/d, increasing to 3.7 km at 1 ha, 6.1km at 40-200ha, and to 9.4km at

450ha. This may represent both foraging requirements and walking distances to water. The experiments were based in extensive farming systems in Australia. New Zealand farms are much smaller than their Australian counterparts, with paddock size in the 1 to 10 ha range. Therefore walking distances in New Zealand would potentially be in the 3 to 6 km/d, based on the research by McGavin et al., (2018).

5.1.3 Literature review summary

Information available on walking distances by grazing livestock is relatively limited. However, average walking distances per day are relatively similar between livestock classes. The exception is dairy cows in milk, when transit distances to the milking parlour increases total distance walked.

The literature search provided no new information that would alter current equations to calculate the energy requirements for foraging.

6. Use of GPS to define walking distances

GPS is a useful and powerful technology. However, there are several considerations to make when interpreting GPS data, particularly for distance travelled for slow moving objects. A summary of the potential sources of error is provided in Appendix 3.

6.1.1 Walking distances using GPS records

Several experiments have been done where estimates of both horizontal and vertical walking distances have been quantified. These have included sheep, beef, dairy cows and deer. The results from these research projects are a mixture of published and unpublished data.

6.1.2 GPS results and discussion

A summary of the data collected across these experiments (Table 4) provides the opportunity to develop an index of animal walking distance, to calculate potential energy expenditure during foraging activities. The environments where these experiments were completed are defined in Table 4. This provides an index from which to calculate potential expenditure of energy during foraging activities (generally defined as animal walking distance) of different livestock classes in different terrain in New Zealand.

The data sets are limited mainly to mature animals. The data sets are also limited in numbers and do not represent the full range of livestock classes and terrains that constitute New Zealands agricultural landscape. However, they do provide a basis from which to explore any differences that may occur.

Most of these measurements were made with a recording interval of between 5 and 15 minutes. While it is recognized that GPS estimates of distance may be over- and under-estimated, depending on recording interval (Ranacher et al., 2015), research by McGavin et al., (2018) suggests that sampling at 10-minute intervals provides a stable outcome for comparison, and that record intervals beyond this do not differ in their estimate of walking distance. They also tested filtering systems to improve data fit and found that distance travelled calculated from data recorded at 10-minute intervals was unaffected by filtering. Therefore, these records provide a stable data set, although it is not possible to estimate the error associated with recording interval, so may over or underestimate actual walking distances.

6.1.3 Dairy cattle

Dairy cow walking distance was very consistent across three time periods, measured on a single farm. Generally, the distance walked by dairy cows while foraging during lactation was consistent between the three measurements during lactation at approximately 3.3 km/d. This does not include the barn-housed situation. This would reflect the relatively stable feed supply conditions that are provided during lactation. The one estimate during the winter was lower and would reflect the lower intake while the cows were not lactating (Stevens & Thompson, 2012). However, over 3 km/d was recorded during winter when cows accessed shelter, indicating that environmental drivers may also influence walking distance.

6.1.4 Beef cattle

Beef cattle walking distance varied more than other stock classes. The variation was at least partly explained by variation in both terrain and feed availability. Declines in both feed quantity and quality appeared to be associated with increased foraging activity (Martin et al., 2015). This is consistent with international literature (see Table 3).

6.1.5 Sheep

Again, the distance travelled by ewes in late lactation and late summer (non-lactating) were similar. The lactating ewes reported in this study were low producing (Bliss et al., 2018), however data available do not enable the separation of effects of stage of lactation, pasture conditions and season on foraging activity.

6.1.6 Deer

The walking distance by deer while foraging also varied considerably. Again, there were large differences in both terrain and feed availability (Wall et al., 2018). Interestingly, there were long distances recorded during the perinatal period. This has been attributed to activity associated with seeking a birthing site (Asher et al., 2014) rather than foraging activity.

6.1.7 GPS summary

Overall, the average distance travelled by livestock while foraging was approximately 3.1 km/d. This varied with terrain and potential feed supply, though often feed supply data were not provided. Generally, the foraging activity of New Zealand livestock, while moderated by farm management practices, reflects the international literature (Table 3).

Table 4. Horizontal and vertical walking distance while foraging measured using global positioning system data, collected at 10 to 15-minute intervals for a range of livestock classes in New Zealand grazing systems. Number of animals in each study ranges from 5 to 10.

Enterprise	Stock type	Terrain	Horizontal walking distance (km/d)		Vertical walking distance (m/d)		Time	Physiological state	Source
			Average	SE	Average	SE			
Dairy cattle	Mixed age cows	Rolling	3.3	0.31	ND		Spring 2012	Early lactation	Unpublished: P 21 Telford Dairy project
Dairy cattle	Mixed age cows	Rolling	3.4[1]	0.49	190	14	Summer 2018	Late lactation	Unpublished: Tokanui dairy farm
Dairy cattle	Mixed age cows	Rolling	3.2[1]	0.32	115	11	Autumn 2018	Late lactation	Unpublished: Tokanui dairy farm
Dairy cattle	Mixed age cows	Rolling	1.2	0.22	ND		Spring 2013	Early lactation/Barn	Unpublished: P 21 Telford Dairy project
Dairy cattle	Mixed age cows	Rolling	2.2	0.08	ND		Winter 2011	Dry/pregnant	Stevens and Thompson 2012
Dairy sheep	Mixed age ewes	Rolling	2.6	0.12	ND		Summer 2017	Late lactation	Bliss et al. 2018
Sheep	Mixed age ewes	Flat	2.7	0.07	12	1	Summer 2018	Dry	Unpublished: Johnstone
Beef cattle	Mixed age cows	Steep hill	3.05	0.04	275	10	Winter 2012 and 2013	Pregnant	Martin et al. 2015
Beef cattle	Mixed age cows	Easy to Steep Hill	6.46	0.32	156	10	Winter 2011	Pregnant	Unpublished: Urine deposition project.
Beef cattle	Rising yearling heifers	Easy to Steep Hill	3.23	0.27	327	28	Summer 2006	Growing	Unpublished: Urine deposition project, Methodology Betteridge et al. 2010
Deer	Mixed age hinds	Easy hill	2.35	0.31	170	20	November 2006	Perinatal	Unpublished: Methodology Wall et al. 2018

Deer	Mixed age hinds	Easy hill	2.17	0.1	231	7	November 2007 to April 2008	Perinatal to lactation	Unpublished: Methodology Wall et al. 2018
Deer	Mixed age hinds	Steep hill	3.53	0.14	517	15	October 2008 to February 2009	Prenatal to lactation	Unpublished: Methodology Wall et al. 2018
Deer	Mixed age hinds	Steep hill	2.73	0.14	425	19	October 2009 to March 2010	Prenatal to lactation	Unpublished: Methodology Wall et al. 2018
Deer	Mixed age hinds	Steep hill	3.39	0.24	452	26	July to October 2011	Pregnancy	Unpublished: Methodology Wall et al. 2018
Deer	Mixed age hinds	Easy hill	3.88	0.3	922	26	October to December 2010	Perinatal	Asher et al. 2014
Deer	Mixed age hinds	Easy hill	3.49	0.63	260	47	October to December 2010	Perinatal	Asher et al. 2014

7. GIS information about NZ farms

7.1.1 GIS methodology

A geographical information systems (GIS) approach was used to develop an inventory of farm type, size, terrain and stock numbers for three years (2008, 2013 and 2018) for the whole of New Zealand.

Satellite imagery was combined with the Agribase farm description inventory, and farms were classified as flat (<7º slope), easy rolling (7-15º slope), hilly (15-25º slope) and steep (>25º slope).

Four livestock enterprises were identified. These were dairy cows, sheep, sheep and beef, and deer. These were classified as per Statistics NZ to identify the size and slope class relevant to that stock class. Within each of these enterprises the proportion of farms in each slope class was calculated.

This provided a fine detail approach to assessing relative potential walking distance in both horizontal and vertical planes, and the changes that may have occurred due to land-use change over that time.

This approach provided the opportunity to quantify the effects of changing farm size on the walking distances encountered by dairy herds moving to and from the milking parlour.

7.1.1.1 Farm stats calculations

Spatial data and attributes were extracted from AgriBase versions 2008, 2013 and 2018 and the NZ Digital Elevation Model (15m increments). The following steps were performed in ArcGIS to clean-up and standardize the data:

Farms filtered by types	Types used: Beef cattle farms, Dairy cattle farms, Deer farms, Sheep farms, Mixed Sheep/Beef farms. (AgriBase Classes BEF, DAI, DEE, SHP, SNB)
Duplicate shapes cleaned	Farms spatial layers were self-intersected (ArcGIS 'Intersect' tool) and resulting duplicate shapes removed (ArcGIS 'Delete Identical' tool with 'Shape' field as input) to get rid of overlapping polygons distorting total areas of farms
Farm shape areas recalculated from sq.m to ha	By default ArcGIS store 'Shape_Area' field values in square meters for NZTM (metric) projection. Values were divided by 10000 to have areas stored as hectares
Numbers of animals recalculated to be proportional with area	As Farm / Enterprise with same FarmID can contain more than one polygon, area coefficients were computed to divide number of animals between them with assumption that animals spread evenly between parts of farm. That operation had no influence on numbers of animals for single-polygon farms

Regions assigned	Region was assigned for every farm using StatsNZ 2017 regional boundaries and ArcGIS 'Spatial Join' tool, with the criteria of majority of area of a farm located within region boundary
Mean altitude (m) extracted	Mean altitude (meters above sea level) was extracted for every farm using NZ DEM 15m dataset and ArcGIS 'Zonal Statistics as Table' tool and farm boundaries
Mean slope (deg) extracted	Mean slope (degrees) was extracted for every farm using NZ Slope 15m dataset and ArcGIS 'Zonal Statistics as Table' tool and farm boundaries
Irrelevant fields deleted, other renamed to have exact same names	All fields except FARM_ID, FARM_TYPE, Region, BEF_NOS, DAI_NOS, DEE_NOS, SHP_NOS, Part_Area_ha, AreaCoeff, Full_Area_ha, MeanAlt_m, MeanSlope_d were deleted from the tables

7.1.2 Results

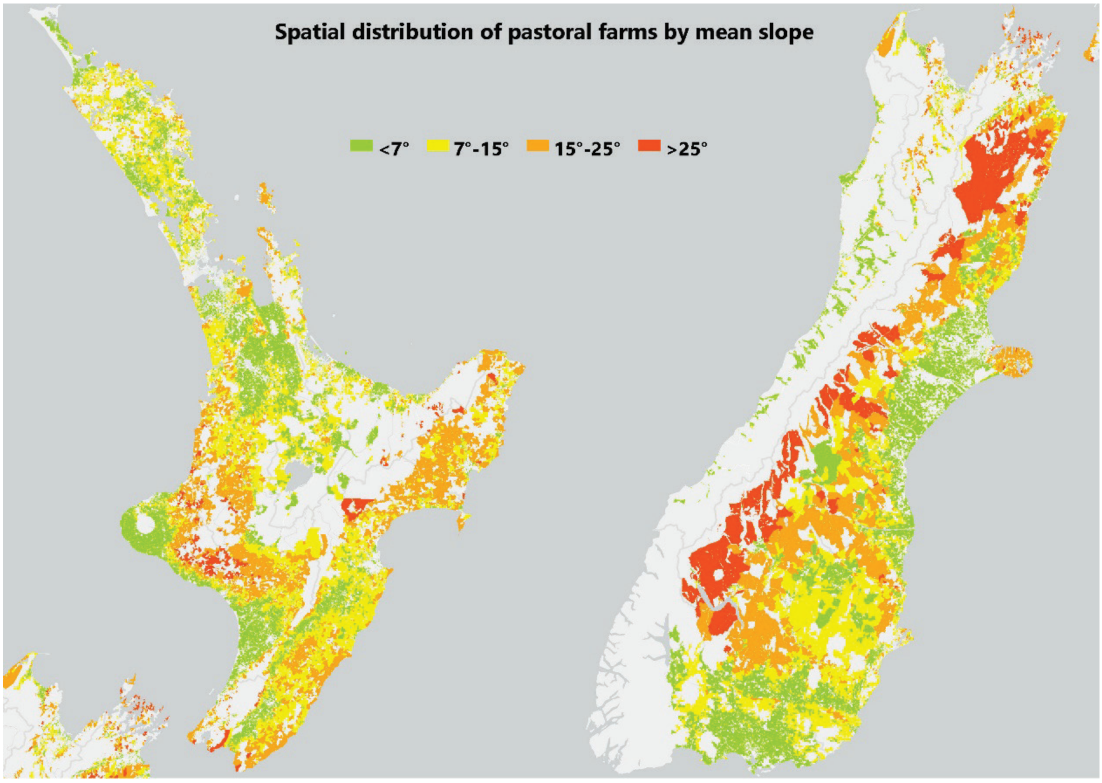

Figure 1: The spatial distribution of pastoral farms by mean slope in 2018.

