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Development of LiDAR Standards for Digital Elevation Models and Volume Maps

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Disclaimer

EXECUTIVE SUMMARY

Light Detection and Ranging (LiDAR) is commonly used to estimate stand volume and to develop Digital Elevation Models (DEMs). There are already many reports and presentations advocating and validating the use of LIDAR. Despite the wide acceptance and increasing use of LiDAR for these applications, there is little information describing the specifications required to achieve these results. In this report we determine the minimum pulse density required to develop DEMs and accurate spatial volume estimations. This was achieved through three objectives:

(i) identify the minimum ground return density required to construct an accurate DEM for engineering purposes;

(ii) develop a model that describes the influence of stand variables on the percentage of ground returns from incident pulses (GR); and

(ii) determine the effect of pulse density and plot size (when using a prior DEM) on LiDAR-volume relationships.

Using results obtained from objectives (i) and (ii), a spreadsheet was built that allows the minimum pulse density for an accurate DEM to be estimated from a known set of stand conditions. This report does not determine the necessary pulse density for individual tree counting. There are many factors that affect the quality of LiDAR data, and whilst the results in this report serve as a excellent guide, they should always be used in conjunction with the recommendations of an experienced LiDAR vendor.

Objective 1: Number of Ground Returns Necessary for a Workable DEM

A North Island east coast forest was flown in such a way that two datasets were provided, one with a minimum of 1 pulse per m^2 and one with a minimum of 2 pulses per m^2. A quantitative comparison was made between the respective DEMs. The difference between the DEMs sharply increased in areas with a low ground return density. Conversely, as the ground return density increased, the reliability of the DEM increased. To obtain a DEM which can be assumed to be 90% within ±0.5 m of a 'superior' DEM with double the ground return density, the recommended minimum ground return density for a DEM was found to be 0.2 ground returns per m^2 (equal to 1 ground return per 5 m^2).

Objective 2: Influence of Stand and Site Conditions on the DEM

Using 381 plots from the LUCAS dataset, a model of percentage ground returns (GR) was constructed. The model of GR included stand age, crop stocking, non-crop stocking and slope. This model accounted for 48% of the variance in GR with RMSE of 13.9%. GR declined exponentially as stand age, crop and non-crop stocking increased and declined linearly with increases in slope. GR was not substantially affected by either the number of pulses per m^2 or whether the stand comprised radiata pine or Douglas-fir.

A simple spreadsheet model has been constructed (and is attached to this report) describing the minimum pulse density required to generate an accurate DEM, under a range of stand conditions. This model is based on outputs from Objectives 1 and 2.

Objective 3: Minimum Pulse Density for Volume Estimation with a Prior DEM

Although a quality DEM is crucial for accurate volume estimation from LiDAR, once this is acquired subsequent flights can be flown at reduced pulse densities and still get good volume estimates. Using the LUCAS dataset, pulse densities could be reduced to around 100 pulses per plot (0.33 pulses per m^2 for 0.03 ha plots; 0.17 pulses per m^2 for 0.06 ha plots) without losing accuracy on the volume function. Plot size was a limiting factor and should not be reduced below a threshold of 0.03 ha.

INTRODUCTION

Light Detection and Ranging (LiDAR), is a widely used remote sensing technique that uses the difference in time between the emission of a pulse of near infrared radiation and its detection by a sensor to provide a highly accurate measure of distance. Although LiDAR has been used in forestry for the last three decades, only recently have technological advances allowed progression of this method to operational use.

One of the most widely used applications of LiDAR is for development of Digital Elevation Models. There are broad guidelines surrounding the minimum pulse density required for development of accurate DEMs in open terrain. However, despite the known attenuation of light by forest cover, little research has investigated how factors such as stand stocking, slope and stand understory affect the number of pulses hitting the ground, and hence an increased minimum pulse density. Characterisation of minimum pulse density required across a range of site types would be of considerable use to forest managers.

Recent research using a national dataset has shown that LiDAR can be successfully used to predict stand volume across broad environmental gradients[1]. Understanding the minimum pulse density required for development of robust relationships between LiDAR and volume would be useful for driving down the cost of this technology. Major reductions in pulse density are likely to be possible after the DEM has been defined and the plot is being flown for canopy metrics only.

Objectives

Using the national LUCAS dataset (both post-1990 and pre-1989, provided by MfE), and a dataset obtained from a mature North Island forest, the objectives of this research were to (i) identify the optimal pulse density of a DEM for engineering purposes, (ii) develop a model that describes the influence of stand variables on the percentage of ground returns from incident pulses and (iii) determine the effect of pulse density and plot size (when using a prior DEM) on LiDAR-volume relationships.

LIDAR TERMINOLOGY

In the following sections we will discuss several practical aspects of LiDAR data collection. For the reader without comprehensive knowledge of LiDAR these technical aspects are defined and discussed here.

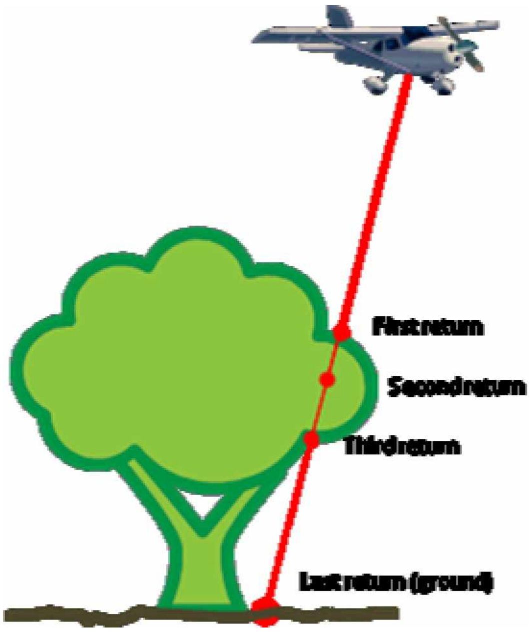
Pulse Density

This is the average number of laser pulses fired from the aircraft per horizontal square metre of ground. This is generally specified as a minimum. The pulse density is a function of the Pulse Repetition Frequency (PRF), aircraft height, aircraft speed, maximum scan angle, and swath overlap. All of these will be varied by the supplier in order to best suit the job.

Return Density

Depending on the LiDAR system, each pulse may give multiple returns. The two Optech 3100EA units we currently have in New Zealand can give up to 4 returns per pulse. Multiple returns occur when the beam hits surfaces that do not completely obstruct it (such as forest canopy) and multiple reflections occur. Surfaces that completely block the beam – such as the ground – will always be the last return. This means that the return density will often be higher than the pulse density over vegetated areas

Ground Return Density



This is what you are after when trying to construct a DEM, although it is unknown until after data capture and can vary significantly. Except under extremely dense vegetation (such as sugar cane), some of the returns will be from the ground, and sophisticated semi-manual filtering algorithms are used to determine this. It is these ground returns that are used to create a DEM for engineering but also for working out the above-ground heights of the other returns. In general, pulse density is specified by the client, but ground-return density is what they need. In this project we demonstrate relationships that relate the two under a range of stand conditions.

Ground Return Ratio

This is the average ratio of ground returns to *pulses* (not *returns*). This is predominantly affected by land cover, as objects such as trees will prevent some pulses from reaching the ground. It is also affected to a lesser extent by aircraft height and the PRF setting.

PRF

PRF stands for Pulse Repetition Frequency, and is the rate at which the laser fires outgoing pulses. The Optech 3100 scanners have to wait for the reflected signal from the pulse before it can fire the next, so the further the target (i.e. the higher the plane), the longer the gap must be between pulses. This means that a plane at 1,000 m or lower can fire 70-100,000 pulses per second, but at 3,000 m only 33,000 pulses per second can be fired. There are systems that can send the next pulse before the last has returned (multipulse systems), but at this stage they are really suitable only for operation in flat terrain where there's no opportunity for the multiple pulses flying backward and forward between the ground and sensor to get mixed up with one another (NZAM pers. comm.). The lasers provide a constant power output, so the more pulses per second the lower the energy per pulse.

Intensity

Intensity is the power per m^2 of radiation, in this case the NIR light from the laser. Intensity can be measured at the ground (incident intensity) or at the receiver (reflected intensity). Both are affected by the PRF setting and the plane altitude.

As the outgoing pulse travels through the air, it spreads out (diverges). This means that for a plane at around 1,000 m using a standard beam divergence of 0.25 mrad (0.014 degrees), the footprint of the laser will be approximately 0.25 m in diameter. The intensity falls off as an inverse square ($1/distance^2$), so clearly returns received by a plane at high altitude will be at a lower intensity than returns from a plane at lower altitude. The laser pulse is in the Near Infrared (NIR) range, which the earth itself is constantly radiating (google "earth's energy budget" and "greenhouse effect" for more on that). So for a return to be detected, it must be of a higher intensity than the background radiation. If the ground is unobstructed and reasonably reflective in the NIR range, then getting ground returns up to 3,000 m is not a problem. Most ground surfaces are good reflectors of NIR, although water is very poor. However, when the ground is covered by forest, understorey and woody debris, the beam may be scattered to the point that some ground returns are not detected, thus reducing the ground return ratio. This means that under heavy vegetation it may be worth setting a lower PRF than necessary for that altitude - sacrificing some pulse density - in order to boost pulse power and improve the odds of yielding a ground return. Given that LiDAR is generally contracted by minimum pulse density not ground return density, it is the mark of a good supplier if they will do this.

Flight Overlap

Doing more overlapping swaths will increase the pulse density, but it will not increase the ground return ratio. It will also cost more. The flight path must be worked out in terms of local topography and the aircraft turn radius, and suppliers will look to use overlap in conjunction with altitude and PRF to achieve the required pulse density.

Objective 1: Number of Ground Returns Necessary for a Workable DEM

Summary

In this section we demonstrate how the ground return ratio varies according to cover for a specific case study, and the DEMs that are created from these data. A sample forest was flown in such a way that two datasets were provided, one with a minimum of 1 pulse per m^2 and one with a minimum of 2 pulses per m^2. The respective pulse densities are shown to meet these minima, and are often higher. The ground return ratio was typically 75-95% in cutover, and less than 10% in mature pine forest and heavy native bush. A comparison of localised DEMs show that many features are better defined at the higher pulse density, although the difference is negligible in cutover. Under forest conditions features such as roads and rivers were often better described at the higher pulse density, although in general these features had less cover than neighbouring forested areas and hence a higher ground return ratio anyway.

A quantitative comparison was made between the DEMs from the 1 and 2 pulses per m^2 data for nine features of interest (Table 1.1), and for 4307 other randomly selected locations. Differences between the DEMs were determined at a 1 m^2 resolution. The DEM at the lower resolution had a slight tendency to overestimate ground height by around 0.05 m. The 90th percentile of the DEM differences was recorded, and sharply increased as the ground return density of the lower resolution dataset declined. Conversely, as the ground return density increased, the reliability of the DEM increased. To obtain a DEM which can be assumed to be 90% with ±0.5 m of a 'superior' DEM with double the ground return density, the recommended minimum ground return density for a DEM is 0.2 ground returns per m^2 (equal to 1 ground return per 5 m^2). This assumption that a DEM generated with more ground return returns is superior to one with less is commonplace and logical, but will be validated next year with field surveying.

Ground Points

Conventional surveying methods for creating a DEM include recording the three-dimensional positions of a series of marker points. This network of points is then used to generate a DEM. LiDAR is much the same in that the data provide a set of ground returns that can also be triangulated into a DEM. The difference is that whilst LiDAR certainly generates these ground points faster, the exact location cannot be specified within the area flown. Field surveying will place points on local high, low and inflexion points. In particular, points will be placed around sites of interest, such as the edges of roads, slips and bluffs, and along ridgelines and spurs. LiDAR cannot guarantee to get a ground point exactly in any one location, but can offer a much greater overall density of ground points for the same cost. In this section we investigate the effect of ground return density on DEM quality.

Pulse Density, Return Density and Ground-return Density Case Study

A steep, mature radiata pine forest in the North Island was flown for LiDAR at 2 pulses per square metre. The acquisition was performed at 50% swath overlap, so that eliminating half of the passes leads to an equivalent 1 pulse per m^2 dataset. This gives us a fair way of comparing DEMs generated over the same area at different pulse densities.

The area flown consisted of mature pine forest, native forest and cutover. Each of the different land covers could be penetrated to some degree by the LiDAR pulses, giving a range of ground-return densities. Figure 1.1 shows: a) the pulse density, b) the return density and c) the ground return density for the forest in the 2 pulses per m^2 dataset. The areas with a black outline are radiata pine blocks, except the block in the Northwest corner which is cutover. Note that all charts are displayed with a 10-m pixel size.