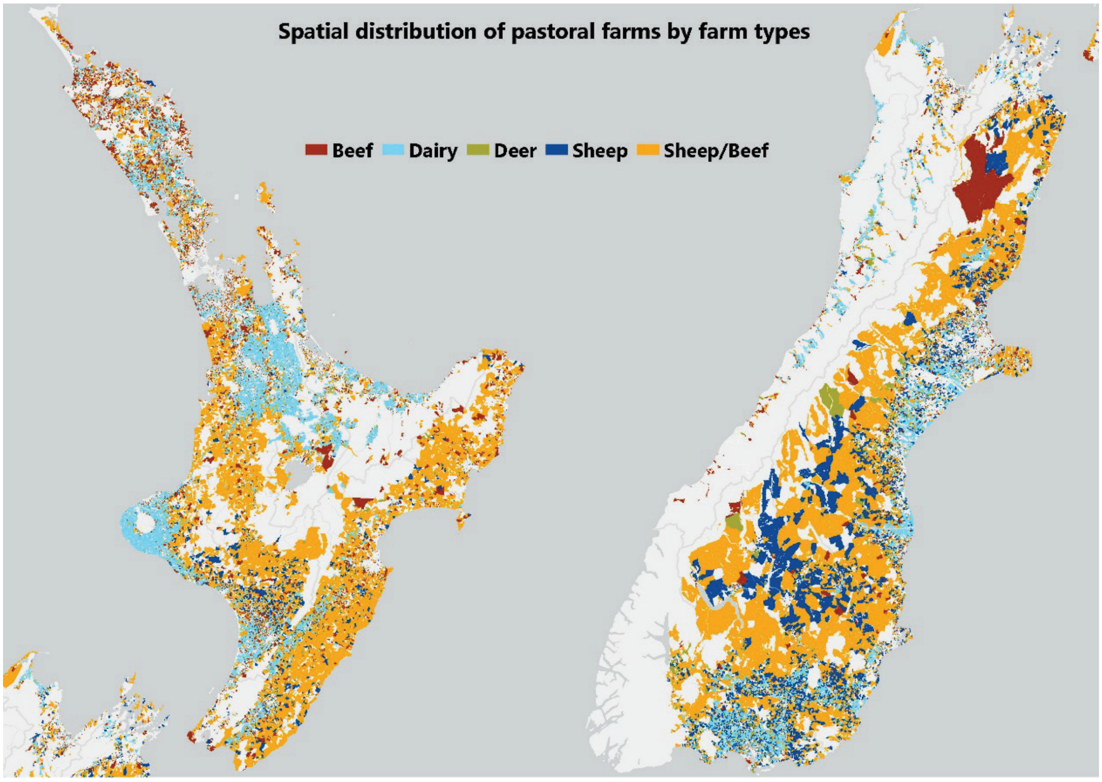

Figure 2. Spatial distribution of pastoral farms by farm types in New Zealand.

Data from Figures 1 and 2 is combined in Table 5 to quantify the area of each farm enterprise that occupies different slope classes. This illustrates that, although much of New Zealand's hill country is often described as steep, only a small percentage actually averages over 25º. Most of the areas farmed are between 7 and 25º. Sheep and beef have been assigned to the category of steep hill for the purposes of the inventory. This will over-estimate the energy required for walking, and hence the annual feed intake and methane output. This is calculated and discussed in Section 9.

Table 5: Area for pastoral farming enterprises categorized by mean slope.

		Area each Year (000 ha)		
Farm enterprise	Slope Class	2008	2013	2018
Beef	<7º	401	405	384
Beef	7-15º	510	528	501
Beef	15-25º	289	292	284
Beef	>25º	410	320	311
Dairy	<7º	1424	1558	1846
Dairy	7-15º	377	393	499
Dairy	15-25º	47	46	49
Dairy	>25º	1	1	1
Deer	<7º	140	120	92
Deer	7-15º	84	77	92
Deer	15-25º	76	67	51
Deer	>25º	31	60	26
Sheep	<7º	697	619	519
Sheep	7-15º	606	564	521

Sheep	15-25°	591	512	499
Sheep	>25°	319	241	176
Sheep and Beef	<7°	793	764	718
Sheep and Beef	7-15°	2491	2530	2490
Sheep and Beef	15-25°	2848	2971	2953
Sheep and Beef	>25°	847	871	728

Table 6. Number of animals of each livestock type summarized by mean slope for 2008, 2013 and 2018.

		Numbers each year (000)		
Animal type	Slope Class	2008	2013	2018
Beef	<7°	1195	1070	1069
Beef	7-15°	1891	1592	1563
Beef	15-25°	964	958	916
Beef	>25°	75	69	54
Dairy	<7°	4746	5555	5471
Dairy	7-15°	770	851	972
Dairy	15-25°	59	76	86
Dairy	>25°	0	1	0
Deer	<7°	612	494	382
Deer	7-15°	417	364	303
Deer	15-25°	160	149	139
Deer	>25°	19	21	13
Sheep	<7°	9617	8205	6900
Sheep	7-15°	13814	12775	11575
Sheep	15-25°	9511	9003	8384
Sheep	>25°	762	737	578

Finally, livestock numbers can be added to farm enterprise and slope class data (Table 6) to identify the location of livestock to define the Terrain parameter that may be applied when calculating GHG emissions.

Further outputs can be created by further defining regional and local scales. This could be used for defining regional farm enterprise, livestock numbers and allocation to slope classes within each of these. In this case the overall impact of defining slope and stock type is calculated as an example in Section 9.

A relative comparison between the numbers calculated using this method and those in the current inventory stock number calculations is presented in Table 7. In this instance we have combined the Agribase data of farm type with GIS data and corrected for Statistics NZ data. A comparison of the adjusted figures with dairy cattle numbers suggests that the methodology has provided an accurate estimate of the populations used in inventory calculations (Table 7). Some investigation into the variation seen in the beef and sheep numbers may be necessary to understand the sources of error.

Table 7. A comparison of the dairy cattle, beef cattle and sheep populations in the inventory (Pickering and Gibbs 2018) and those estimated by the GIS/physical database estimates.

Year	Dairy cattle populations		Beef cattle populations		Sheep populations	
	Inventory	GIS estimates	Inventory	GIS estimates	Inventory	GIS estimates
2008	5,578	5,575	4,393	4,125	34,088	33,703
2013	6,484	6,483	3,734	3,688	30,787	30,719
2018	na	6,530	na	3,602	na	27,438

7.1.3 GIS summary

The use of GIS and physical databases using adjusted farm level data was able to estimate populations at an industry level.

This can be used to aggregate slope classes and farm enterprise across regions and nationally.

This opens the way to calculate more precise estimates of the energy requirements while foraging.

8. Satellite imagery for Herbage mass estimation

8.1 Introduction

The problem of taking spatial and temporal variation of pasture energy content into account for methane inventory emissions purposes has been explored in a context of New Zealand farmland (Dymond et al. 2006). Normalized difference vegetation index or NDVI (Rouse, et al., 1974) derived from SPOT-4 and SPOT-5 satellites VEGETATION sensors with a spatial resolution of 1.15 km/px was used for statistical modelling. The results provided no evidence of improvement in estimating average metabolizable energy of pasture compared to the nominal uncertainty assigned from expert judgement. Similar research into spatiotemporal variability of pasture dry matter content predicted from remote sensing data was performed for Waikato region dairy farms with results demonstrating the capability of using NDVI to predict paddock mean pasture biomass across a season using satellite imagery with an accuracy level comparable to field-based techniques (Edirisinghe et al., 2012). Technological advancements developed in remote sensing during the past decade led to an increase in both spatial and temporal resolution of data and therefore the potential for improvement of pasture biomass estimates.

8.2 Method

Satellite imagery from three different satellites was used to determine potential improvement in pasture biomass estimates.

Sensor	Spatial resolution	Temporal resolution / Revisit time	Data availability (archive)
Terra & Aqua Moderate Resolution Imaging Spectroradiometer (MODIS)	250m	Daily	2000-Present
Sentinel-2 MSI	10m	5 days	2016-Present
Planet PlanetScope	3m	Daily	2016-Present

Table 8. Comparison of spatial and temporal resolution of satellite platforms

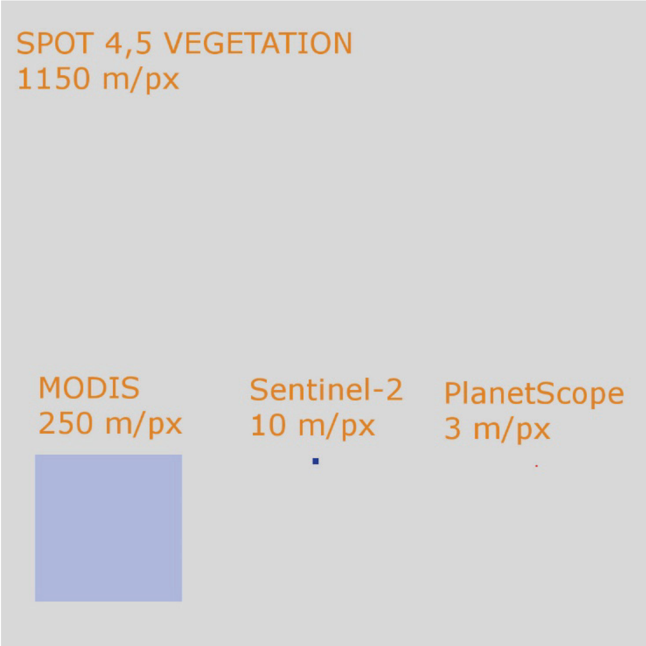

Figure 3. Visual comparison of spatial resolution for satellite platforms

Pasture height was measured with C-Dax pasture meter for 11 paddocks of Woodlands research farm (Southland, New Zealand) during 3 weekly grazing cycles with sheep. After computing mean pasture height for each paddock, the following equation recommended for Southland by C-Dax was used for conversion to dry matter:

pasture_mm_height * 17.7 + 825

Red and Near Infrared reflectance bands of satellite imagery, processed to Level 2 (atmospheric correction), were combined to produce the NDVI

NDVI = (NIR – Red) / (NIR + Red)

Depending on the spatial resolution of remote sensing data, mean values of NDVI were either calculated on paddock basis (Sentinel-2) or for group a of paddocks that fitted into a pixel (MODIS). Log-transformed values of DM were regressed against values of NDVI.

During the verification stage, the resulting regression equation was applied to predict pasture DM from NDVI data for a farm in Canterbury, also with approximately 3 weekly grazing cycles, but with dairy cows, that also had pasture DM measured by C-Dax.

8.3 Results calibrating NDVI

Strong positive correlation (0.749) between NDVI and pasture DM was observed (Figure 4). Data distribution pattern shows similarity to the data collected in Waikato in 2006 (Edirisinghe et al., 2012).

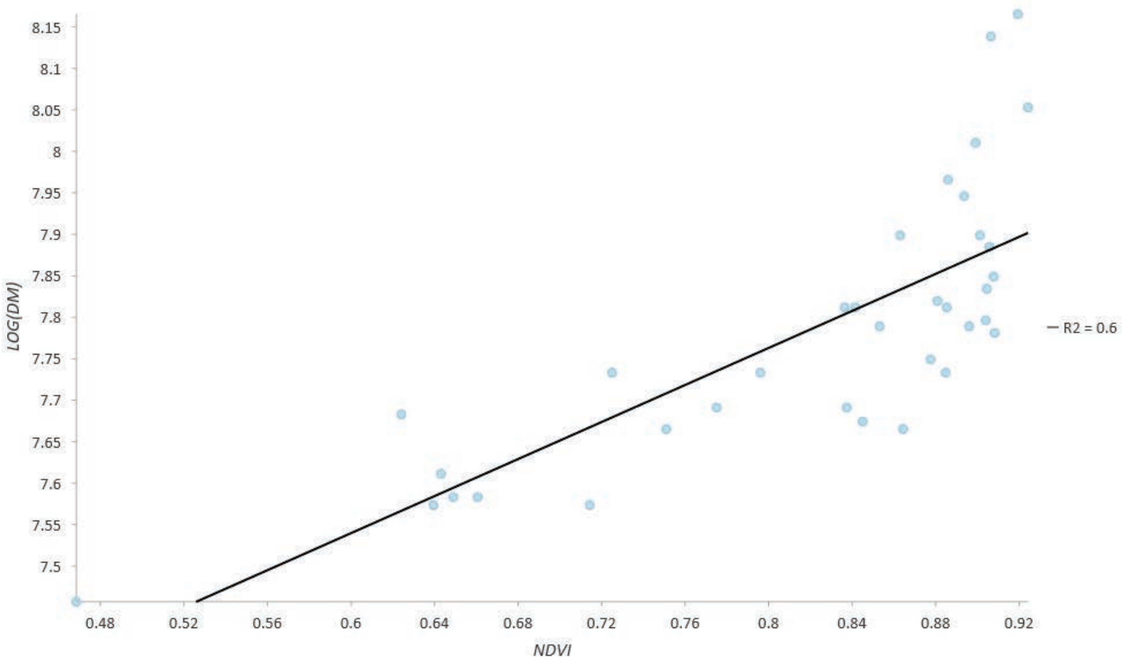

Figure 4. Relationship between NDVI and Log(DM)

The relationship was represented by the following equation

LOG_DM = 1.1165 * NDVI + 6.8699

Correlation coefficient = 0.749

Mean absolute error = 0.0827

Further analysis was done to test if the calibration gained from the single data set was able to be used to predict dry matter production in another situation where herbage mass had been measured using the same methodology (C-Dax). NDVI values derived from Sentinel-2 satellite imagery captured during the same dates were transformed to DM values using the regression equation obtained during Woodlands data calibration.

Predicted values for DM were then validated against measured values taken at the same time but under different circumstances (Figure 5). While the correlation between the predicted and actual values was strong (R^2=0.94), the predicted values were 350 kg DM/ha lower than the measured values at 1800 kg DM/ha measured, and 1000 kg DM/ha lower than those measured at 3600 kg DM/ha. The data set also show a significant propensity toward saturation when herbage mass was greater than 3000 kg DM/ha.

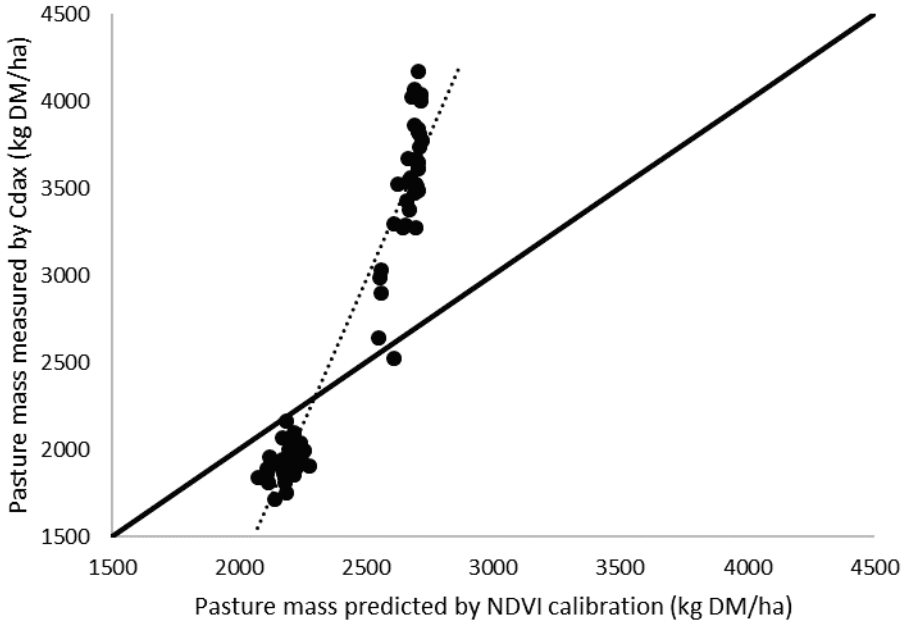

Figure 5. Comparison of NDVI prediction equation estimates calibrated from a sheep grazing experiment in Southland with actual pasture mass measurements from a dairy farm in Canterbury, (solid line is the 1:1 correlation line).

8.4 Discussion of using satellite imagery for herbage mass estimates

Modelling pasture dry matter content from remote sensing data has several known limitations. As NDVI approaches the upper limit of 1.0 for pastures with DM content around 3500 kg/DM/ha-1 in a phenomenon known as 'saturation', accuracy of predictions drops significantly. Another known issue is the inability to perform NDVI measurements where clouds cover the area of interest in the imagery: that decrease temporal resolution of data and requires producing weekly or monthly image composites to create cloud-free imagery. Spatial resolution has significant influence on the accuracy of measurements. While 250 m/px imagery available daily from MODIS Terra and Aqua satellites is potentially useful tool on a national scale, it tends to mask difference between different pasture cover types and provide higher NDVI values than higher resolution satellite imagery for the same area, which eventually lead to overestimation of dry matter.

The data compared here shows that the saturation point may also occur at different pasture mass in sheep pastures compared with dairy pastures. While previous measurement techniques have highlighted a difference between dairy and sheep pastures, due to changes in tiller density and leaf size, this information regarding saturation provides new insight into the challenge of using NDVI in a pasture economy.

Developing algorithms which are calibrated and validated for farms located across New Zealand remains very challenging. The work of Dymond et al. (2006) and the Pastures from Space project in Australia have demonstrated potential, yet the challenge of the scale of ground-truthing required remains a major obstacle. Future machine-learning' and artificial intelligence building off smaller data sets holds significant future promise. Lack of reliable field biomass measurements for farms located in different regions and topography is another problem that decreases the accuracy of calibration. Other issues such as shading due to satellite and sun angle in hill country and the amount of dead matter in pasture may also compromise the ability of any one calibration to provide a repeatable prediction of herbage mass. This was evident in the data presented by Edirisinghe et al. (2012), though this work used SPOT4 and SPOT5 imagery, which represent individual areas of over 100 ha/px.

The algorithm developed in the calibration process in this study was unable to accurately predict herbage mass measured at another site, thus validation failure. This highlights the technical challenges that are still apparent in creating algorithms that can be used at a national scale. There is potential for a machine learning approach to utilising satellite imagery, though this would hinge on the ability to utilise herbage mass data that was collected on-farm. Industry and government investment is increasing the agricultural sectors capacity to collect and utilise farm data (e.g. FarmIQ, Farmax). The use of data collection software, such as Agrigate (Fonterra/LIC), which provides a platform to upload on-farm data such as pasture cover, may enable this to occur in the future.

The opportunity remains to develop algorithms to estimate pasture herbage mass across NZ. Both appropriate sensors and ground truthing are required to calibrate and validate the relationships. The existing MPI-funded research for remote sensing of pasture quality included the development of a sampling protocol for national pasture sampling (Giltrap et al., 2018) which could inform an initiative to develop remote, nation-wide pasture herbage mass collection. Satellite remote sensing opportunities will increase, as will aircraft mounted cameras and sensors and cost per image will decline. At the same time, industry are making increasing number of aligned services available- this will increase availability for digital elevation maps at fine scale and hyperspectral imagery. To further improve calibration accuracy, future research should be considered to ensure that the many initiatives that are underway collect reliable pasture yield data in the field for different regions and different types of pasture cover. This would enable more rapid development of appropriate tools for use at a national scale.

9. Transit walking for milking

Animal walking distances to and from the milking parlour are not currently included in the inventory. Changes in the distribution of farms throughout New Zealand, increasing farm size and increasing herd size may impact on walking distance, energy use and methane emissions.

GIS data can be used to aid the prediction of potential walking distances, and this can be verified using GPS data from individual animals.

A simple method to investigate the relative effect of transit distance on energy requirements has been developed in this study.

9.1 Method development

A model square farm of 48 paddocks was created, with a milking parlour in the centre (7x7 square, Figure 6). This was chosen as representative to approximate potential type of movements to and from the shed during the milking season. A theoretical laneway system was created that saw cows moving through any of 6 quadrants to and from the shed depending on feed supply. Distance moved to any quadrant equals one third of half of the distance between boundaries (as the shed is in the middle). It is presumed that all paddocks are used equally during the milking season. Therefore, the proportion of walking events and their distance can be calculated and then summed to equate a 276 day lactation (DairyNZ, 2018). For example, 4 out of 48 walking events will take cows to a quadrant 6, while 12 out of 48 events will take cows to a quadrant 3. Larger farms with more paddocks can also be simulated using this approach.