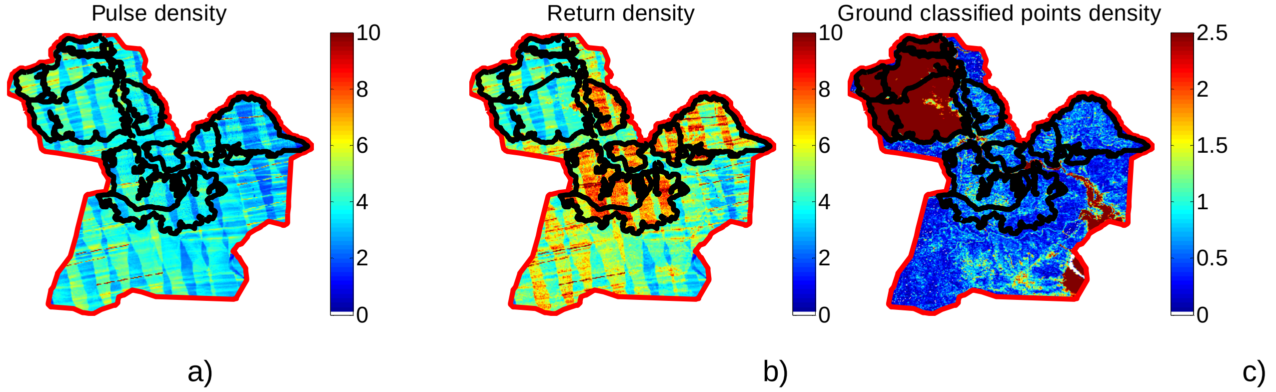


Figure 1.1 – a) Pulse density b) return density and c) ground return density

Notice in Figure 1.1 how the minimum specified pulse density was 2 pulses per m^2, but in order to achieve this many areas have significantly greater pulse densities. Figure 1.2 shows histograms for pulse density for both the 1 and 2 pulses per m^2 datasets, showing that whilst a minimum is specified, the actual pulse density may be much higher. These data were found by selecting 4307 randomly located 40x40 m samples in the DEM across all cover types.

It is also apparent in figure 1.1 that the pulse density is relatively constant across land cover types, whereas return density increases over forest (especially radiate pine), and ground return density decreases. Ground return density is highest over cutover and the river that travels ESE through the site, whilst in forested areas ground return densities are much less than the pulse density, typically 0.1 to 0.5 ground returns per m^2.

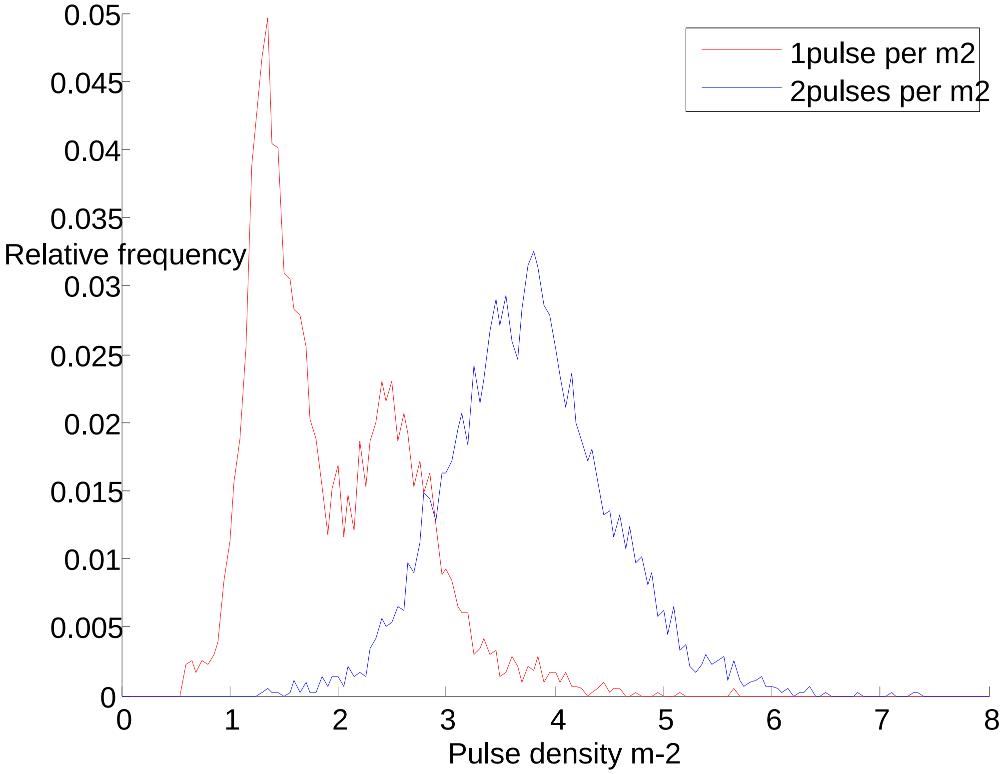


Figure 1.2 – Histograms of pulse density for the 1pulse per m^2 and 2pulses per m^2 datasets, defined across 4307 randomly selected 40x40 m samples.

Comparison of DEMs at Different Ground Return Densities

Figure 1.3 shows a specific location in the study forest where an old road (probably from planting) runs parallel to a river. The road is not visible in the photograph, but was GPSed on the ground during a field visit. Figure 1.4 shows the DEMs generated from the 1 pulse per m^2 and 2 pulses per m^2 dataset, looking south down the valley. Because of the variation in flight overlaps and topography, the actual minimum pulse densities for these two 100x100 m areas were 1.28 and 3.75 pulses per m^2. These yielded 0.117 and 0.251 ground returns per m^2, respectively, and a 9.2% and 6.7% ratio of pulses to ground returns. Figure 1.5 shows where these ground returns fell.

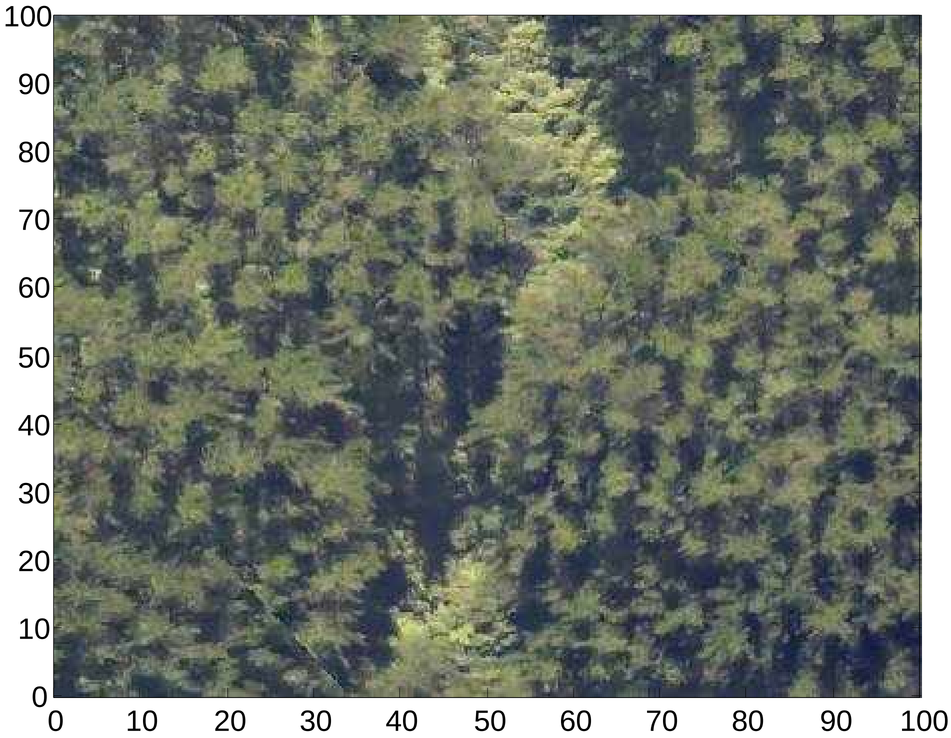
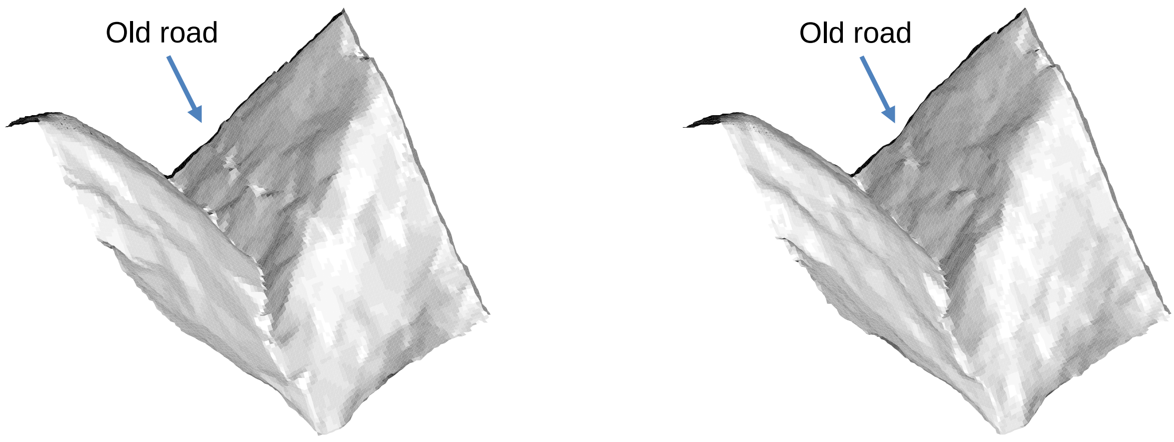


Figure 1.3 – Location of an old road next to a river. In this figure and subsequent ones the values on the horizontal and vertical axes are distance (in metres).

Figure 1.4 – DEMs generated of the same area for: left) 1.3 pulses per m^2 (0.117 ground returns per



m^2) and right) 3.8 pulses per m^2 (0.251 ground returns per m^2)

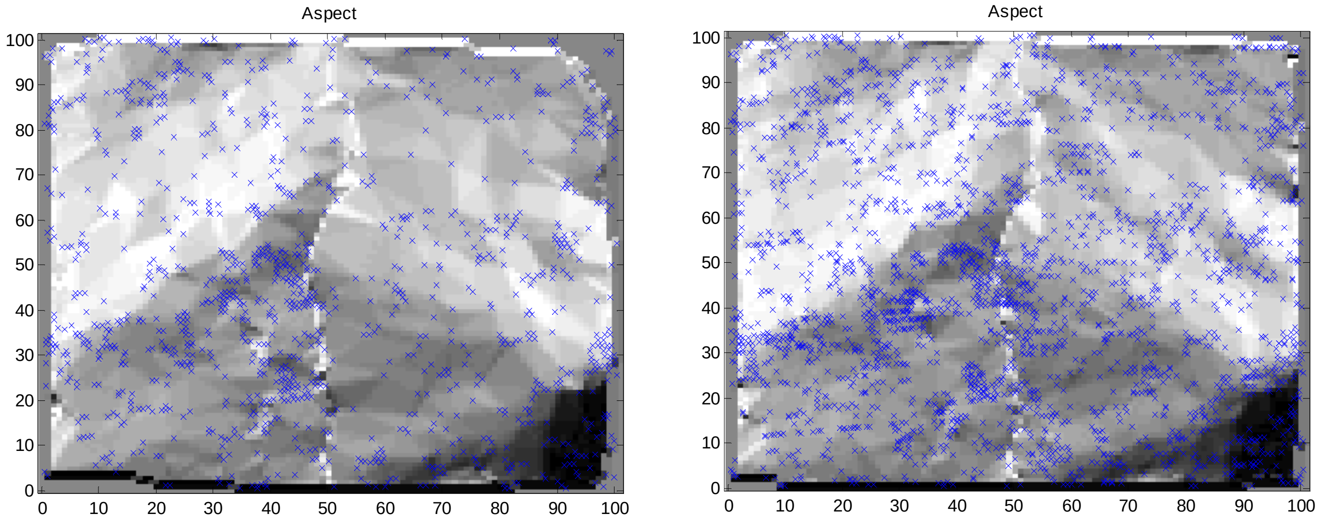


Figure 1.5 – Aspect-shaded DEMs of the same area for: left) 1.3 pulses per m^2 (0.117 ground returns per m^2) and right) 3.8 pulses per m^2 (0.251 ground returns per m^2). Ground returns are shown as blue crosses.

Figure 1.5 shows that ground returns are clustered around openings such as roads, slips and rivers. A close inspection of figure 1.4 reveals that the DEM is more triangulated in the 1 pulse per m^2 than the 2 pulses per m^2, although anomalously and intriguingly the old road is actually more visible. In this site it is hard to visually assess whether the additional ground returns provided by 2 pulses per m^2 improved the DEM significantly.

In figure 1.6 we show the aerial photography of a hairpin corner cut into the cutover. As there was no tree cover most pulses yielded a ground return. The 2 pulses per m^2 dataset actually covered this area at a minimum 3.49 pulses per m^2 – which gave a minimum of 2.59 ground returns per m^2. The 1 pulse per m^2 was covered at a minimum of 1.60 pulses per m^2 which yielded a minimum of 1.53 ground returns per m^2. Note that the two DEMs in figure 1.7 are almost identical. This suggests that for this kind of engineering (roading etc.) in cutover (or unvegetated sites), 1 pulse per m^2 is more than adequate.

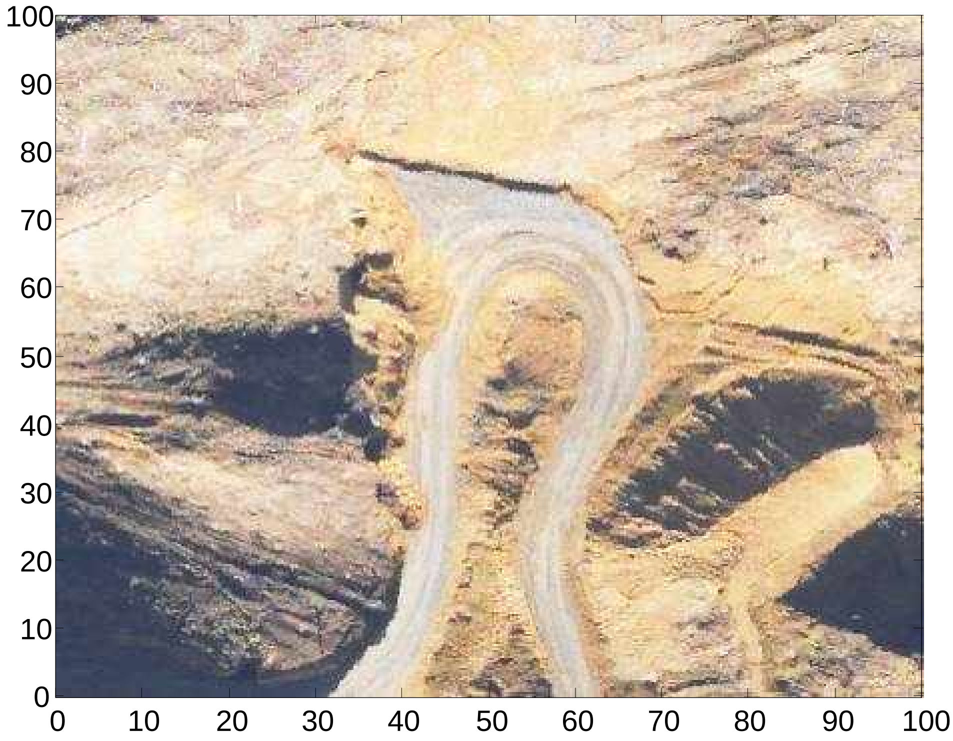


Figure 1.6 – Hairpin corner cut into the cutover.

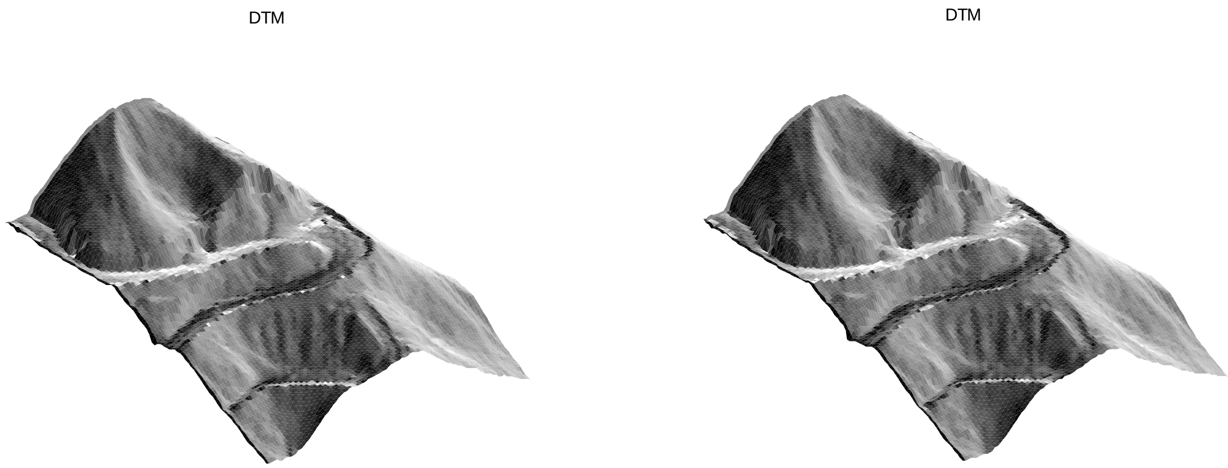


Figure 1.7 – Two aspect shaded DEMs from: left) 1.60 pulses per m^2 (1.53 ground returns per m^2) and right) 3.49 pulses per m^2 (2.59 ground returns per m^2)

As a final example, in figure 1.8 we show a ridge near a steep face with a river at the bottom (as GPSed out in the field), and in figure 1.9 the two DEMs at the two different pulse densities.

Note how in figure 1.9 the river is less clearly defined at the lower resolution (left hand figure). The high scattering of heavy foliage has led to a low ground return density, and at 2.35 pulses per m^2 the river could not be as clearly defined. Whether this is important or not would depend on the engineering required. If the river needed to be crossed or redirected, this level of detail is important, but if the river were not touched then it wouldn't.

Figure 1.8 – Ridge next to steep face

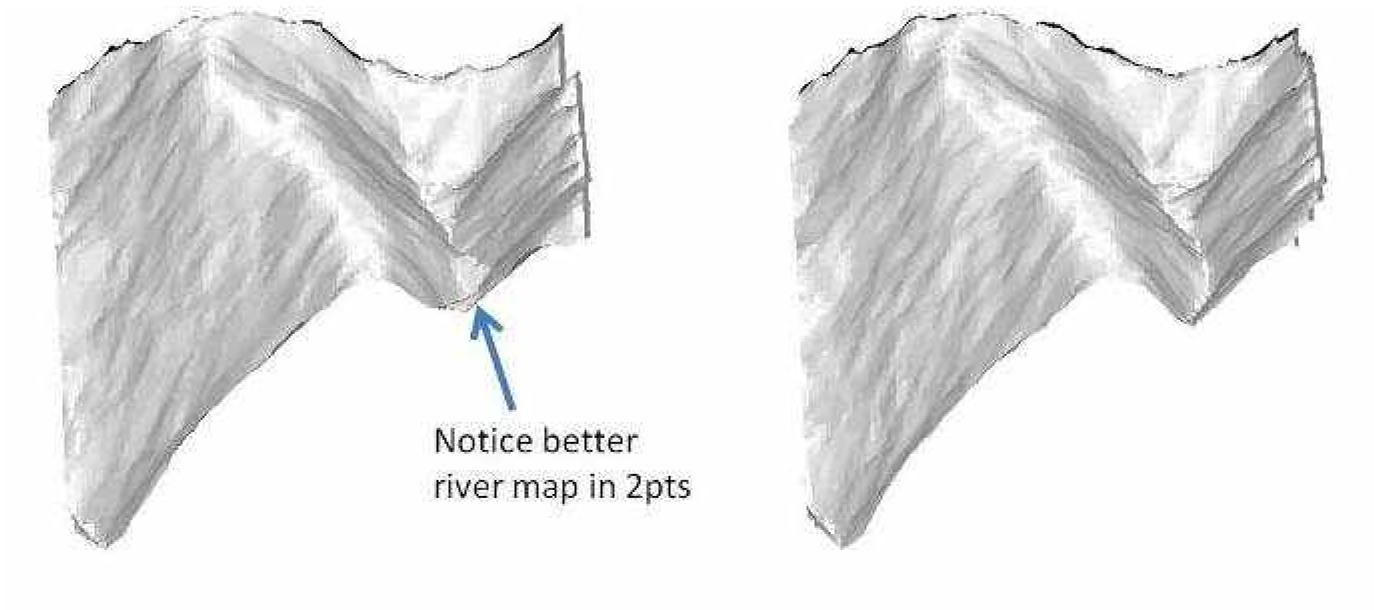


Figure 1.9 – DEMs generated at two different resolutions showing left) 2.35 pulses per m^2 (0.196 ground returns per m^2) and right) 3.72 pulses per m^2 (0.284 ground returns per m^2). The arrow on the left map shows an area that is not as well described at the lower resolution.

Even though the DEMs look very similar to the naked eye, Figure 1.10 shows the difference between the two found by subtracting the heights of each respective 1m^2 pixel. A positive value (red) shows that the low pulse density placed the DEM higher than the high pulse density DEM, and vice versa for blue (negative). The differences in height could be up to ±3 m in places. A large difference is shown over the river (remembering that the 3D DEM was facing south and this plot is facing north), but small discrepancies appear across the whole landscape. Figure 1.11 shows a histogram of the differences, which shows that the two DEMs have no bias and the average difference is almost zero. However, there is an error distribution that falls off exponentially. By taking the 90th percentile of the absolute difference, we can say that 90% of the time the DEM taken at 2.35 pulses per m^2 is within 0.92 m of the DEM taken at 3.72 pulses per m^2. In comparison, in the cutover the DEM taken at 1.60 pulses per m^2 was 90% within 0.25 m of the DEM taken at 3.49 pulses per m^2, showing that there was much less benefit to having the higher pulse density.

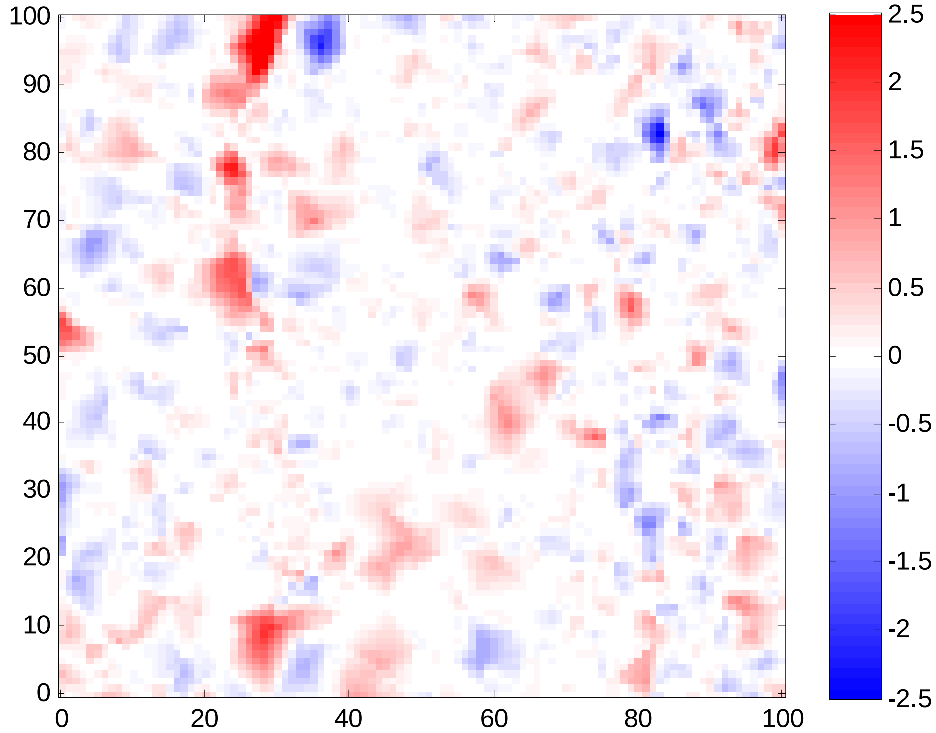


Figure 1.10 – Difference between the two DEMs in figure 1.9

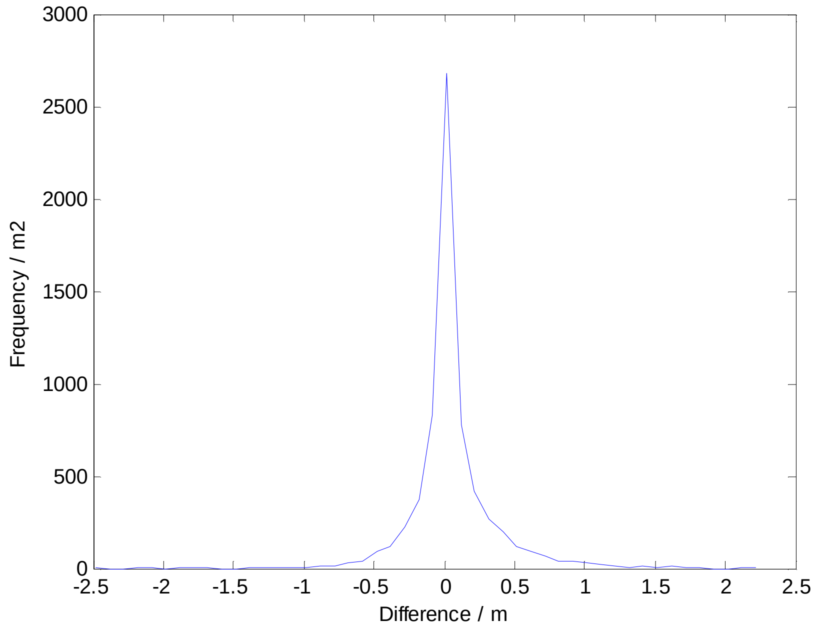


Figure 1.11 – Histogram of differences (shown in Figure 1.10) between DEMs.

Table 1.1 summarises the nine sites that were GPSed in the field as sites of interest (including these examples here), showing the pulse density, return density, ground return density, ground return ratio, and 90% difference between the two DEMs. The aerial imagery and DEMs for each site (at the higher pulse density) are in Appendix 1. Table 1.1 shows that 90% of the difference between the two DEMs was less than 0.25 m in the two sites with cutover, but up to 1.68 m in areas with heavy forest cover. It is a fair assumption that DEMs with more ground returns will be better, so in these vegetated sites there is a clear benefit from having the extra pulses. In the cutover areas there was little benefit from the extra pulses.

Table 1.1 – Pulse densities, ground return densities and DEM difference for nine sites between two flights with a minimum of 1 pulse per m^2 and 2 pulses per m^2. Features are sorted in order of descending 90% differences.