The final outcome is the following equation

Average Transit Distance travelled (km per milking season) =

$$= (\frac{\sqrt{FarmSize}}{2} * (\frac{\frac{\frac{\sqrt{PaddockNumber}}{2}}{(\sqrt{PaddockNumber})-1}}{2} * 2 * No.\,Daily\ Milkings * Days\ in\ milk)/1000$$

6	5	4	3	4	5	6
5	4	3	2	3	4	5
4	3	2	1	2	3	4
3	2	1	SHED	1	2	3
4	3	2	1	2	3	4
5	4	3	2	3	4	5
6	5	4	3	4	5	6

Figure 6. Diagrammatic representation of the relative distance from milking shed to paddocks. (1= 1 unit of walking, equal to farm width/2/3)

Table 8. An estimate of the average farm size, dimensions and walking distances to transit to the dairy shed for milking each day, based on current herd size distribution in New Zealand (Dairy NZ 2018).

Herd size (number of cows)	Percentage of herds	Estimated size (ha)	Dimensions (mxm)	Av walking distance (m/day)
150	16	54	732	1708
250	24	89	945	2205
350	17	125	1118	2609
450	12	161	1268	2958
550	8	196	1402	3270
650	6	232	1524	3555
750	4	268	1637	3819
850	3	304	1742	4065
1000	8	357	1890	4410
National weighted average		149	1159	2703

Dairy NZ data provides the average farm and herd size in New Zealand (Table 8). This provides a basis to estimate the relative dimensions of farms in each herd size category. This data can be used to estimate the average transit distances to and from milking. Statistics of the percentage of farms in each category can then be used to estimate total walking distances, using average days in milk data to confirm visits to the milking shed.

Energy and feed intake are then calculated using current standard values for energy concentration in the pasture during lactation, and emissions calculated from this. It is presumed that all components of intake used for walking, including nitrogen, are excreted, and so an additional nitrous oxide loading can be calculated. These calculations are presented in Section 9.

Actual walking distance while transiting to and from the milking shed have been recorded using GPS technology. These are shown in Table 9. Relative estimated transit distances using the methodology described above are also presented. GPS measurements and estimates of walking distance are similar in the three cases available.

Table 9. Transit walking distances to and from the dairy shed for cows and sheep milked twice a day, measured by GPS and calculated using the described method.

Enterprise	Stock type	Terrain	Farm size	Transit distance (km/d)		Calculated transit distance (km/d)	Time
				Average	SE		
Dairy cattle	Mixed age cows	Rolling	267	3.7	0.49	3.82	Spring 2012
Dairy cattle	Mixed age cows	Rolling	300			4.04	Summer 2018
Dairy cattle	Mixed age cows	Rolling	300			4.04	Autumn 2018
Dairy cattle	Mixed age cows	Rolling	267	3.3	0.11	3.82	Spring 2013
Dairy sheep	Mixed age ewes	Rolling	197	3.0	0.30	3.27	Summer 2017

9.1.1 Transit distance summary

The methodology proposed to estimate the average transit distances to and from the milking parlour needs further validation from actual on-farm dairy cow movements before inclusion in the inventory. Validation can be done using current farm records, rather than GPS tracking. Most farms record which paddocks are used each day, and this, in association with farm maps, could be used to track the movements of herds during a milking season to provide more detailed information of average movements and variation related to farm size, shape and topography. These actual movement records could then be compared to theoretical calculations of transit distance proposed above.

10. Testing the effects of the new information on inventory calculations

10.1 Using Global Positioning Systems (GPS) to calculate the energy cost of animal movements

10.1.1 Using GPS estimates of walking distance to calculate energy expenditure during grazing

The records reported in Section 6 have been used to provide a data set with which to test the GHG inventory calculations. These calculations are presented in Table 10.

When calculating the energy costs of walking, the cost of walking downhill has been assumed to be the same as the cost of walking in the horizontal plane. This is based on the work of Minetti et al. (2002) who found that, while energy use for walking downhill at a 10% slope (5.7º) was lower than walking in the horizontal plane, this advantage was lost by the time the gradient increased to 25% (14º). It has been assumed that only walking uphill increases energy expenditure and needs to be accounted for in calculations.

10.1.2 Walking distance of dairy cattle

Results in Table 10 demonstrate that the average energy expenditure calculated in the inventory for dairy cows (based on the live weight of the cows in each study) is slightly lower than that estimated from GPS walking distances while grazing (6.7 cf. 7.0 MJME/d; excluding the barn-housed estimate). It appears from the data that the estimate using GPS data during the milking season is between 8 and 15% higher than inventory estimates, while it is 25% lower when the cows were dry. This would be consistent with a change in feed requirements and grazing area, and therefore foraging efforts, between the two physiological states. An alternative option would be that the amount of feed on offer to meet the requirements of the animal were lower than the 3500 kg DM/ha used in the inventory calculation. The higher requirement would infer that the amount of feed on offer was between 2500 and 3000 kg DM/ha (using the sensitivity graph in Section 4). Reported pasture allowances suggest that much of the New Zealand dairy herd is presented pasture ranging between 2700 and 3000 kg DM/ha (Roach et al., 2016), which falls within the range of under-estimate by the inventory.

However, this data set is limited to only three records while lactating and one record while non-lactating. Further investigation is required to better define those relative changes. No records of young stock were available.

10.1.3 Walking distance of beef cattle

Beef data consisted of three data sets, two of mixed age cows and one of yearling stock. Again, the inventory calculations were lower than those predicted from GPS walking distances. The values for mixed age cows were 9.1 cf 14.5 MJME/d. This significant difference may be best explained by the amount of available herbage. When the inventory calculation is made using the average pasture on offer of 1400 kg DM/ha (Martin et al. 2015) then a value of 13.8 MJME/d is calculated, slightly higher than the 12.6 MJME/d calculated from GPS walking distance.

10.1.4 Walking distance of sheep

Only two data sets were available for sheep. Inventory calculations were greater than those estimated using GPS data (1.24 cf 0.76 MJME/d, respectively) when transit time to the milking parlour was removed. However, the sheep in both studies were on flat to rolling terrain. When the inventory calculation is made with a Terrain parameter of 1 (flat) then the value, 0.82 MJME/d is much closer to the GPS estimate.

Again, with the sheep dataset, no values were available for young and growing stock.

10.1.5 Walking distance of deer

The deer data set is relatively comprehensive with seven sets covering pregnancy through to late lactation, with data covering the months from July to February. However, the inventory does not provide a separate calculation for activity. Average calculations indicate that mature hinds expend 1.43 and 2.14 MJME/d on walking in the horizontal and vertical planes respectively. If the standard inventory equations for activity were used (assuming a Terrain parameter of 1.5, as for sheep and beef), then activity would be estimated at 2.05 MJME/d, while the GPS estimates were 3.05 MJME/d (excluding one record that included significant fence-pacing activity around parturition). This may be explained by the relatively low herbage availability often common in deer systems and would equate to approximately 1400-1500 kg DM/ha available (see sensitivity analysis in Section 4).

10.1.6 Summary of GPS estimates of walking distance to calculate energy expenditure during grazing

In summary, the GPS data collected to date provides an insight into the accuracy of the current inventory equation that represents the activity of the grazing animal in foraging. It must be recognized that these GPS data sets are limited in their representation of the range of livestock classes, terrains and forage availability that are present in New Zealand agriculture. While there are differences between the values calculated from the inventory equation and those calculated using horizontal and vertical distance travelled during grazing, these differences can be explained by modifying either the Terrain parameter, or the green forage on offer parameter in the current equation. This provides evidence that, while the equations are not the most recent (Bown et al., 2013), they appear to be fit for purpose. However, some modification of the current default values for both Terrain (T) and forage available (GF) should be considered. The potential to vary these parameters is explored in Section 7 (GIS information about New Zealand farms).

Table 10. Calculations of the activity energy of livestock while grazing (MJME/d), by the current inventory equation ((LW*(0.05T/(GF+3))/0.65); where LW=live weight, T=1 for dairy cattle and 1.5 for sheep and beef, GF=3.5tDM/ha, 0.65=k_m) and actual distance travelled ((LW*((0.0026*H)+(0.000028*V))/0.65); where LW=live weight, H=horizontal distance travelled in kilometres, V=vertical distance travelled in kilometres, 0.65=k_m).

Enterprise	Stock type	Terrain	Liveweight (kg)	Inventory (MJME/d)	Walking energy (MJME/d) Horizontal	Vertical	Total Activity (MJME/d)
Dairy cattle	Mixed age cows	Flat	550	6.51	7.26	0.00	7.26
Dairy cattle	Mixed age cows	Rolling	600	7.10	8.16[1]	4.91	13.07
Dairy cattle	Mixed age cows	Rolling	600	7.10	7.68[1]	2.97	10.65
Dairy cattle	Mixed age cows	Flat	550	6.51	2.64[2]	0.00	2.64
Dairy cattle	Mixed age cows	Rolling	550	6.51	4.84[3]	0.00	4.84
Dairy sheep	Mixed age ewes	Rolling	70	1.24	0.73	0.00	0.73
Sheep	Mixed age ewes	Flat	70	1.24	0.76	0.04	0.79
Beef cattle	Rising yearling heifers	Easy to Steep Hill	245	4.35	3.17	3.45	6.62
Beef cattle	Mixed age cows	Steep hill	525	9.32	6.41	6.22	12.62
Beef cattle	Mixed age cows	Easy to Steep Hill	500	8.88	12.92	3.36	16.28
Deer	Mixed age hinds	Easy hill	110	NC	1.03	0.81	1.84
Deer	Mixed age hinds	Easy hill	110	NC	0.95	1.09	2.05
Deer	Mixed age hinds	Steep hill	115	NC	1.62	2.56	4.18
Deer	Mixed age hinds	Steep hill	115	NC	1.26	2.11	3.36
Deer	Mixed age hinds	Steep hill	115	NC	1.56	2.24	3.80
Deer	Mixed age hinds	Steep hill	122	NC	1.89	4.85	6.74
Deer	Mixed age hinds	Easy hill	122	NC	1.70	1.37	3.07

[1] Values derived once 4 km of transit distance removed.

[2] Estimates for a barn system with grazing access once a day, overnight.

[3] Non-lactating cows on winter forage crop.

10.2 Using geographical information systems to refine inventory calculations

Geographical information systems (GIS) have the power to define farm enterprise when combined with other data bases.

10.2.1 GIS use to test changes in the Terrain parameter

The more detailed assessment of terrain provided by the GIS approach (Section 7) can be used to estimate the impacts of varying the Terrain parameter (T) within the current inventory equations (0.05 * T/(GF + 3)). Data from Table 5 has been used to calculate methane emissions for dairy cattle, beef and sheep. Three test years, 2008, 2013 and 2018 were chosen to represent the potential changes in distribution of farm enterprises across the range of terrain in New Zealand.

To calculate the impacts of a more detailed assessment of terrain on the energy requirements and subsequent methane emissions four Terrain parameters (1, 1.2, 1.4 and 1.6) were applied to the populations of livestock assigned on a per farm basis. The average live weight of beef cattle was estimated from data published by MPI (2017), as only approximately 30% of total beef numbers are mature adults. Mature ewe live weight was taken as a proxy for sheep live weight, and milking cow live weight as a proxy for the dairy industry, as the mature adult animal represents the majority of livestock reported on.

The values calculated here are done to provide insight into the relative importance of making a change to the Terrain parameters used, rather than providing an absolute value. A full development of all stock classes in each Terrain class would be needed for that outcome.