Description	Cover	Pulse density (m^{-2})		Ground return density (m^{-2})		Ground return ratio		90% difference (m)
		Min 1pulse per m^2	Min 2pulses per m^2	Min 1pulse per m^2	Min 2pulses per m^2	Min 1pulse per m^2	Min 2pulses per m^2	
Nose of ridge	Pine	2.10	3.24	0.17	0.27	8.3%	8.3%	1.68
Old road above river	Dense pine and river	1.28	3.75	0.12	0.25	9.1%	6.7%	1.62
Steep gully	Pine and native	1.22	4.59	0.13	0.32	10.9%	7.0%	1.30
Top of a ridgeline	Pine	1.22	2.65	0.11	0.22	9.1%	8.4%	1.13
Ridge end by steep face	Pine and dense native bush	2.35	3.72	0.20	0.28	8.3%	7.6%	0.92
Large slip near river in pine forest, 100m long x 10m wide	Pine and slip	2.49	3.84	0.31	0.48	12.4%	12.4%	0.81
Ridge with steep drop off to west	Dense pine	2.41	3.67	0.16	0.25	6.8%	6.9%	0.63
Hairpin road in cutover	Cutover	1.60	3.49	1.53	2.59	95.4%	74.1%	0.25
Cutover	Cutover	2.38	3.87	1.77	2.46	74.4%	63.5%	0.14

To investigate this more rigorously, 4307 randomly located 40x40-m samples were cut from the 1pulse per m^2 and the 2 pulses per m^2 datasets. The difference between the central 20x20 m was found for each (to eliminate edge interpolation effects). The difference was found for each of the 400 1m^2 pixels, and sorted into a distribution (such as Figure 1.11). As a means of quantifying this distribution, the mean difference and the 90th percentile of the absolute difference were found. The samples were grouped into Radiata, Native or Cutover based on whether they fell into the harvest areas supplied by the forest manager, and whether those harvest areas had been felled. Land cover was not manually checked for all 4307 samples, so there will inevitably be a small proportion of incorrectly classified samples. This is not a major problem given how much land cover varies within each of those categories anyway.

The mean difference over all samples was found to be 0.052 m – meaning that the DEM flown at 1 pulse per m^2 had a tendency to (slightly) overestimate ground height. This varied from 0.063m over native samples, to 0.048m over radiata and 0.029m over cutover (where the difference would be expected to be less). This tendency for lower-resolution DEMs to slightly overestimate ground heights matches the personal experiences of one of the engineers working with these data.

Figure 1.12 shows a scatterplot of the 90th percentile of difference against the 1 pulse per m^2 ground return density. We see that the difference between the DEMs reduces as the ground return density increases, indicating that the benefits of using a higher pulse density reduce. At very low ground return densities (<0.1ground return per m^2) the 90th percentile of difference in DEMs could be as much as 6.3m, whereas when the ground return density was greater than 2 per m^2 the DEMs difference never exceeded 0.27 m. This conclusively shows that DEM reliability is related to ground return density (amongst many other factors).

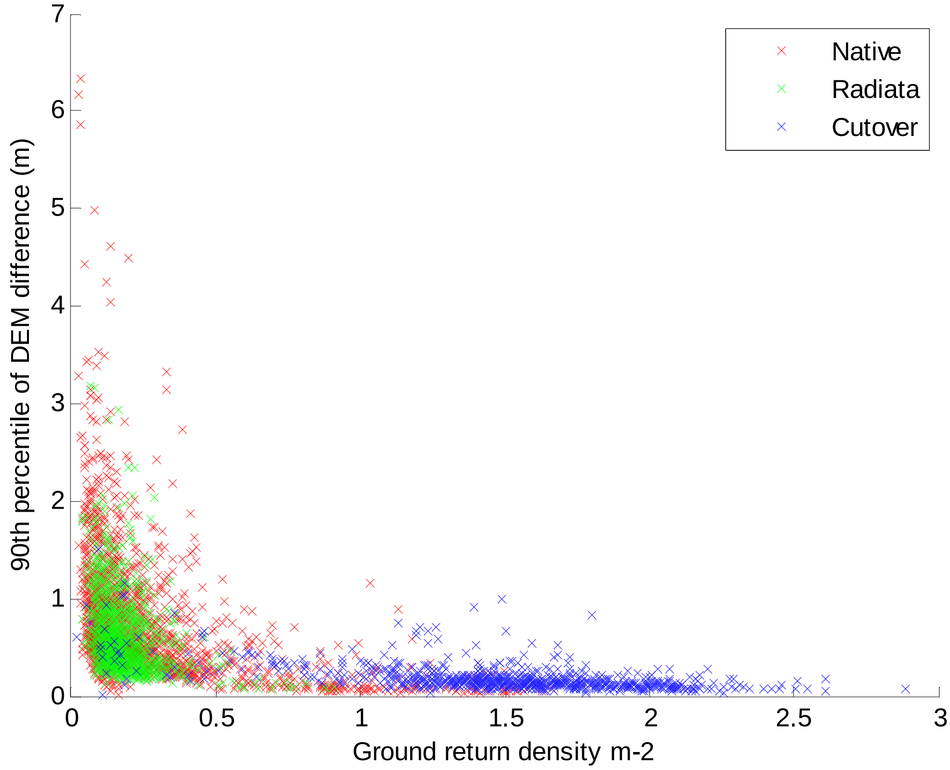


Figure 1.12 – Scatterplot of 90th percentile of DEM difference between 1 and 2 pulses per m^2, vs. ground return density at 1 pulse per m^2

To uphold the assumption that the DEM at 2 pulses per m^2 is better than the DEM at 1 pulse per m^2 (and therefore making the DEM comparison meaningful), these data can be thinned to include only samples where the ground return density at 2 pulses per m^2 was at least double that at 1 pulse per m^2. This left 761 points. In Figure 1.13 these points are plotted, again as the 90th percentile of difference vs. ground return density at 1 pulse per m^2. A line of best fit has been added with the equation $y = 0.1485x^{-0.6957}$. Although this line of best fit has an R^2 of 27%, it is intended only as a 'rule-of-thumb' to show the diminishing benefit of increasing ground return density. According to this function, to get a DEM which should be 90% within ±1 m of a DEM taken at double the ground return density, 0.06 ground returns per m^2 will do on average. To get it within ±0.5 m, 0.17 ground returns per m^2 are required, and within ±0.25 m you'll need 0.47 per m^2. Given the improvement in reliability with ground return density, and the desirability of a DEM within ±0.5 m of a 'superior' DEM, the recommended minimum ground return density for a DEM used for engineering design is 0.2 ground returns per m^2 (equal to 1 ground return per 5 m^2). LiDAR with a ground return density lower than this may be useful to gain a strategic overview of the forest for route planning purposes. It is however still up to individual engineers to look at DEMs such as Figure 1.3 to decide if the lower resolution pulse density is adequate for their forest.

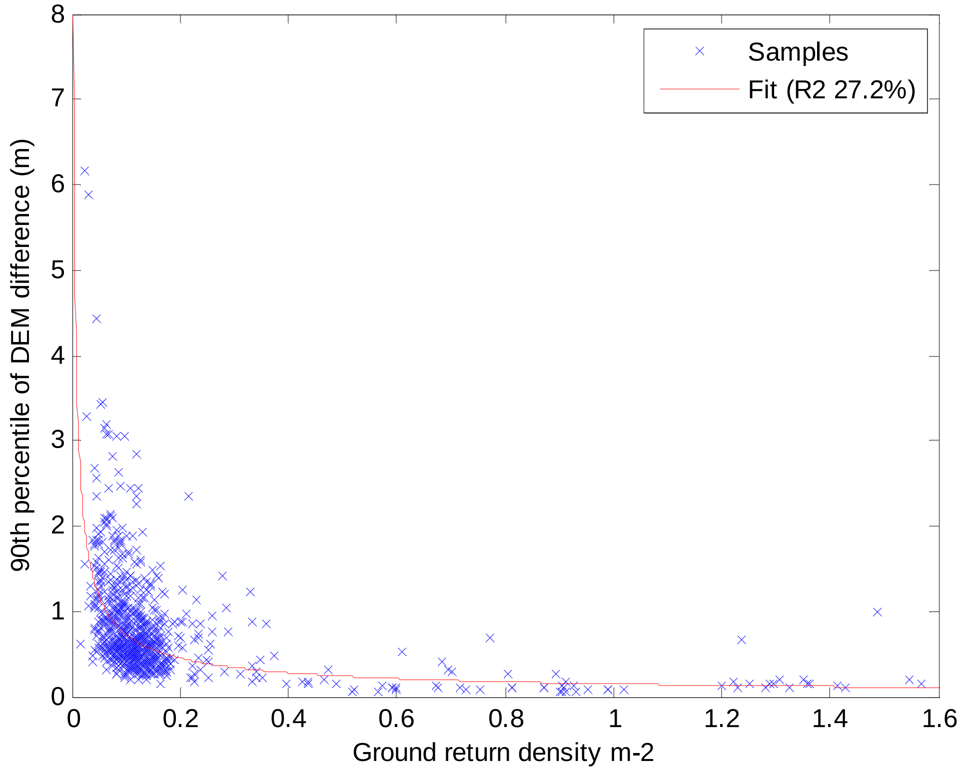


Figure 1.13 – Scatterplot of 90th percentile of DEM difference between 1 and 2 pulses per m^2, vs. ground return density at 1 pulse per m^2 with line of best fit.

In the above analysis, we have been comparing a DEM generated at a low pulse density with one created at a higher pulse density. The (commonly made) assumption is that the DEM at a higher pulse density is based on more data, and hence will be more accurate. This assumption seems reasonable, but ultimately needs validation with real-world measurement. The managers of this forest intend to use field surveying techniques to manually determine a DEM in a few small sections, and this will provide an excellent reference for our assumption. These data are expected to become available within the next year, and will be duly reported on. Similarly, this study does not determine the accuracy of DEMs created using pulse densities of less than 1 pulse per m^2. In the near future the same area will be flown at 0.19 pulses per m^2 as part of the BOPLAS project (expected end of summer 2012), and a report on these data will follow.

Objective 2: Influence of Stand and Site Conditions on the DEM

Summary

In Objective 1 we showed that the percentage of ground returns varies substantially according to land cover. To quantify this, the LUCAS LiDAR and field data, which consists of several hundred plots that span New Zealand on a 4-km grid, were used. Although only forested sites were sampled, this still covers a wide range of forestry conditions. By determining the ratio of ground returns to incident pulses for each site (GR) (as well as the site conditions of stocking, species, age, non-crop stocking and slope), a model was developed to gauge the average number of ground returns that could be expected for a given number of incident pulses.

Within this dataset GR averaged 30.5% ranging from 0.73 to 92.2%. The final model of GR included stand age, crop stocking, non-crop stocking and slope, and accounted for 48% of the variance in GR with RMSE of 13.9%. GR declined exponentially as stand age, crop and non-crop stocking increased and declined linearly with increases in slope. GR was not substantially affected by either the number of pulses per m^2 or whether the stand comprised radiata pine or Douglas-fir.

A simple spreadsheet model has been constructed (and is attached to this report) describing the minimum pulse density required to generate an accurate DEM, under a range of stand conditions. This model is based on outputs from Objectives 1 and 2.

Methods

Dataset Used

The dataset used was from a national inventory of plantation forests undertaken to measure and monitor temporal change in national carbon stocks. This inventory was undertaken to enable New Zealand to meet its obligations under the Kyoto Protocol and the United Nations Framework Convention on Climate Change.[2]

From the plots available from the data-managers *Interpine*, 361 plots (or 92%) were established within radiata pine (*Pinus. radiata),* with a lesser number of plots in Douglas-fir (*Pseudotsuga mensieii*) (20 plots, 5%). As plots in species other than radiata pine or Douglas-fir comprised less that 3% of the total, these were excluded from the analysis, as replication was inadequate to test for a species effect. After these exclusions, 381 plots were available for the modelling. The distribution of these plots is shown in Figure 2.1.

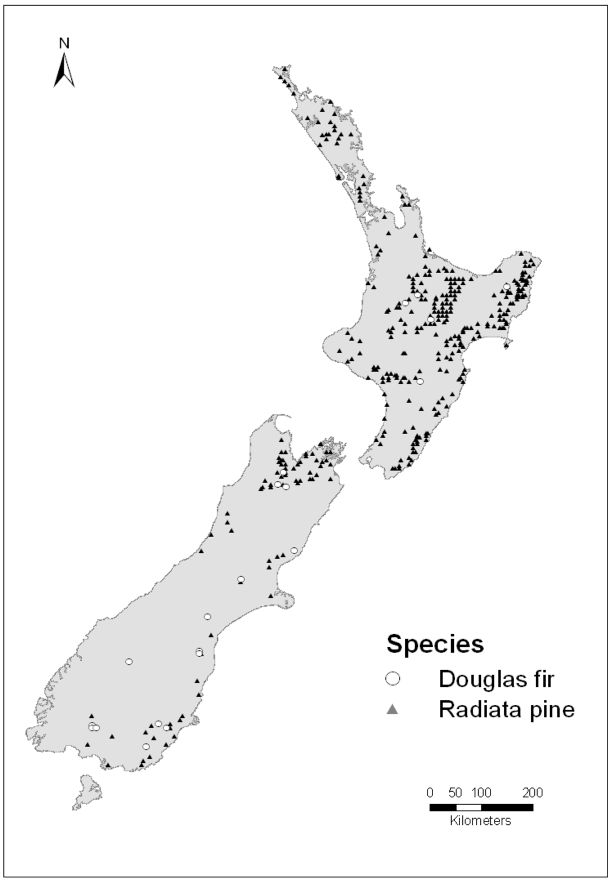


Figure 2.1 – Distribution of LUCAS sample plots used throughout New Zealand.