10.2.1 Dairy calculations

The majority (85%) of dairy farms are located on slopes below 7º. Therefore, the contribution of foraging to energy consumption was relatively unchanged by increasing the accuracy of the Terrain parameter. A small increase was noted (Table 11) as some farms were on terrain over 7º. Overall the increase of approximately 3.2% was similar in each year.

Table 11. Impacts of using a variable value for Terrain parameter (T) on estimates of the energy, dry matter intake and annual methane emissions for dairy cattle in 3 years.

Dairy		Year		
		2008	2013	2018
Stock number (000)		5,575	6,483	6,530
Energy for walking (MJME/d)	Current (T=1)	5.3	5.4	5.4
	Variable T	5.5	5.5	5.6
Annual DM (000 t)	Current (T=1)	946	1107	1122
	Variable T	976	1141	1162
Annual methane emissions (000 t)	Current (T=1)	20.4	23.9	24.2
	Variable T	21.1	24.7	25.1
Total difference (000 t)		0.65	0.74	0.85
Change (%)		3.2%	3.1%	3.5%

10.2.2 Beef calculations

Changing the Terrain parameter from a standard 1.5 to a range between 1 and 1.6, to match average slope of individual farms generated a significantly reduced requirement of energy for foraging. Overall, the weighted average (Table 12) was reduced by approximately 20% in the three test years chosen. This approach provides greater utility in being able to calculate specific emissions outputs down to the farm scale if required. The contribution of walking energy for foraging did not vary significantly between years.

Table 12. Impacts of using a variable value for Terrain parameter (T) on estimates of the energy, dry matter intake and annual methane emissions for beef cattle in 3 years.

Beef		Year		
		2008	2013	2018
Stock number (000)		4,125	3,688	3,602
Energy for walking (MJME/d)	Current (T=1.5)	7.3	7.3	7.3
	Variable T	5.8	5.8	5.8
Annual DM (000 t)	Current (T=1.5)	1049	938	916
	Variable T	818	751	731
Annual methane emissions (000 t)	Current (T=1.5)	22.6	20.3	19.8
	Variable T	17.7	16.2	15.8
Total difference (000 t)		-4.97	-4.03	-3.99
Change (%)		-22.0%	-19.9%	-20.2%

10.2.3 Sheep calculations

Like beef farms, the increasing accuracy of Terrain parameter resulted in a reduction in the contribution of walking distance to greenhouse gas emissions (Table 13). This decrease was approximately 15%, so was intermediate between beef and dairy cattle. There is a trend for the relative difference to be declining, which is following the trend for land-use change as dairy use of flat and easy land displaces the sheep populations towards steeper terrain.

Table 13. Impacts of using a variable value for Terrain parameter (T) on estimates of the energy, dry matter intake and annual methane emissions for sheep in 3 years.

Sheep		Year		
		2008	2013	2018
Stock number (000)		33,703	30,720	27,438
Energy for walking (MJME/d)	Current (T=1.5)	1.07	1.12	1.11
	Variable T	0.86	0.91	0.90
Annual DM (000 t)	Current (T=1.5)	1260	1204	1067
	Variable T	1015	975	867
Annual methane emissions (000 t)	Current (T=1.5)	47.39	44.8	39.8
	Variable T	40.1	38.0	33.9
Total difference (000 t)		-7.289	-6.73	-5.88

Change (%)	-15.4%	-15.0%	-14.8%

10.2.4 Summary of GIS Terrain parameters on methane calculations

Geographic information systems can provide a sophisticated analysis of the terrain encountered on New Zealand farms

Coupling GIS with physical databases, AgriBase and Statistics NZ provided an accurate method to link livestock types to specific average farm slope classes.

This information can be aggregated at local and regional levels to provide more precise estimates of energy expenditure during foraging, by applying a finer Terrain parameter in calculations.

This approach had no significant impact on the methane outputs of dairy cattle, but reduced beef cattle outputs associated with walking by 20% and for sheep by 15%. With these values estimated to be approximately 9% of the total, then beef cattle values would decline by 1.8% and sheep by 1.35%.

10.3 Calculating the impacts of transit walking distances for milking on greenhouse gas emissions

10.3.1 Methods of calculation

National herd size statistics (Dairy NZ, 2018) have been used to create the profile of dairy farms representative of average farm sizes (based on the average stocking rate of 2.8 cows per hectare). Farm size has been converted to dimensions, representing a square, as per the method described in Section 8. This was used to calculate the average walking distance per day for each representative farm size and then expressed as a proportion of the daily walking distance of the national herd (Table 8).

The full implications of transit distances to the dairy shed on greenhouse gas emissions are presented in Table 14. These calculations use the methodology in Section 8 to estimate distances walked and use the relationship between total dairy stock numbers and the proportion of milking cows (Pickering and Gibbs 2018) to calculate the impacts of transit distance on the milking herd. Both methane and nitrous oxide emissions are calculated as per current national inventory equations below (Pickering and Gibbs 2018).

Methane output (kg/cow) = DMI*21.6/1000

Methane emissions (t/annum) = Methane output*milking cow population/1000

Urine N output (kg/cow) = (10.5*0.037+0.34)*DMI*0.037

Nitrous oxide output (kg/cow) = 44/28*Urine N output*0.01

Nitrous oxide emissions (t/annum) = Nitrous oxide output*milking cow population/1000

10.3.1 Transit distance results

The energy required to walk to and from the shed during milking is calculated in Table 14. This table used the data recorded using GPS in the experiments reported in Section 5. This data is compared to that calculated from the theoretical model.

Table 14. Estimates of the energy requirement of dairy cows and sheep walking to and from the shed for twice-daily milking calculated from GPS measured distances and estimated from farm size.

Enterprise	Stock type	Terrain	Farm size	Transit distance (km/d)		Calculated transit distance (km/d)	Energy requirement (MJME/d)
				Average	SE		
Dairy cattle	Mixed age cows	Rolling	267	3.7	0.49	3.82	8.14
Dairy cattle	Mixed age cows	Rolling	300			4.04	9.696
Dairy cattle	Mixed age cows	Rolling	300			4.04	9.696
Dairy cattle	Mixed age cows	Rolling	267	3.3	0.11	3.82	7.26
Dairy sheep	Mixed age ewes	Rolling	197	3.0	0.30	3.27	0.84

Calculations based on the GPS results (Table 14) demonstrate that, while a small part of the total energy requirement, the energy required walking to and from the milking parlor is not negligible when considered over the course of a full lactation of 276 days for dairy cows and 180 days for dairy sheep. Calculated transit distances were slightly larger than those recorded with GPS. This may be a function of an increased number of paddocks as farm size increases. This increase in paddock number will reduce the average distance between shed and paddock.

Calculations based on the model suggest that cows walk, on average, 2.7 km/d, or 675 m per transit to or from the shed. This is within the range suggested by Thomson and Barnes (1993) of 2-7 km. Interestingly there are very little data available of actual or estimated transit distances in the literature. Experimental models (e.g. Clark et al. 2010) often locate the cows near the milking parlor and therefore the data is not representative of the national herd.

Further to this, extra pasture eaten to achieve this energy requirement has no role in other aspects of production, such as supplying protein for production. As such, all of the extra protein intake to meet this requirement will be excreted, contributing further to nitrous oxide emissions.

Calculations in Table 15 indicate that energy requirements during transit to and from the milking parlour contribute an extra 2 to 3% to annual intake. This has increased over the three years chosen, as farm sizes increase.

Table 15. Estimates of the potential contribution to methane and nitrous oxide emissions from the feed required to meet the energy demands of transit distance to and from the milking parlour for the dairy industry in New Zealand.

					Methane		Nitrous oxide	
Year	Average Farm Size (ha)	Total milking cows ('000,000)	Transit distance walked (km/cow/annum)	Feed intake (kg DM/cow/annum	kg/cow	Total (t/annum)	kg/cow	Total (t/annum)
2008	152	4.348	793	127	2.74	11912	0.054	234
2013	170	5.056	840	134	2.90	14669	0.057	288
2018	183	5.092	872	139	3.01	15341	0.059	301

10.3.2 Summary of the impact of transit distance

The use of GPS data to validate potential transit distances to and from the milking parlor in the New Zealand dairy industry provides an insight into the impact of a relatively small variation in the total intake of dairy cows. The extra feed required represents only 2 to 3% of the annual intake. Current estimates, for example, of the methane emissions are approximately 85 kg/cow/annum (Pickering and Gibbs 2018), making the transit distance estimates an addition of approximately 3.4%.

11. Summary

Information available on walking distances by grazing livestock is relatively limited. However, average walking distances per day are relatively similar between livestock classes. The exception is dairy cows in milk, when transit distances to the milking parlour increases total distance walked.

The literature search provided no new information that would alter current equations to calculate the energy requirements for foraging.

Overall the average distance travelled by livestock while foraging was approximately 3.1 km/d. This varied with terrain and potential feed supply, though often feed supply data was not provided. Generally, the foraging activity of New Zealand livestock, while moderated by farm management practices, reflects the international literature.

the GPS data collected to date provides an insight into the accuracy of the current inventory equation that represents the activity of the grazing animal in foraging. While there are differences between the values calculated from the inventory equation and those calculated using horizontal and vertical distance travelled during grazing, these differences can be explained by modifying either the Terrain parameter (T), or the Green Forage parameter (GF) in the current equation.

It must be recognized that these GPS data sets are limited in their representation of the range of livestock classes, terrains and forage availability that are present in New Zealand agriculture.

The use of GIS and physical databases provides an accurate dataset down to farm level.

This can be used to aggregate slope classes and farm enterprise across regions and nationally.

This opens the way to calculate more accurate estimates of the energy requirements while foraging.

Geographic Information Systems can provide a sophisticated analysis of the terrain encountered on New Zealand farms

Coupling GIS with physical databases, AgriBase and Statistics NZ provided an accurate method to link livestock types and populations to specific average farm slope classes.

This approach had no significant impact on the methane outputs of dairy cattle, but reduced beef cattle outputs associated with walking by 20% and for sheep by 15%. With these values estimated to be approximately 9% of the total, then beef cattle values would decline by 1.8% and sheep by 1.35%.

The use of GPS data to validate potential transit distances to and from the milking parlor in the New Zealand dairy industry provides an insight into the impact of a relatively small variation in the total intake of dairy cows. The extra feed required represents only 2 to 3% of the annual intake. Current estimates, for example, of the methane (CH_4) emissions are approximately 85 kg/cow/annum (Pickering and Gibbs 2018), making the transit distance estimates an addition of approximately 3.4%.

The methodology proposed to estimate the average transit distances to and from the milking parlor needs much further validation before use. Validation can be done using current farm records, rather than GPS tracking. Most farms record which paddocks are used each day, and this, in association with farm maps could be used to track the movements of herds during a milking season to provide more detailed information of average movements and variation related to farm size, shape and topography.

12. Recommendations

Recommendation: Current equations within the GHG inventory calculations are adequate to estimate the energy expenditure of livestock for grazing.

A search of the literature provided no new information to inform changes in the way the activity of grazing livestock is calculated.

Recommendation: GPS data, while available, needs to represent a larger range of livestock types and physiological conditions before this data can be effectively incorporated into the Inventory calculations.

GPS data recording walking distances of grazing livestock compared favourably with current estimates of energy requirements during grazing. The variation present in the data sets could be explained by potential differences in the Terrain parameter, or in the Green Forage parameter.