All plots were measured in the field by Interpine contractors using a slope-corrected area of 0.06 ha. The plots were circular, and plot centres were located using a 12-channel differential GPS to within ± 3 m.

The LiDAR survey was flown in February 2008 for the post-1990 forests, and 2010 for the pre-1989 forests, using a small footprint Optech ALTM 3100EA system. The LiDAR settings used achieved pulse densities of at least 3 pulses per m^2.

Analysis

Statistical models used to predict the percentage of ground returns to incident pulses (GR) accommodated a range of linear and non-linear functional forms. Variables were introduced sequentially into each model starting with the variable that exhibited the strongest correlation, until further additions were either (i) not significant, (ii) not biologically reasonable or (iii) did not markedly improve model precision.

Variable selection was undertaken manually, and plots of residuals were examined prior to variable addition to ensure that the variable was included in the model using the least biased functional form.

Model precision was determined using the coefficient of determination (R^2) and the root mean square error (RMSE). Model bias was determined through plotting predicted GR against measured GR, and residual values (measured GR – predicted values) against predicted GR and all independent variables in the model. Model generality was assessed through plotting residual values against a number of key variables not included in the model.

Results

Data Range

The percentage of ground returns (GR) averaged 30.5% and ranged widely from 0.73 to 92.2%. The greatest percentage of GR occurred between 20-30% and the distribution was right skewed (Figure 2.2).

Plots were located within stands aged between 0 and 38 years. They covered virtually all aspects (0–359°) and were located on sites with slopes ranging from flat to very steep (maximum slope of 45°). Crop stocking ranged from 0 to 2,283 stems ha^{-1} while non-crop stocking ranged from 0 to 10,833 stems ha^{-1} (Table 2.2).

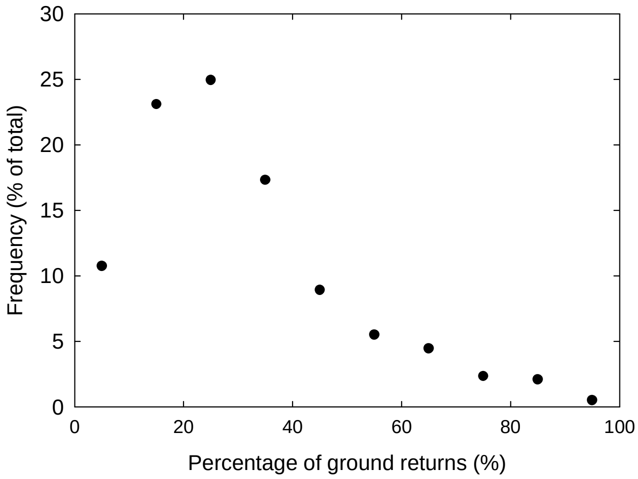


Figure 2.2 – Frequency distribution of the percentage of ground returns.

Correlations between GR and Independent Variables

GR was most strongly related to total stocking (Fig. 2.3), non-crop stocking, crop-stocking, slope and stand age (Fig.2.3, Table 2.2). Using a linear model, all variables showed significant negative relationships with GR, as indicated by the negative correlation coefficients (Table 2.2). For non-crop stocking (S_{nc}), the strength of the relationship diminished as smaller diameter plants were excluded from the analysis (Table 2.2). Neither aspect nor the incident pulse density was significantly related to GR using simple linear equations (Table 2.2) or more complex forms with curvilinearity (data not shown).

Table 2.2 – Mean and range for variables used in analyses. Also shown are summary statistics describing the strength and significance of the relationship with the percentage of ground returns. Shown are the correlation coefficient (*R*) and *P*-value for simple linear correlations. The total number of plots used in analyses was 381.

Term	Mean	Range	*R*	*P*-value
Age (years)	13.7	0-38	-0.30	<0.0001
Stocking –all (stems ha^{-1})	872	17-11,183	-0.37	<0.0001
Crop stocking (stems ha^{-1})	434	0-2,283	-0.14	0.0048
Non-crop stocking (S_{nc}) – all (stems ha^{-1})	438	0-10,833	-0.34	<0.0001
S_{nc} : Diameter (*D*) > 250 mm (stems ha^{-1})	7.1	0-483	-0.14	0.0058
S_{nc} : *D* > 275 mm (stems ha^{-1})	5.2	0-433	-0.13	0.013
S_{nc} : *D* > 300 mm (stems ha^{-1})	3.5	0-367	-0.12	0.025
S_{nc} : *D* > 350 mm (stems ha^{-1})	1.9	0-267	-0.11	0.040
S_{nc} : *D* > 500 mm (stems ha^{-1})	0.39	0-50	-0.11	0.036
S_{nc} : *D* > 750 mm (stems ha^{-1})	0.09	0-17	-0.07	0.18
S_{nc} : *D* > 1000 mm (stems ha^{-1})	0.04	0-17	-0.05	0.29
Aspect (º)	185	0-359	-0.01	0.80
Slope (º)	16.9	0.2-44.5	-0.23	<0.0001
Incident pulse density (pulses m^{-2})	3.84	2.27-10.38	-0.05	0.32

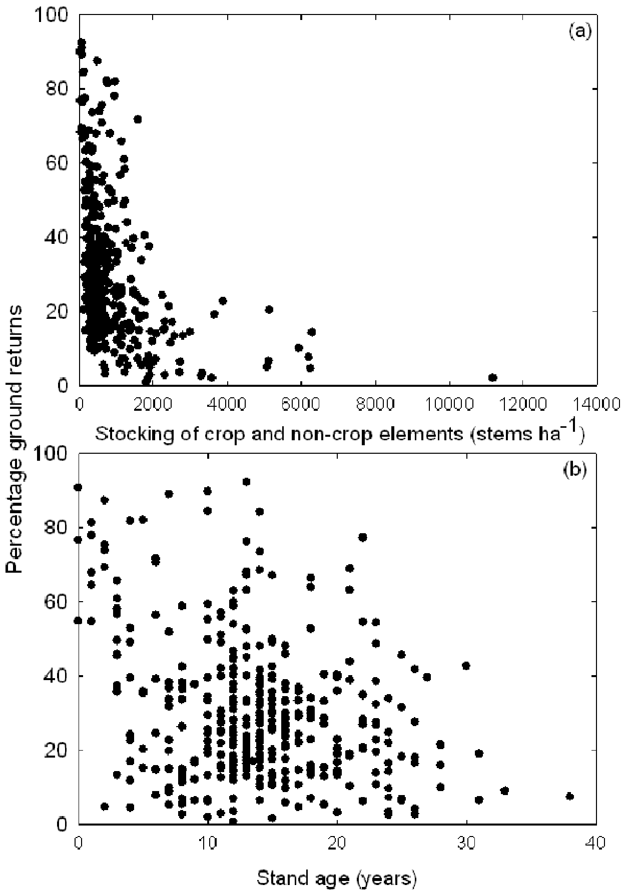


Figure 2.3. Relationship between percentage of ground returns and (a) stocking of crop and non-crop elements and (b) stand age.

Regression Model to Predict GR

The final regression model used to predict GR included age, crop stocking (S_c) and slope. The stocking of all non-crop stems (S_{nc}) was also included in the model. The final model formulation was as follows:

$$GR = 27.899e^{-0.0011S_{nc}} + 47.1411e^{-0.1744Age} + 28.3712e^{-0.00348S_c} - 0.5863Slope \quad (1)$$

The final model accounted for 48% of the variance in the dataset and had RMSE of 13.9%.

Predicted values of GR using the final model exhibited little apparent bias against actual values (Figure 2.4), and residual values for the model exhibited little apparent bias against any of the variables included in the model or aspect (Figure 2.5). Examination of residual values showed species had little effect on the relationship.

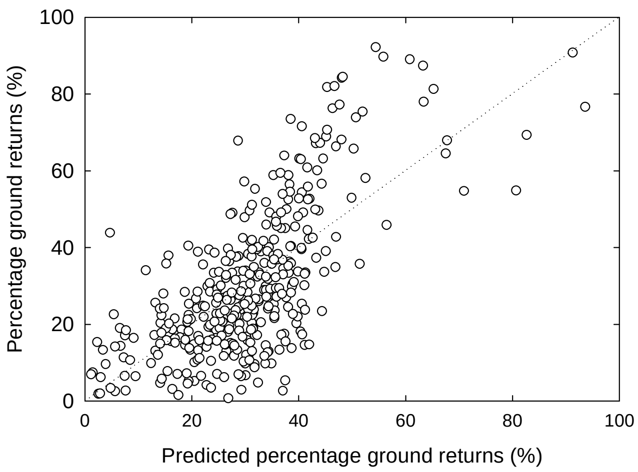


Figure 2.4 – Relationship between predicted and actual percentage ground returns.

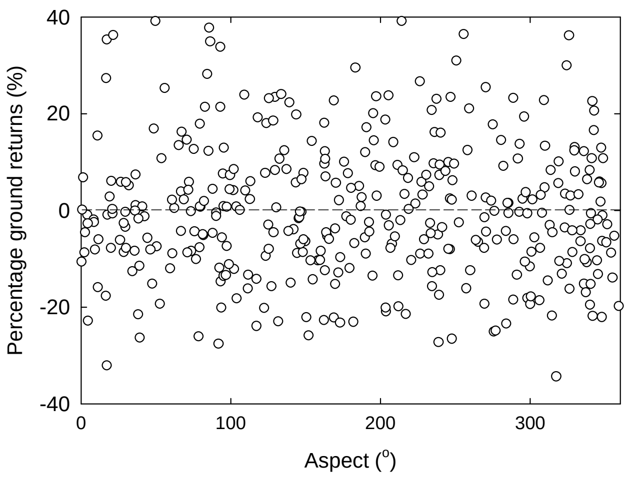


Figure 2.5 – Relationship between residual percentage ground returns and stand aspect.

Partial response functions, generated by holding all model terms at average values, apart from the variable shown, are described in Figure 2.6. These functions show that GR declined exponentially with stand age, and both crop and non-crop stocking. There was a linear decline in GR with stand age. GR was most sensitive to stand age, as demonstrated by the considerable reduction in GR over the first 20 years, from ca. 61% to 15%. However, at stand ages above 20 years little decline from 15% was observed.

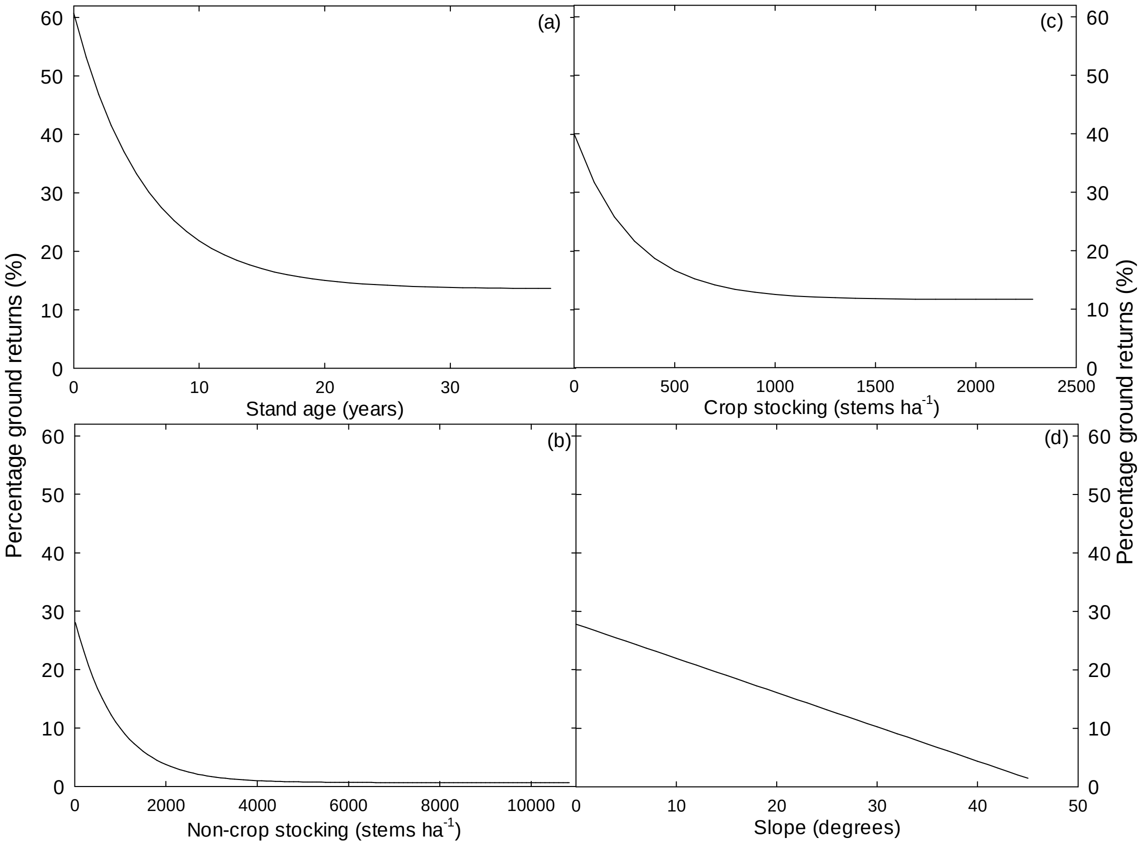


Figure 2.6 – Partial response functions showing variation in percentage ground returns as a function of (a) stand age, (b) non-crop stocking, (c) crop stocking and (d) slope.