Recommendation: GIS techniques should be incorporated into the inventory calculations to provide a more accurate application of the Terrain parameter, T.

Geographic Information Systems can provide a sophisticated analysis of the terrain encountered on New Zealand farms

Coupling GIS with physical databases, AgriBase and Statistics NZ provided an accurate method to link livestock types and populations to specific average farm slope classes.

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15. Appendix 1: Literature search

15.1 Literature search methods

A review of livestock walking distances and terrain encountered during grazing was conducted. Drivers of animal walking distances, including feed on offer were searched for.

The scholarly journal databases BIOSIS, CAB Abstracts and SCOPUS were searched using a variety of related keywords by an experienced knowledge advisor. Further searches were conducted through the New Zealand Grassland Association and New Zealand Society of Animal Production publications and the DairyNZ website.

Recent research and data was compiled, relating to:

- Grazing patterns for dairy cattle, beef cattle, sheep and deer
- The distance travelled by these animals while grazing
- The type of terrain encountered while grazing and the availability of forage

15.1.1 Search scope

Literature 1990 – present

Statistics: relating to

Changing demographics in this time period

Size of herds

Sheep demographics and farm size

15.1.2 Resources searched:

CABAbstracts, Scopus, MPI, DairyNZ, Beef + Lamb New Zealand, StatsNZ

15.1.3 Search strategy:

The following key terms were used

Dairy cattle, cow*, beef cattle, sheep, deer (farmed, captive), livestock

Distance*, travel*, walk*, mobility, movement*, locomotion

Behavio?r*, motivation

Graz*, pattern*, distribution

Agricultur*, farm*, pasture*

Nutrition, forag*, feed*

Energy, metabol* energy requirements

Select*, prefer*

15.1.4 Further defining comments of the search

As well as the papers that included walking distance measurements, those that focused on grazing patterns / forage availability and energy requirements were included to check if walking distances were measured.

Literature containing walking distances of farmed deer was limited to New Zealand (e.g. Wall et al. 2018 researched red deer movements on a high country station). Most papers examined free ranging / rangeland activities from an ecological perspective.

Papers were grouped into those that focused on terrain and technology or modelling separately.

15.1.5 Reporting

The report below has statistics and literature grouped under the headings:

- Statistics
- Reviews
- Walking distance – beef cattle, dairy cows, sheep, deer, livestock – co-grazing
- Grazing patterns - beef cattle, dairy cows, sheep, deer, livestock – co-grazing
- Technology focus / Modelling

An EndNote library was compiled, and along with the full literature search, is supplied separately.

An EndNote library has been compiled. The following table summarises the papers which actually measured either energy requirements or walking distances under different circumstances.

16. Appendix 2. Relevant results from the literature search

16.1 Tabulated results from the literature

Authors	Year	Title	Journal	Species	Size	Distance walked	Energy required	Method	Feed supply
Aharoni, Y., A. Dolev, et al. Dolev, A., Z. Henkin et al.	2013 2014	Foraging behavior of two cattle breeds, a whole-year study: I. Heat production, activity, and energy costs II. Spatial distribution by breed and season	Journal of Animal Science	a) Beefmaster x Simford b) Baladi	a) 581 ± 76 kgs b) 268 ± 60 kgs	a) 3504 ± 587 m b) 4303 ± 464 m	a) 102.5 kJ/kg MBW b) 93.9 kJ/kg MBW	Number of units [fraction of the day for foraging, distance (m/d) for HD and PVD, and number of steps per day] multiplied by the energy cost of 1 unit (i.e., specific cost) of foraging.	*Hordeum bulbosum* L., *Echinops* spp., *Bituminaria bituminosa* L., *Avena sterilis* L., *Bromus* spp., *Trifolium* spp., and *Medicago* spp. Stocking rates: High = 1.8 cows/ha, Low = 0.9 cows/ha
Aharoni, Y., Z. Henkin, et al. 2009	2009	Grazing behavior and energy costs of activity: A comparison between two types of cattle	Journal of Animal Science	a) Beefmaster x Simford b) Baladi	a) 581 ± 76 kgs b) 268 ± 60 kgs		a) 89 kJ/(MBW x d) b) 93 kJ/(MBW x d)	Number of units [fraction of the day for foraging, distance (m/d) for HD and PVD, and number of steps per day] multiplied by the energy cost of 1 unit (i.e., specific cost) of foraging.	*Hordeum bulbosum* L., *Echinops* spp., *Bituminaria bituminosa* L., *Avena sterilis* L., *Bromus* spp., *Trifolium* spp., and *Medicago* spp. Stocking rates: High = 1.8 cows/ha, Low = 0.9 cows/ha
Braghieri, A., C. Pacelli, et al.	2011	Time budget, social and ingestive behaviours expressed by native beef cows in Mediterranean conditions	Livestock Science	a) Chianina b) Podolian c) Romagnola	a) 600-680 kgs b & c) No weight specified but range of 550-700kgs given	a) 1000 ± 160 m b) 1130 ± 170 m c) 840 ± 180 m	a) 63.96 b) 56.84 c) 62.38	"Data expressed as a percentage of time" ?	Graminaceae (*Arrhenatherum elatius* L., *Dactylis glomerata* L., *Festuca arundinacea*, *Phleum pratense*, *Lolium* spp.), Leguminosae (*Lotus corniculatus, Trifolium* spp.), Asteraceae (*Achillea millefolium, Cardus* spp.), Hypolepidaceae (*Pteridium* spp.), Rosaceae (*Potentilla*, Rosa Canina), Fagaceae (*Fagus* spp., *Quercus* spp.) Total herd size = 240 animals, so ~2.1ha/cow

Ganskopp, D. and D. Bohnert	2006	Do pasture-scale nutritional patterns affect cattle distribution on rangelands?	Rangeland Ecology and Management	Hereford X Angus steers	359 ± 4.7 kg	4359 m	No specific stats but "cattle were willing to forage more extensively and expend more energy in the senescent areas to obtain high-quality forage"	N/A	Wyoming big sagebrush (*Artemisia tridentata* subsp. *wyomingensis* Beetle) and an understory of crested wheatgrass. Pastures were 13-14ha, half pre-grazed and held 5 cows (~2.7ha/cow)
Hart, R.H., J. Bissio, et al.	1993	Grazing systems, pasture siz and cattle grazing behaviour, distribution and gains	Journal of Range Management	Beef cattle (cows and calves, unspecified)	Not specified	Dependent on pasture size (207-ha = 6100m/day; 24-ha rotational = 4200m/day; 24-ha continuous = 3200m/day)	Not specified	N/A	Not specified
McGavin, S.L., G.J. Bishop-Hurley, et al.	2018	Effect of GPS sample interval and paddock size on estimates of distance travelled by grazing cattle in rangeland, Australia	The Rangeland Journal	a) Angus (*Bos taurus*) b) Brahman (*B. indicus*) c) Belmont Red Composite (*B. indicus x B. taurus)* *d)* Brahman-cross	a) 650kgs b) 430kgs c) 430kgs d) 500kgs	Large range depending on pasture size and GPS sampling intervals.	Horizontal = 2.6 kJ km–1 kg–1 LW Vertical = 28 kJ km–1 kg–1 LW	PISC (2007) - 'Nutrient Requirements of Domesticated Ruminants.'	Not specified

Gregorini, P., C. Clark, et al.	2011	Short communication: Feeding station behavior of grazing dairy cows in response to restriction of time at pasture	Livestock Science	Holstein-Friesian	470 ± 47 kgs	a) pasture offered for 8 hours after milking (1x8) = 644.2m b) pasture offered for 4 hours after each milking (2x4) = 389.3m c) control (24hrs) = 334.3m	Not specified, but eating time, walking velocity while eating and number of feeding stations higher in (a)	N/A	*Lolium perenne* L.; pre-grazing herbage mass was 3191 kg DM/ha and daily herbage allowancewas 0.07 kgDM/ kg live weight/day
Hessle A., F. Dahlström, et al.	2014	Effects of breed on foraging sites and diets in dairy cows on mountain pasture	International Journal of Biodiversity Science	a) Swedish Mountain cattle b) Holstein	a) 368 49 kgs b) 554 68 kgs	a) 6300 m b) 5000m	Not specified	N/A	Ten vegetation types dominated by bilberry forest (33%), mixed forest (28%), and grass and sedge fen (12%). Although grass-dominated pasture comprised only 0.3% of the area, the cows spent, on average, 27% of their time there.

Islam, M.R., C.E.F. Clark, et al.	2015	Modelling of pasture-based automatic milking system herds: The impact of large herd on milk yield and economics	Asian-Australasian Journal of Animal Sciences	Dairy cattle (unspecified)	600 kgs	Moderate pasture utilisation: a) herd size 400 = 3500m b) herd size 800 = 6300m	a) 21 MJ ME/cow/d c) high pasture utilisaiton in 400 cow herd = 209 MJ ME/cow/d d) HPU in 800 cow herd = 15 MJ ME/cow/d +3.5 MJ ME/cow/d for every km increase in total walking distance -87% energy for increase in herd size from 400 to 800	Metabolisable energy (ME) expended on walking to and from the parlour, and simultaneous grazing and walking against each total distance walked was calculated as: ME (MJ/cow) = W[C·DMI(0.9–D)+0.026H]/km (CSIRO, 2007; equation 2)	Moderate pasture utilisation = 15.0t (DM/ha), high pasture utilisation = 19.7t (DM/ha) Kikuyu-ryegrass (short rotation), where ryegrass was oversown with kikuyu in autumn
Krohn, C.C., L. Munksgaard, et al.	1992	Behaviour of dairy cows kept in extensive (loose housing/pasture) or intensive (tie stall) environments I. Experimental procedure, facilities, time budgets - diurnal and seasonal conditions	Applied Animal Behaviour Science	a) Danish Friesians b) Red Danish	Weight not specified, but aged 4 months at the beginning of the trial	Extensive) Average 1700m (summer = 2500, winter = 800) Intensive) 220 m (no seasonal difference)	Not specified	N/A	E) Grass and mixed rations I) mixed rations only Mentions that 8-10kgs DM in good quality pasture requires 1.8-2.6kms of walking/day
Lopes, F., W. Coblentz, et al.	2013	Assessment of heifer grazing experience on short-term adaptation to pasture and performance as lactating cows	Journal of Dairy Science	Holstein Holstein x Jersey	Average = 583.25 kgs	Day 1 vs Day 61 PSTPST 4900m; 4500m PSTCNF 4600m; 4000m CNFPST 5200m; 2700m CNFCNF 3200m; 2000m	Not specified	N/A	PST = 41.5% tall fescue (*Festuca arundinacea* 'Bariane'), 41.5% meadow fescue (*Festuca pratensis* 'Pradel'), and 17.0% Kopu II white clover (*Trifolium repens*) CNF = TMR

Motupalli. P.R., L.A. Sinclair, et al.	2014	Preference and behavior of lactating dairy cows given free access to pasture at two herbage masses and two distances	Journal of Animal Science	Holstein-Friesian	No weight specified but cows were 229 ± 82.9 (mean ± SD) days in milk	Preference shown for the near pasture (38m, as opposed to 254m)	Not specified	N/A	Preference shown for high herbage mass (3000 ± 200 kg DM/ha, compared to 1800 ± 200 kg DM/ha)
Schutz, K., D. Davidson, et al.	2006	Do different levels of moderate feed deprivation in dairy cows affect feeding motivation?	Applied Animal Behaviour Science	Friesian	517.9 ± 445 kgs	0 hours = 30.7m 3 hours = 46.7m 6 hours = 64.7 9 hours = 76.9m	(1.9–2.0 J/kg)m^{-1}	(Thomson and Barnes, 1993; NRC, 2001)	Various levels of feed restriction (0, 3, 6 or 9h)
Chrupek, D., J. Groberek, et al.	2006	Characteristic of Polish heath sheep grazing behaviour on fallow lands during vegetative period, concerning pasturage time and weather conditions	Archiv fur Tierzucht	Polish heath sheep	Not specified	June: 4873.00 ± 621.81 July: 4633.11 ± 575.68 August: 6831.50 ± 621.81 September: 4920.11 ± 664.74 October: 6219.77 ± 664.74	No value specified, but "sheep walked more slowly on pasture in June and September, whereas in October - more speedily."	LSM analysis in SPSS with the following model: yijk = µ + ai +bj + abij + eijk	8-year-fallow land
Dobos, R.C., D.B. Taylor, et al.	2015	Characterising activities of free-ranging Merino ewes before, during and after lambing from GNSS data	Small Ruminant Research	Merino ewes	Not specified	Before: 10.6 ± 0.95 m During: 6 ± 0.54 m After: 3 days = 7.9 ± 0.71 m 7 days = 8.8 ± 0.79 m	Not specified	N/A	*Festcua arundinacea* (fescue grass), *Lolium perenne* (ryegrass) and *Trifolium* (clover)
Fierro, L.C. and F.C. Bryant	1990	Grazing activities and bioenergetics of sheep in native range in Southern Peru	Small Ruminant Research	Corriedale ewes	Not specified	4.6km/day (not correlated with forage availability)	113 ± 2.7 kcal/11.5h observation period (45% of total energy expenditure)	Daily energy expenditure (kcal/day) = Σ(Kt) W where: K= energetic cost of grazing (0.45kcal/h/kg W) per unit time, t = time (hours) involved in grazing per day, and W= mean body weight of animals.	*Festuca dolichophylla, Calamagrostis antoniana* and *Muhlenbergia fastigiata.*

Garcia, F., P. Carrere, et al.	2005	Characterisation by fractual analysis of foraging paths of ewes grazing heterogeneous swards	Applied Animal Behaviour Science	Romane ewes (INRA 401)	54.8 ± 1.15 kg	P1) HSR=1853m LSR=1584m P2) HSR=4583m LSR=3063m P3) HSR=4688m LSR=1989m P4) HSR=2407m LSR=1989m	Not specified	N/A	2-year-old cocksfoot sward (*Dactylis glomerata* cv. Lupre´)
Gross, J.E., C. Zank, et al.	1995	Movement rules for herbivores in spatially heterogeneous environments: Responses to small scale pattern	Landscape Ecology	Bighorn sheep (*Ovis canadensis*)	74-87 kgs	Average distance moved between plants by the sheep was 5.33 m, and sheep most often travelled to the nearest, or second-nearest plant	Not specified	N/A	36 individual alfalfa (*Medicagosativa* L.) plants
Rook, A.J., A. Harvey, et al.	2004	Bite dimensions and grazing movements by sheep and cattle grazing homogeneous perennial ryegrass swards	Applied Animal Behaviour Science	a) Holstein-Friesian hiefers b) Scottish Halfbred (Border Leicester × Cheviot) ewes	a) 312 ± 8.3 kg b) 97 ± 3.9 kg	a) 5.8 m per grazing bout b) 1.7 m per grazing bout	3.84 (heifer) or 1.09 (sheep) g DM are eaten per meter forward movement	Rutter et al., 2002 and Penning et al., 1995	Perennial ryegrass
Pepin, D., N. Morellet, et al.	2009	Seasonal and daily walking activity patterns of free-ranging adult red deer (*Cervus elaphus*) at the individual level	European Journal of Wildlife Research	Red deer (*Cervus elaphus*)	Not specified (but 2kg collars were <1.5% of the BW of the lightest individual)	Differs by season and sex: F1: W=1355±134 Sp=2413±277 S=1990±218 Rut=1696±277 A=2103±248 F2: W=2657±264 Sp=2319±206 S=2075±193 Rut=1641±341 A=2645±224 M1: W=810±73 Sp=1119±121 S=1173±165 Rut=3490±546 A=1272±144 M2: W=1011±136 Sp=2299±227 S=1655±157 Rut=3912±889 A=2052±365	Not specified	N/A	Study site was composed of mixed forest (*Pinus sylvestris, Abies alba, Fagus sylvatica, Quercus* sp., *Castanea sativa*) and moorland (*Erica* sp., *Calluna vulgaris, Vaccinium* sp.)

Clark, P.E., D.E. Johnson, et al.	2017	Contrasting daily and seasonal activity and movement of sympatric elk and cattle	Rangeland Ecology and Management	a) Elk (*Cervus elaphus* L.) b) Cattle (*Bos taurus* L.)	Not specified	Daily travel distance (summer and autumn) = a) s=1420m a=1240m b) s=1110m a=1040m	Not specified	No specific values given, but "During fall, when forage quality was limiting, elk exhibited a more foraging-centric mobility strategy while cattle emphasized an energy conservation strategy"	Ponderosa pine (*pinus poderosa),* Douglas-fir (*Pseudotsuga menziesii)* and grand fir (*Abies grandis*) with a pinegrass understory (*Calmagrostis rubescens*) Barn pasture = 1108-2237 kg DM/ha in summer and 641-821 kg DM/ha in autumn. Cuhna pastures = 2901-4039 kg DM/ha in summer and 1252-1546 kg DM/ha in autumn.
Bailey, D.W., D.D. Kress, et al.	2001	Relationship between terrain use and performance of beef cows grazing foothill rangeland	Journal of Animal Science	Hereford (HH), Tarentaise (TT), ³⁄₄ Hereford × ¹⁄₄ Tarentaise (3H1T), ¹⁄₂ Hereford × ¹⁄₂ Tarentaise (HT), and ¹⁄₄ Hereford × ³⁄₄ Tarentaise (1H3T)	By age and year (kg): 1997 - 3= 525±7 4= 568±8 >4= 604±5 1998 - 4= 577±8 5= 575±6 >5= 619±6	Horizontal and vertical distances to water for lactating and nonlactating: 1997 - H, L=445±5, NL=440±13; V, L=49±1, NL=58±2 1998 - H, L=836±9, NL=828±38; V, L=62±1, NL=70±3	No specific stats but "Energy requirements of nonlactating cows are lower than those of lactating cows… Nonlactating cows used higher terrain and steeper slopes"	N/A	Lower elevations with gentle slopes were dominated by Kentucky bluegrass (*Poa pratensis* L.), nd very steep slopes (>40%) were dominated by rough fescue (*Festuca scabrella* Torr.). Kentucky bluegrass, rough fescue, bluebunch wheatgrass (*Pseudoregnaria spicara*) and Idaho fescue (*Festuca idahoensis*) were dominant in the majority of each pasture. In all pastures, less than 15% of the pasture contained any trees such as Ponderosa pine (*Pinus ponderosa*) and aspen (*Populus tremuloides*).
Bailey, D.W., H.C. VanWagoner, et al.	2006	Individual animal selection has the potential to improve uniformity of grazing on foothill rangeland	Rangeland Ecology and Management	Hereford X Tarentaise	Not specified (but aged 3-9 years)	Horizontal distance to water (m) - Hill climber= 588±26, Bottom-dweller= 547±26 Vertical distance to water (m) - HC= 48.1±1.9, BD=42.5±1.9	Not specified	N/A	1209 and 813 kg/ha at the Thackeray Ranch and Ross Ranch, respectively. Grasses composed from 59% to 86% of the total herbaceous standing

Brosh, A., Z. Henkin, et al.	2010	Energy cost of activities and locomotion of grazing cows: A repeated study in larger plots	Journal of Animal Science	Simford (Simmental × Hereford)	ActY = 479±12 ActN = 420±21 at beginning of trial	3550 m/d in September	94.5 kJ·kg of $BW^{-0.75} \cdot d^{-1}$	$HP_{ijkm} = K + A_i + AC_m + DH + DV + M_j + (M_j \times H_k) + e$	"A total of 166 herbaceous plant species were identified in the experimental plots" (Sternberg et al., 2000)
Ganskopp, D., R. Cruz, et al.	2000	Least-effort pathways: a GIS analysis of livestock trails in rugged terrain	Applied Animal Behaviour Science	Hereford X Angus cow/calf pairs	Not specified	Path lengths: Trail = 2162 Pathway = 2450	Mean travel costs: Trail = 183 Pathway = 170 (not significantly different)	Doesn't give formula, but states "Our algorithm for estimating travel cost was curvilinear in nature, and examination of figures supplied by Yousef et al. 1972. suggests that this might be an appropriate form for a model."	Vegetation is characterized by a dispersed western juniper (*Juniperus occidentalis* Hook.) overstory. A shrub layer is dominated by low sagebrush *(Artemisia arbuscula* Nutt.), Wyoming big sagebrush (*Artemisia tridentata* subsp. *wyomingensis* Beetle.) or mountain big sagebrush *(Ar. tridentat*a subsp. *vaseyana* (Rydb.) Beetle). The herbaceous dominants include bluebunch wheatgrass *(Agropyron spicatum* (Pursh) Scribn. and Smith), Idaho fescue (*Festuca idahoensis* Elmer), or Sandberg's bluegrass (*Poa sandbergii* Vasey).