As a DEM is generally generated at harvest, Table 2.3 shows the percentage of ground returns around varying slopes, and crop stockings, at an average harvest age of 28 years. Note that little change would be expected if harvest age was earlier than this, as GR was found to be generally insensitive to stand age above an age of 20 years. As GR was relatively invariant to crop stocking above a stocking of 1,000 stems ha^{-1}, no values are shown at stockings above these. Values are shown for a mean non-crop stocking of 438 stems ha^{-1} and the most common non-crop stocking of 0 stems ha^{-1}, as this latter stocking represented 48% of observations in the dataset. This can be interpreted as 'typical' forests with and without non-crop trees present

Table 2.3 – Percentage of ground returns as a function of slope, crop stocking for the mean non-crop stocking (438 stems ha^{-1}) and the most common non-crop stocking (0 stems ha^{-1}). All values are shown for the mean New Zealand rotation length of 28 years. Note that a minimum value of 0.7% was assumed for GR as this was the lowest value recorded in the LUCAS dataset.

	Non-crop stocking of 0 stems ha^{-1}				Non-crop stocking 438 stems ha^{-1}			
	Crop stocking				Crop stocking			
Slope	250	500	750	1000	250	500	750	1000
0	40	33	30	29	29	23	20	18
5	37	30	27	26	27	20	17	16
10	34	27	24	23	24	17	14	13
15	31	24	22	20	21	14	11	10
20	28	22	19	17	18	11	8	7
25	25	19	16	14	15	8	5	4
30	23	16	13	12	12	5	2	1
35	20	13	10	9	9	2	0.7	0.7
40	17	10	7	6	6	0.7	0.7	0.7
45	14	7	4	3	3	0.7	0.7	0.7

Results show a wide range in GR from 40% under the lowest slope, crop and non-crop stocking to 0.7% for high values of crop stocking and slope under mean values of non-crop stocking. The predicted values were constrained to the lowest value in the LUCAS dataset of 0.7%.

Using the minimum of 0.2 ground returns m^{-2} recommended in Objective 1, the predicted GR in Table 2.3 can be used to formulate broad guidelines for development of an accurate DEM. Table 2.4 shows recommended minimum pulse densities for the stand conditions outlined in Table 2.3. It should be emphasised that as the RMSE was approximately 14% (effectively the average error), these values should be treated as indicative rather than absolute.

Table 2.4 shows a wide range in minimum pulse densities. For stands with no non-crop element, values are less than 7 pulses m^{-2} under all combinations of slope and crop stocking. For stands with an average non-crop stocking minimum pulse densities are relatively low for low crop stockings and slopes, but increase markedly to 27 pulses m^{-2} for high slopes and high crop stockings.

Table 2.4 – Minimum pulse density (pulses m^{-2}) required to produce at least 0.2 ground returns m^{-2} as a function of slope, crop stocking for the mean non-crop stocking (438 stems ha^{-1}) and the most common non-crop stocking (0 stems ha^{-1}). All values are shown for the mean New Zealand rotation length of 28 years.

	Non-crop stocking of 0 stems ha^{-1}				Non-crop stocking 438 stems ha^{-1}			
	Crop stocking				Crop stocking			
Slope	250	500	750	1000	250	500	750	1000
0	0.5	0.6	0.7	0.7	0.7	0.9	1.0	1.1
5	0.5	0.7	0.7	0.8	0.7	1.0	1.2	1.3
10	0.6	0.7	0.8	0.9	0.8	1.2	1.4	1.5
15	0.6	0.8	0.9	1.0	1.0	1.4	1.8	2.0
20	0.7	0.9	1.1	1.2	1.1	1.8	2.5	2.9
25	0.8	1.1	1.3	1.4	1.3	2.5	4.0	5.0
30	0.9	1.3	1.5	1.7	1.7	4.0	10	20
35	1.0	1.5	2.0	2.2	2.2	10	27	27
40	1.2	2.0	2.9	3.3	3.3	27	27	27
45	1.4	2.9	5.0	6.7	6.7	27	27	27

A spreadsheet showing the minimum pulse density as a function of slope, stand age, crop and non-crop stocking is included with this report.

Objective 3: Minimum Pulse Density for Volume Estimation with a Prior DEM

Summary

In this section we give guidelines for the minimum pulse density required for LiDAR-based volume estimation in forests that already have a high quality DEM (probably from an earlier LiDAR flight). Although a quality DEM is crucial for accurate volume estimation from LiDAR, once this is acquired subsequent flights can be flown at reduced pulse densities and still get good volume estimates. Using the LUCAS dataset, pulse densities could be reduced to around 100 pulses per plot (0.33 pulses per m^2 for 0.03-ha plots; 0.17 pulses per m^2 for 0.06-ha plots) without losing accuracy in the volume function. Plot size was a limiting factor and should not be reduced below a threshold of 0.03 ha. LiDAR volume functions were relatively stable across pulse densities and plot sizes until the above limitations were reached, although plot size stability is dependent on how uniform the trees in the plot are. When the plots are small relative to their homogeneity (i.e. the plot composition varies significantly if the plot is moved even slightly), scale effects lead to poor curve fitting and varying coefficients. 0.03ha as a minimum is a guideline, and in stands with high variability and low stockings plots will need to be larger.

Using a Pre-existing DEM

DEMs require higher pulse densities than canopy metrics for volume estimation. It is essential to get a good horizontal spread of ground returns for a DEM, as a DEM is assumed to be horizontally heterogeneous (if your DEM is completely flat then why are you bothering to measure it?). LiDAR volume functions on the other hand are based on the assumption that there is a reasonable level of homogeneity across the trees in the plot (i.e. the trees within a small area are roughly similar), and hence a thorough horizontal coverage is less important. However, the canopy metrics for volume estimation are reliant on a good DEM, as the canopy returns must be ‘degrounded’ to convert them from heights above sea-level to heights above ground. Because the ground changes significantly only under exceptional circumstances, it is possible for forest owners to fly once at a high pulse density for a DEM, and then re-fly some years later at a lower pulse density to obtain accurate estimates of standing volume. By using the existing DEM, quality LiDAR canopy metrics can be obtained at a lower pulse density and hence lower cost.

In this object we thin out the LIDAR point clouds from the LUCAS plots (see Methods in Objective 2 for dataset description), and assess the viability of using these reduced datasets for volume estimation. The technique of thinning LiDAR point clouds is described in Gobakken and Naesset[3], who use a DEM from the highest pulse density and recalculated LiDAR metrics for thinned down point clouds. These metrics were used to find mean tree height, stand basal area and stand volume. It was found that return densities down to 0.06 returns per m^2 created only a minor increase in error. When thinning out the datasets, all returns were removed from a randomly selected proportion of the pulses (i.e. at 50% thinning, all returns belonging to a 50% sample of pulses were removed, as opposed to simply removing 50% of returns, which is erroneous). It should be noted that this is not quite the same as actually *flying* at a lower pulse density, as factors such as PRF setting and plane altitude will affect the intensity per pulse and hence their ability to penetrate the canopy. This may lead to slightly different values for the metrics, although as long as this change is consistent across the forest and the volume function is recalibrated for the new data, it is only a minor caveat.

Variation of LiDAR Metrics

LiDAR metrics commonly used in volume functions include percentiles of the height distribution, e.g. the 30th or 95th height percentiles. This is the height above ground that 30% or 95% of all returns were under for a given sample. Also canopy cover is often used, which is the percentage of returns above a given cut off (typically 0.5 m but dependent on understorey), divided by the total number of returns. In Figure 3.1 we show how three LiDAR metrics vary from their original values as the pulse density decreases for a 0.06 ha plot.

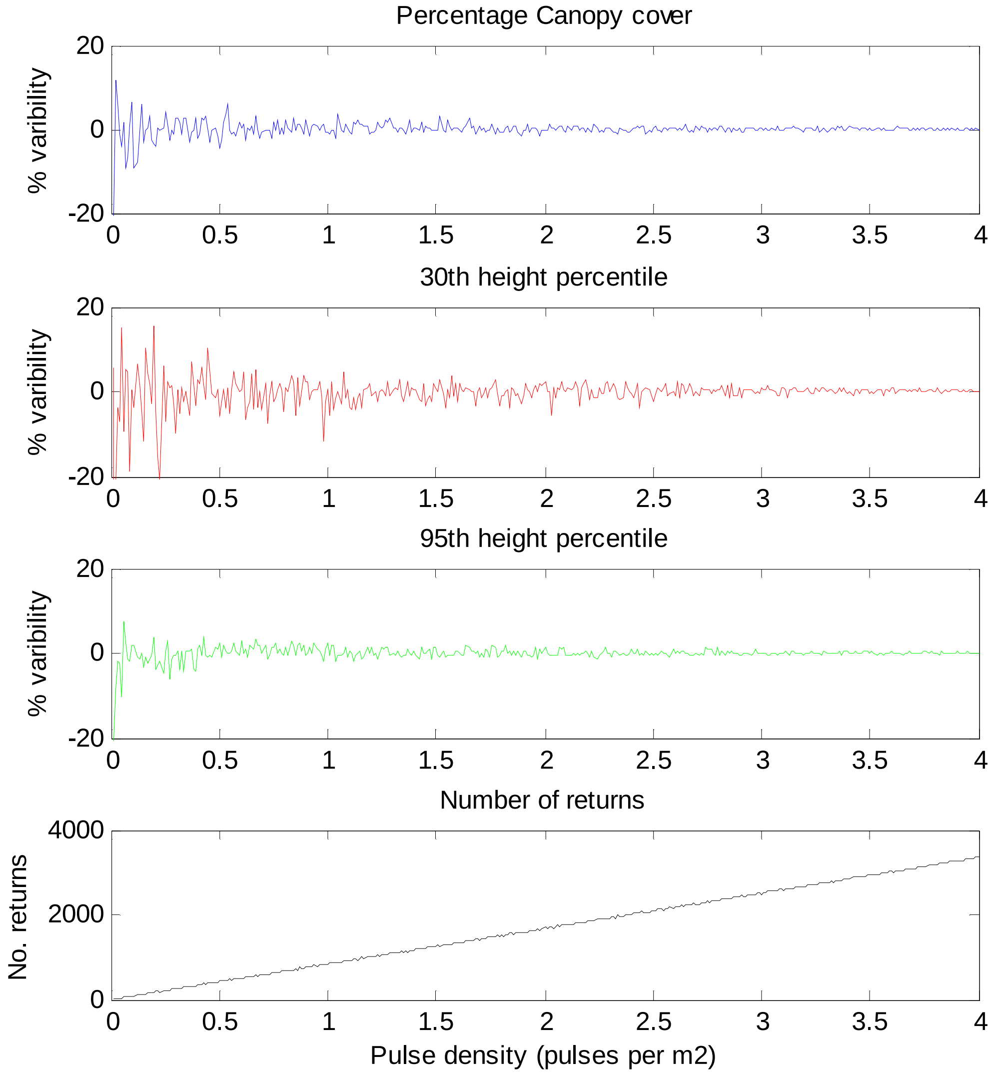


Figure 3.1 – Percentage change of LiDAR metrics for one plot as a function of pulse density for (from top to bottom) percentage canopy cover, 30th height percentile and 95th height percentile. Shown on the bottom is the number of returns in relation to the pulse density.

At lower pulse densities when the variables themselves have a higher degree of uncertainty the fit of a volume function is reduced. However, Figure 3.1 shows that the pulse density can be reduced a long way until significant variation occurs.

Variation of Volume Estimation across Pulse Density

A set of LiDAR metrics (30^{th}, 70^{th} and 95^{th} height percentile, mean height and canopy cover) was derived for 227 LUCAS plots using the unthinned LiDAR data. A linear regression was used to derive a volume function of best fit from these metrics, the best form of which was found to be a combination of the 30^{th} height percentile and canopy cover of the form

$$V = \alpha P_{30} + \beta C + \gamma \qquad (2)$$

V is the predicted volume in m^3 per hectare, P_{30} is the 30^{th} height percentile, *C* is the canopy cover, and α, β and γ are the regression coefficients. This matches the findings of Stephens *et. al.*[4] who were looking to link LiDAR metrics with carbon. The R^2 of this function is 0.76, which is slightly lower than the values from similar experiments such as Gonzalez-Aracil[5] who obtained an R^2 of 0.84 and Watt and Watt [1] (R^2 0.83). This is due in part to a slightly different set of assumptions and plots, and also the use of a quadratic function form in both Gonzalez-Aracil and Watt and Watt which for reasons explained below we have avoided in this study.

Once the form of the volume function was established with the unthinned dataset, then the metrics were recalculated at 84 different pulse densities ranging from 4 pulses per m^2 to 0.01 pulses per m^2. As before, a volume function was then derived to link these thinned-LiDAR metrics to the volume. The coefficients (but not the form) of the volume function were allowed to vary at reduced pulse densities to maximise the quality of the fit, which also enables us to investigate the stability of the function.

Figure 3.2 shows how the R^2 value of the volume function varied with pulse density. As would be expected, the R^2 value declines, but only shows a marked decrease once the pulse density falls below 0.1 pulses per m^2. The coefficients in the volume function and the variation in their values compared to the 'original' values at 4 pulses per m^2 are shown in Figure 3.3. The coefficients are almost constant above 1 pulse per m^2 (varying by less than 3%), and only vary by more than 10% with pulse densities less than 0.1 pulses per m^2. It is reassuring that the volume function is stable across most pulse densities, as pulse density would naturally vary across any LiDAR acquisition (see Figure 1.2). Indeed, if the coefficients are fixed at their values found at 4pulses per m^2, the drop in R^2 is on average 0.01% from the value obtained for that pulse density with varying coefficients (figure 3.2), and never more than 0.5%. This is too small to be significant, so it is completely appropriate to use the same LiDAR volume function across different pulse densities.

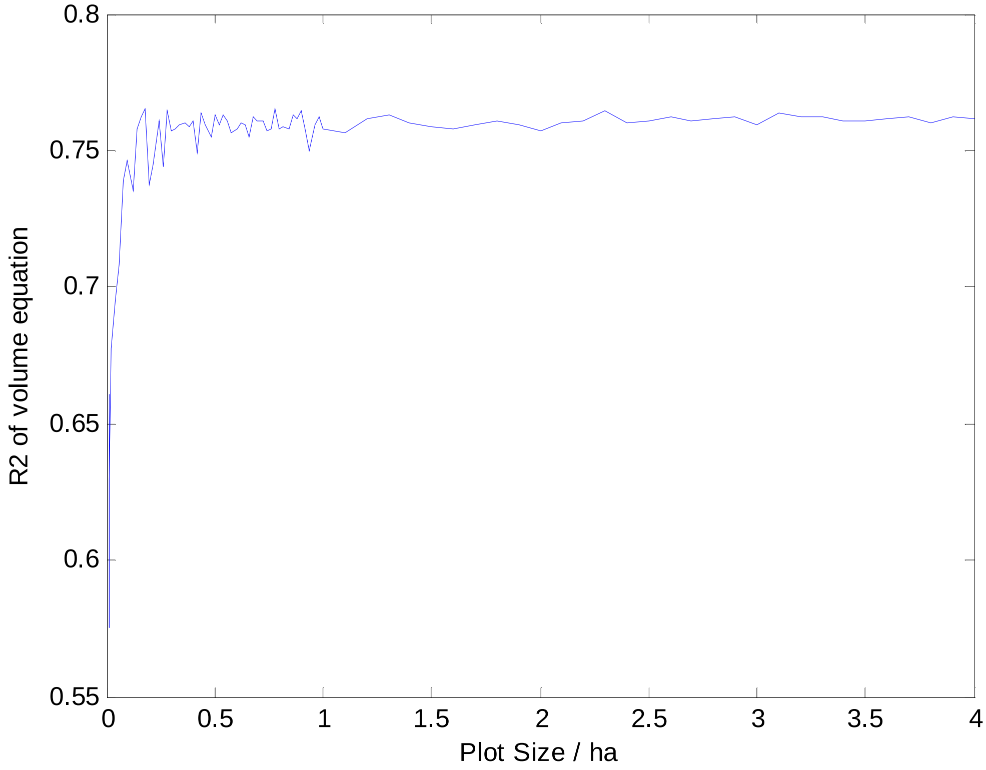


Figure 3.2 – Variation in R^2 value of volume function for 227 LUCAS plots as the pulse density was thinned out.

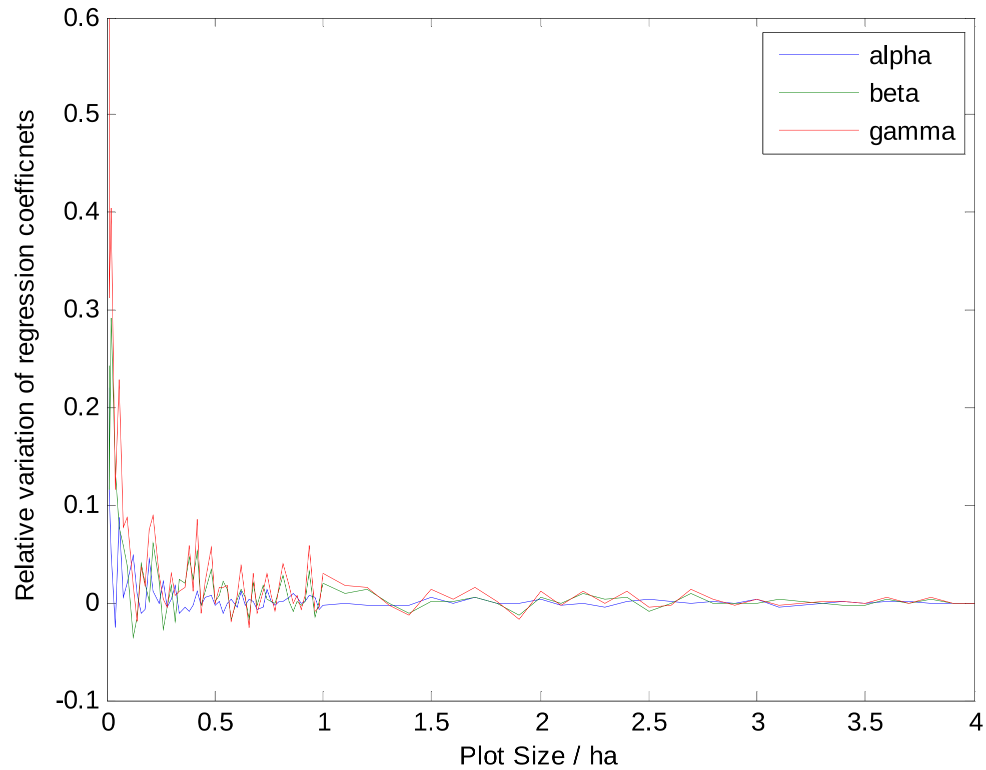


Figure 3.3 – Variation in regression coefficients for LiDAR volume function (see equation 2)

Variation of Across Plot Size

As the LUCAS plots used were all 0.06 ha, the limiting value of 0.1 pulses per m^2 corresponds to 60 pulses per plot. However, a forest owner with different sized plots may well find a different limiting pulse density. A forest with 0.03 ha plots for example, would only receive 30 pulses per plot at 0.1 pulses per hectare, and hence have fewer data and expect worse results.

In Gonzalez-Aracil[5] the effect of plot size on volume functions was trialled, utilising the fact that the LUCAS plots had distance and bearing for every tree, thereby enabling us to effectively reduce plot size. Volume by tree was obtained based on a taper function derived from individual diameters and a sample of heights, and total plot volume was calculated based on a slope-corrected radius for each plot size from 0.06 ha to 0.01 ha. The report found that regression coefficients varied substantially with plot size (which demonstrates that the homogeneity assumption does not hold across plot sizes), and that plot size could be reduced to 0.03 ha without compromising the fit (R^2 and RMSE) of LIDAR volume functions.

In this report we repeat the experiment, but also vary pulse density as a second independent variable. Figure 3.4 shows how the R^2 values varied by plot size and pulse density (note the log scale for pulse density). These results show that R^2 declines smoothly with plot size and pulse density. The R^2 declines significantly only with plot sizes smaller than 0.02ha and/or pulse densities lower than 0.1 pulses per m^2. This combination equals a lowly 20 pulses per plot.

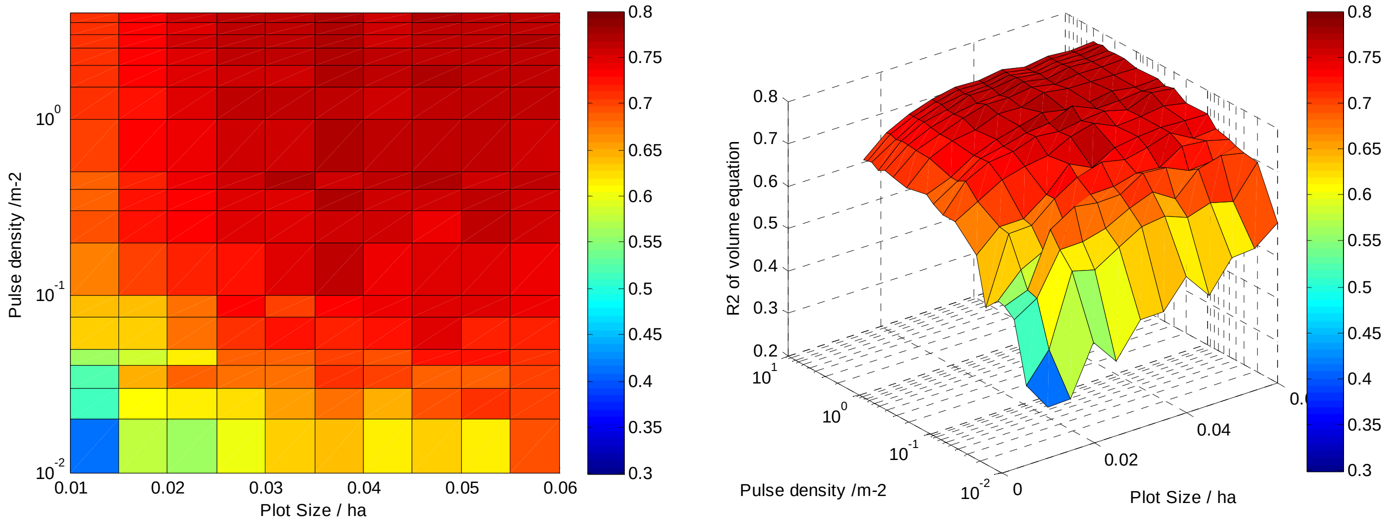


Figure 3.4 – R^2 of volume function for LUCAS plots as a function of plot size and pulse density, shown as a checkerboard plot and as a 3D surface. The colour scale shows R^2 values. Higher R^2 values indicate a more accurate estimate of stand volume.

As in the previous section, we allow regression coefficients (but not function form) to vary. Figure 3.5 shows the average relative variation of the three coefficients compared to their values at 0.06ha and 4 pulses per m^2. Intriguingly, we see that the volume functions are relatively stable across plot sizes, except at low pulse densities. This is in contrast to Gonzalez-Aracil whose coefficients showed marked variation. This is due to the metrics used (30th height percentile and canopy cover here, mean height in Gonzalez-Aracil), and also crucially because here we sacrifice a few % R^2 and use a linear volume function, whereas in Gonzalez-Aracil a quadratic model was used. With a quadratic model the higher powers necessitate larger changes in coefficients. It is clearly undesirable to have a volume function with coefficients that are highly dependent on plot size (or pulse density), and it appears that a linear volume function has greatest stability. For this reason plots below 0.03 ha (at which point the coefficients begin to show significant variation) are not recommended as the homogeneity assumption appears to be failing.

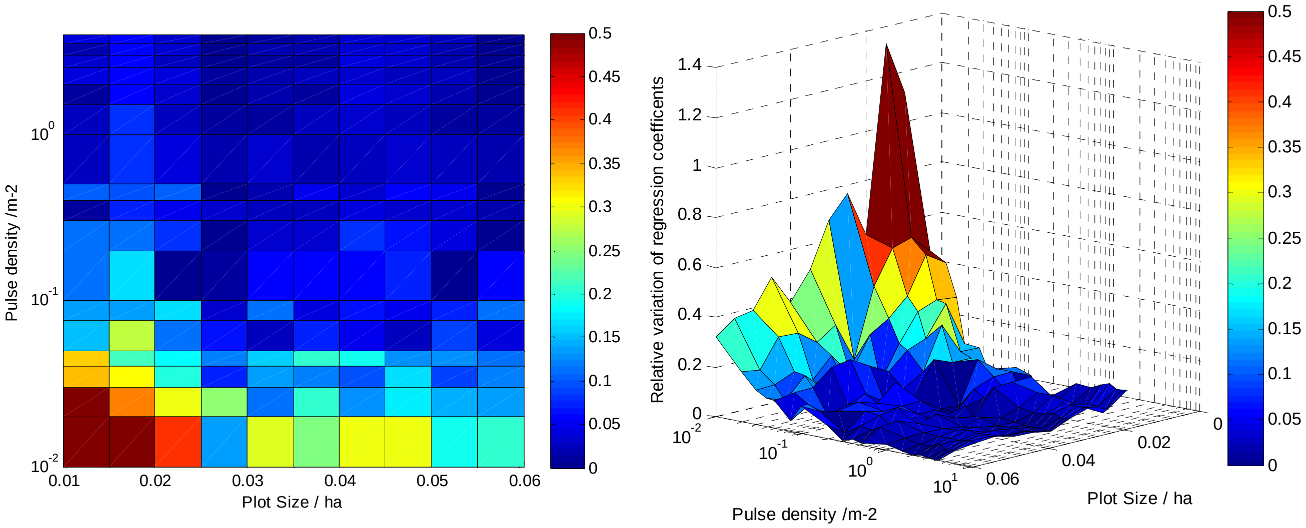


Figure 3.5 – Variation in regression coefficients for LiDAR volume function (see equation 2) against plot size and pulse density as a checkerboard plot and 3D surface.