Marco, O.N.d., and M.S. Aello	1998	Energy cost of cattle walking on the level and on a gradient	Journal of Range Management	Angus steers	298±38kgs		(in kcal.hour^{-1}.100kg BW^{-1}) Walking 2km/h: First km = 105.6 Fourth km = 107.4 Walking 4km/h: First 2km = 115.8 Second 2km = 117.3 Walking on the grade: Ascending = 113.7 Descending = 116.5	CO_2 entry rate technique (Young 1970). Heat production energy calculated from Sahlu et al. 1988 and Elia et al, 1988 (5.26kcal/L CO_2)	Alfalfa hay (1kg DM/100kgs BW)
Martin, N.P., R.E. Hickson, et al.	2015	Walking distance and energy expenditure of beef cows grazing on hill country in winter	Proceedings of the New Zealand Society of Animal Production	Angus, Angus X Friesian or Angus X Jersey	2012 = 518±6kg 2013 = 534±6kg	2012 = 2730 ± 40 m/day 2013 = 3360 ± 50m/day	2012 = 7.17 ± 0.13 MJ/ME/d 2013 = 8.43 ± 0.11 MJ/ME/d	Uphill EE (kJ/km/kg live weight) = 2.6cosθ +28sinθ, where θ is the slope of the ground.	Herbage was made up largely of mature stalky pasture of poor quality and low covers in 2012. Quality improved in 2013 but herbage quickly declined and cows had to be moved after 6 weeks
Williams, B., S. Walls, et al.	2011	Management considerations for conserving hill areas highlighted by range analysis of hill sheep	Tearmann	Scottish Blackface ewes	Not specified	By season (in kms): S=39.9±13; A=25.6±8.8; W=24.3±10.3; Sp=23.8±9.1	No stats, but "Scottish Blackface prefer to forage across the slope, rather than uphill or downhill… This is probably related to energetics as grazers take the path of least resistance when choosing the direction of travel"	N/A	The dominant habitats were blanket bog and wet heath, with fragmented patches of acid grassland (described in full by Williams et al. 2010)

Funston, R.N., D.D. Kress, et al.	1991	Grazing behavior of rangeland beef cattle differing in biological type	Journal of Animal Science	a) Hereford b) Angus X Hereford c) Simmental X Hereford (50/50) d) Simmental X Hereford (75/25)	a) 570±28 b) 586±22 c) 608±22 d) 623±28	In m/day: a) 3100±200 b) 3400±200 c) 4000±200 d) 2800±200	Not specified	N/A	The major grasses on the study site were rough fescue (*Fesrucu scubrella*), Idaho fescue (*Fesrucu idahoensis*), and bluebunch wheatgrass (*Agropyron spicutum*) on the upland areas and Kentucky bluegrass (*Pou prarensis*) on the lowland areas. Stocking rates were 0.67 and 1.2ha/Animal Unit Month in 1985 and 1986, respectively.
Hessle, A., M. Rutter, et al.	2008	Effect of breed, season and pasture moisture gradient on foraging behaviour in cattle on semi-natural grasslands	Applied Animal Behaviour Science	a) Vaneko b) Charolais	a)309 ± 43 kgs b) 431 ± 51 kgs	a) 10900m (average/season) b) 9600 (average/season)	Metabolizable energy (MJ): Dry=9.9; Mesic=9.4; Wet=9.0	Lindgren, 1979	Herbage mass (tonnes DM/ha): Dry=0.8; Mesic=1.1; Wet=1.6
Thanner, S., F. Dohme-Meier, et al.	2014	The energy expenditure of 2 Holstein cow strains in an organic grazing system	Journal of Dairy Science	Holstein-Friesian dairy cattle from: a) Switzerland b) New Zealand	a) 616 ± 30.9 kgs b) 570 ± 55.9 kgs	Average walking distance from the barn to the paddocks was 460m	EE (MJ/6h per cow) = a) 37.9 b) 31.8	EE[2] (kJ/6h/kgBW$^{0.75}$) (calculation method described in Kaufmann et al. 2011)	Predominantly grasses (mainly *Lolium perenne, Dactylis glomerata*, and *Phleum pratense*), clover (mainly *Trifolium repens*) and other herbs (mainly *Taraxacum officinale*).
Roguet, C., S. Prache, et al.	1998	Feeding station behaviour of ewes in response to forage availability and sward phenological stage	Applied Animal Behaviour Science	Romanov X Limousine ewes	61.4 kgs	Distance walked per bite: a) Vegetative (V)= 3.6-5.6cm b) Reproductive (R)= 5.4-6.9cm	Not specified. However, "profit, in terms of intake per unit distance declined with green leaf mass from 3.1 (V) and 2.0 (R) to 1.0g DM/m"	N/A	Cocksfoot sward (*Dactylis glomerata* cv. Lully)

Ortega, I.M.	1992	Deer and cattle foraging strategies under different grazing systems and stocking rates	Dissertation Abstracts International. B, Sciences and Engineering	White-tailed deer	Not specified	Stocking rate (heavy or moderate): H=973m M=995.5m Grazing system (short-duration and continuous): SD=984.1m CG=984.5	Not specified	N/A	Stocking rates: Moderate= 1AU/4.9ha/yr and heavy = 1AU/2.4ha/yr Moderate stands of honey mesquite (*Prosopis glandulosa*), interspersed with mottes of brasil (*Condalia hookeri*), and Texas persimmon (*Dyospiros texana*). Buffalograss (*Buchloe dactyloides*), pink tridens (*Tridens congestu*), and bermudagrass (*Cynodon dactylon*) are the dominant grasses. Among forbs Prairie coneflower (*Ratibida columnaris*), western ragweed (*Ambrosia psilostachya*), clay violet (*Ruelia nudiflora*), and patches of wood-sorrel (*Oxalis dillenii*) are the dominants. Sumpweed (*Iva annua*) was a dominant forb
Beker, A., T.A. Gipson, et al.	2010	Energy expenditure and activity of different types of small ruminants grazing varying pastures in the summer	Journal of Applied Animal Research	a) Angora b) Boer c) Spanish goat d) Rambouillet sheep	a) 20.3 b) 34.2 c) 26.7 d) 75.7	In km/day a) 2.98 b) 3.17 c) 2.85 d) 3.04	In kJ/kgBW$^{0.75}$ a) 465 b) 499 c) 390 d) 466	Beker et al. 2009	Three 0.4ha paddocks, with varying numbers of mimosa (*Albizia julibrisin*) trees
Matsui, K.	1998	A new data-logger for automatic recording of the steps taken by grazing cattle	Animal Science and Technology	Holstein heifer	Not specified (but aged 19 months)		Not specified	N/A	Orchard grass and tall fescue
Mora-Delgado, J., N. Nelson, et al.	2016	Application of GPS and GIS to study foraging behavior of dairy cattle	Agronomia Costarricense	Holstein	650kgs	4677±414m 3385 ± 712 m/day	Not specified	N/A	Forage availability > 20000 kg/ha DM

Armstrong, H.M. and A. Robertson	2000	Energetics of free-ranging large herbivores: when should costs affect foraging behaviour?	Canadian Journal of Zoology	Domestic sheep (*Ovis aries* L.)	N/A	N/A	E_{graze} = M [0.05N (0.90 – D_{dm}) + E_w] where E_w is the energetic cost per unit live mass of walking for a prescribed distance along a particular gradient, N is dry-matter intake and D is dry-matter digestability	A term predicting the energy required for walking (Brockway and Boyne 1980) is combined with a term that predicts the energy required for eating by a sheep in pasture conditions (SCA 1990)	N/A

17. Appendix 3: GPS accuracy

17.1 Principles of GPS accuracy

There are many places that error is introduced into GPS readings. The following is a short summary of potential issues.

Atmospheric conditions (ionospheric and tropospheric propagation delays) affect accuracy continuously, and their effects vary with position of GPS receiver and time of measurement.

GPS error sources reducing precision (errors of ~15m per satellite) include

"User range errors" ("signals in space errors"), which can be reduced by differential GPS such as SBAS, and multi-frequency techniques such as dual-band GPS and precise point positioning (PPP):

(a) PRN code noise (~1m)

(b) There was intentional degradation of non-military standard positioning service data by the US Department of Defence (Coarse acquisition code accuracy reduced from ~30m to ~100m) from the first Iraq war, until selective availability was deactivated in May 2000 by President Bill Clinton.

(c) Ephemeris errors (satellite orbital trajectory errors) contribute bias errors of around 1m. Ephemeris errors are dependent on the frequency with which the almanac of available satellites is updated within the GPS receiver.

(d) Satellite clock errors (up to ~1m).

Geometric dilution of precision:

(e) The signal from navigation satellites has a fixed precision, dependent on the number of satellites visible and the layout of satellites and relative satellite-receiver geometry, if the atmospheric effects in point 1 above are ignored. This precision is measured on a scale called DOP (dilution of precision, sometimes referred to as triangulation accuracy). There is a good Wikipedia article on DOP, showing how its values are calculated.

(f) Dilution of precision can be magnified by obstruction of satellite signals by hills, trees, buildings, vehicles, etc

User equipment errors:

(g) Noise within the receiver (~1m)

(h) Multipath reception can be impossible to detect and can cause bias errors of unknown magnitude.

(i) Errors due to electromagnetic interference

(j) Errors due to antenna orientation

Operator errors:

(k) Use of incorrect geodetic datum

(l) Use of incorrect projection

Accuracy is sometimes broken down into several categories and specified as:

(a) Relative accuracy (accuracy with which one GPS device measures position compared to another GPS device)

(b) Repeatable accuracy (accuracy with which a GPS device can measure a position measured previously by the same GPS)

(c) Predictable or absolute accuracy (accuracy of GPS measured locations compared to known positions on a map)

Estimation of accuracy and precision ("static drift test"):

Find any convenient unobstructed place, continuously record the GPS location for several days, and plot.

(a) GPS accuracy: The degree of closeness of the indicated readings to the actual position.

(b) GPS precision: The degree to which the readings can be made. The smaller the scatterplot circle, the higher the precision.

(c) CEP (Circular Error Probability): Refers only to the horizontal plane. CEP is defined as the radius of a circle centered on the true location value that contains 50% of the actual GPS measurements. So a receiver with 10 metre CEP accuracy will be within ten metres of the true position 50% of the time. The circle indicating the 95% probability is sometimes used and is often referred to as the R95 probability circle.

17.2 Handling error

17.2.1 GPS on a post (static test): A note about the error distribution.

Most of the errors from the main error sources (propagation delay, ephemeris, clock drift, signal reflections, and unfavourable satellite geometry) are spatially and temporally auto-correlated, biased, and non-Gaussian.

A sufficient number of such errors (100,000 say) added together in empirical GPS error studies show an approximately Gaussian distribution in any one direction, and that is the principle which we invoke in calculating the Circular Error Probability ratings for a GPS device, from the chi-square distribution of course (sum of squares of Gaussian).

17.2.2 Line length (distance walked): The errors do not "cancel out".

Trampers and distance runners who routinely use GPS know this. (Many who wear GPS watches don't know this.)

For trampers and runners the over-estimation of the range is typically +10% to +20%.

The distance is always over-estimated, unless the GPS device is following a "twisty" course and the time and distance thresholds for recording are set way too high, in which case there is under-estimation, i.e. low sampling rate interpolation error.

If the animals have different behaviours, the "average effect" of the errors is not the same for each animal.

Over-estimation of distance can be calculated using the Salzburg formula (named for the university where it was discovered). For any line segment, this calculation involves the actual distance, the variance of the positional error (which changes spatially and temporally), and the autocovariance of the positional error (which changes spatially and temporally).

The important points here are

- The overestimation is not trivial. It has been rigorously examined both mathematically and empirically, especially with regard to pedestrian distances (see for example INTERNATIONAL JOURNAL OF GEOGRAPHICAL INFORMATION SCIENCE, 2016 VOL. 30, NO. 2, 316–333 http://dx.doi.org/10.1080/13658816.2015.1086924

- The overestimation increases as the spread of the positional error increases, and the increase is not trivial. An animal walking 1km in the shade of the shelter belt with poor satellite reception will have a larger over-estimation of distance walked than an animal walking 1km out in the open with better satellite reception. Using the CEP ratings for the collars from the static tests in the shade of the shelter belt and out in the open, we can estimate the maximum inflation of the distances walked (which is one reason for doing static tests first).

If we estimate the ranges of the distances and they don't overlap, then we know that the animals have walked different distances.

But if different animals prefer different parts of the paddock, in paddocks where reception varies spatially, it is unreasonable to expect that GPS errors "average out", that they have the same effect for different animals.

To do things properly, one should be mindful of how the errors affect the measurements, and one should estimate their possible magnitudes.

To quote the article that I quoted above:

"If the variance and the spatio-temporal autocorrelation of a GPS device in a particular recording environment are known, one is able to calculate the expected overestimation of distance in the trajectory data. This information can be used to give a more realistic estimate of the distance that a moving object has travelled."