If we multiply plot size with pulse density, we get the number of pulses per plot. This is shown plotted against R^2 in Figure 3.6 (both with and without a log scale for number of pulses). From this we can see that as long as you have at least 100 pulses per plot, there is minimal benefit of more pulses in terms of an R^2 for a volume function. At our recommended minimum plot size of 0.03 ha (also the findings of Gonzalez-Aracil), pulse density should not be below 0.33 pulses per m^2.

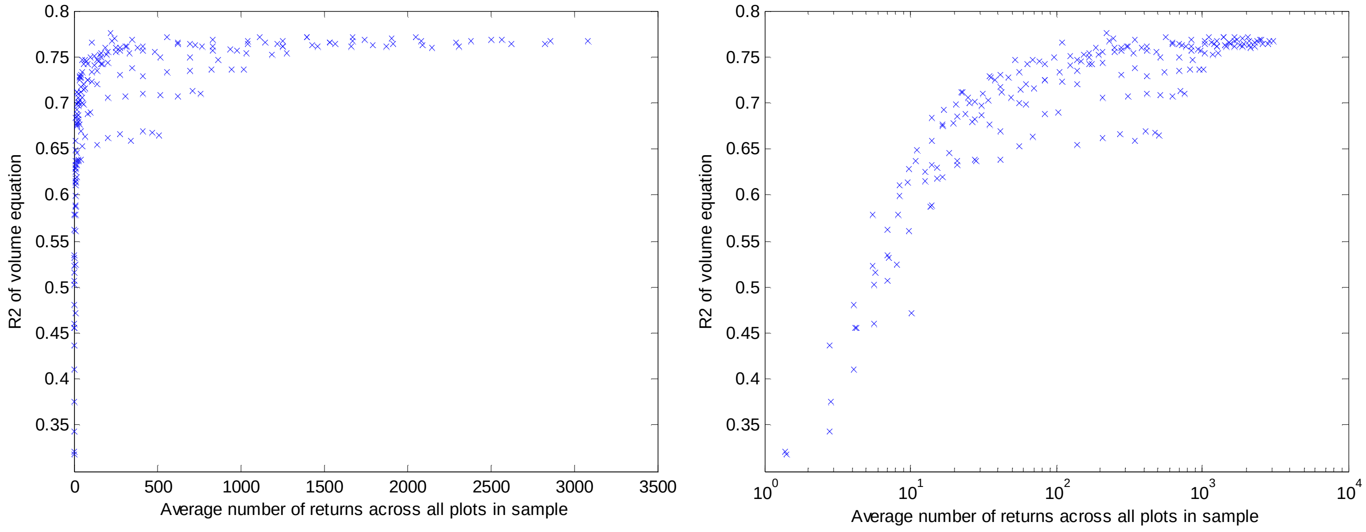


Figure 3.6 – R^2 of volume function vs. number of pulses per plot, left linear scale, right log scale.

Caveats to LiDAR Volume Relationships

There are many other factors that affect the applicability of a volume function. For example, volume functions can often be improved by adding known management information (e.g. stocking or age), or environmental factors such as topex, temperature or rainfall. Volume functions may also be severely compromised by poor GPS measurements of plot locations, time differences between LiDAR collection and field measurement, DEM quality, unusually high understorey or a small number of field plots. The LUCAS plots contain trees across all ages, and hence the height-based metrics show variations of many metres. When volume functions are defined over a set of plots from a single age class (such as in pre-harvest inventory), heights do not vary as much, as the function cannot be expected to obtain an R^2 as high as in these national models. In these situations having plots large enough to give some level of within-plot homogeneity is essential to reflect accurately any stand-wide variation. Previous experiments with pre-harvest inventory data using 0.04ha plots containing an average of 9 trees per plot did not give good results. The common practice of aiming for at least 20 trees per plot is highly recommended.

In this study, the coefficients in the volume function remained fairly constant across pulse densities and plot sizes, unless either was taken to the extremes. This is because the homogeneity assumption of trees being roughly equivalent held for these plots. In an unpublished study by Forestry Tasmania, the coefficients in LiDAR volume functions were found to stabilise when plots were around 0.02 ha in size for unthinned Eucalytus plots, 0.04 ha for thinned, and as large as 1 ha in size for natural forest (D. Mannes, *pers. comm.*). This is because the highly stocked unthinned Eucalyptus plots were highly homogenous (as they contained a lot of trees and not much gap), so could afford small plot sizes. After thinning, gaps were more prevalent and plots needed to be larger for homogeneity to be approximated. Natural forests are so varied that plot sizes must be enormous to get a robust representation of the locality. This highlights the need to work out the optimal function for each forest on a case by case basis.

ACKNOWLEDGEMENTS

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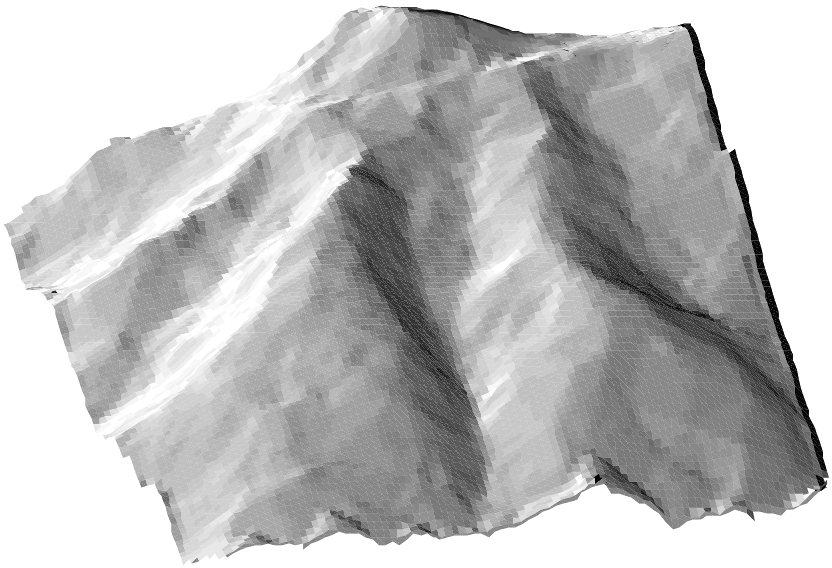
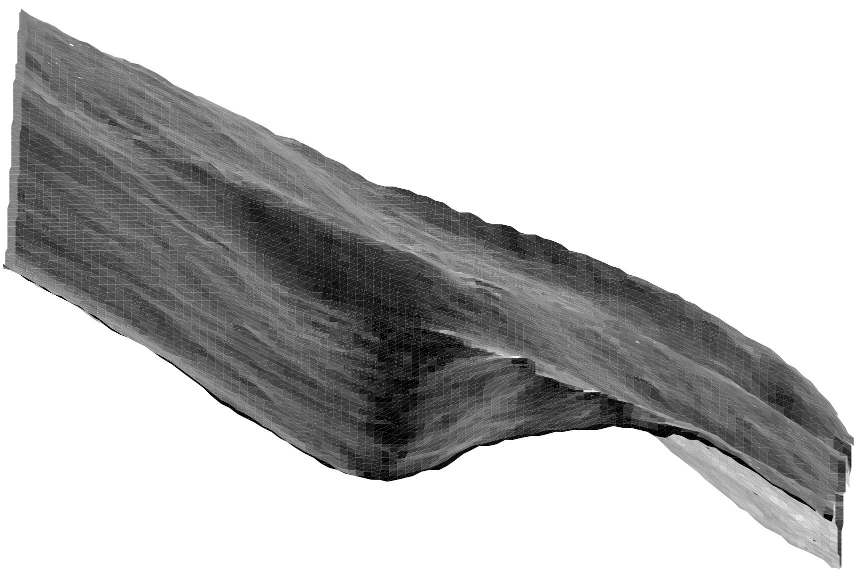
APPENDICES

Appendix 1 - Aerial imagery and DEMs for examples given under Objective 2

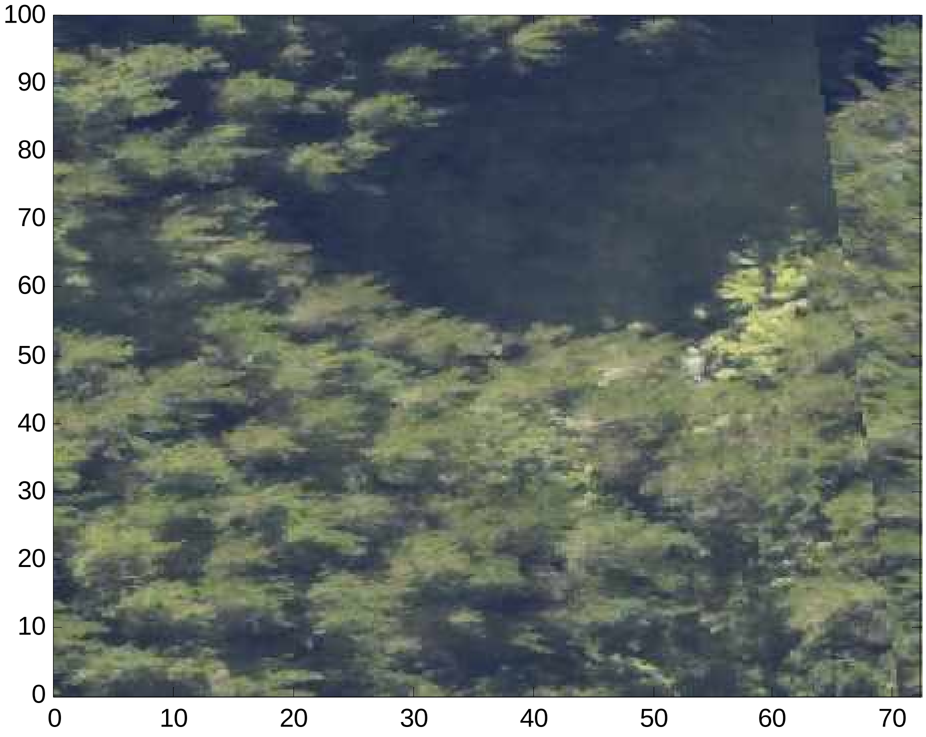
1 - Large slip near river in pine forest, 100 m long x 10 m wide

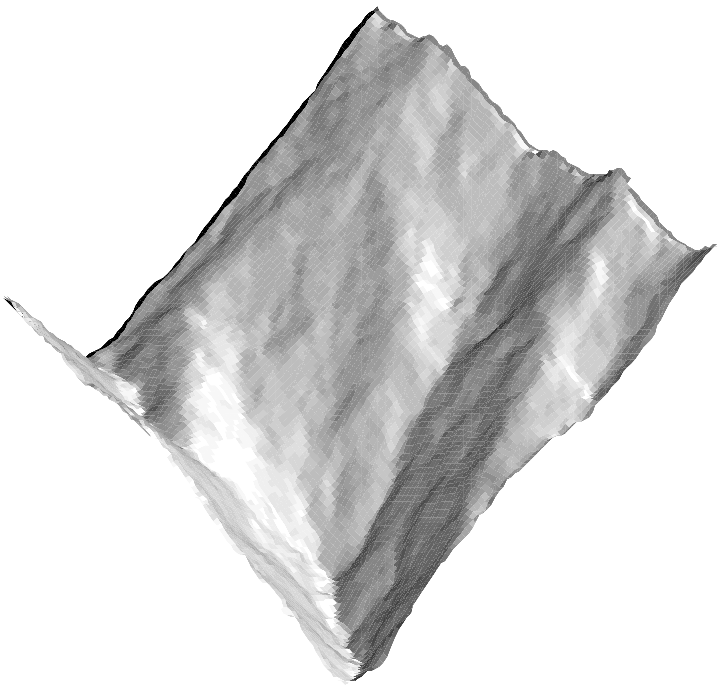


2 - Cutover

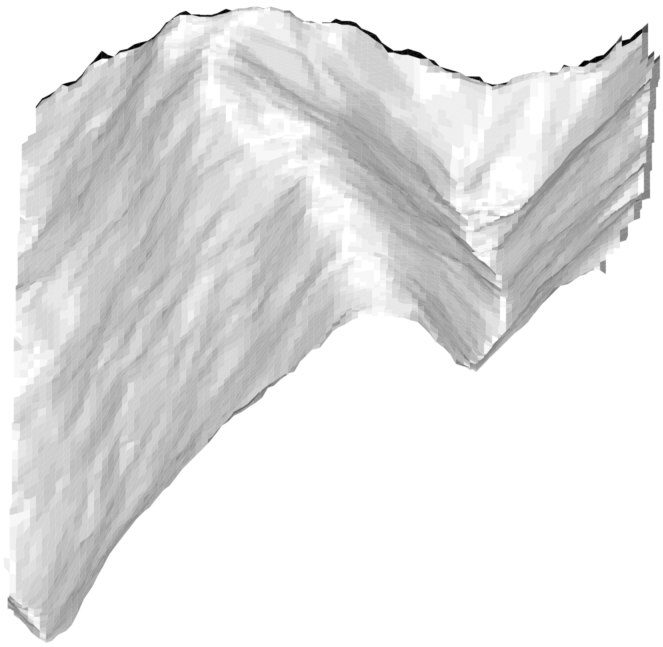


3 – Steep gully

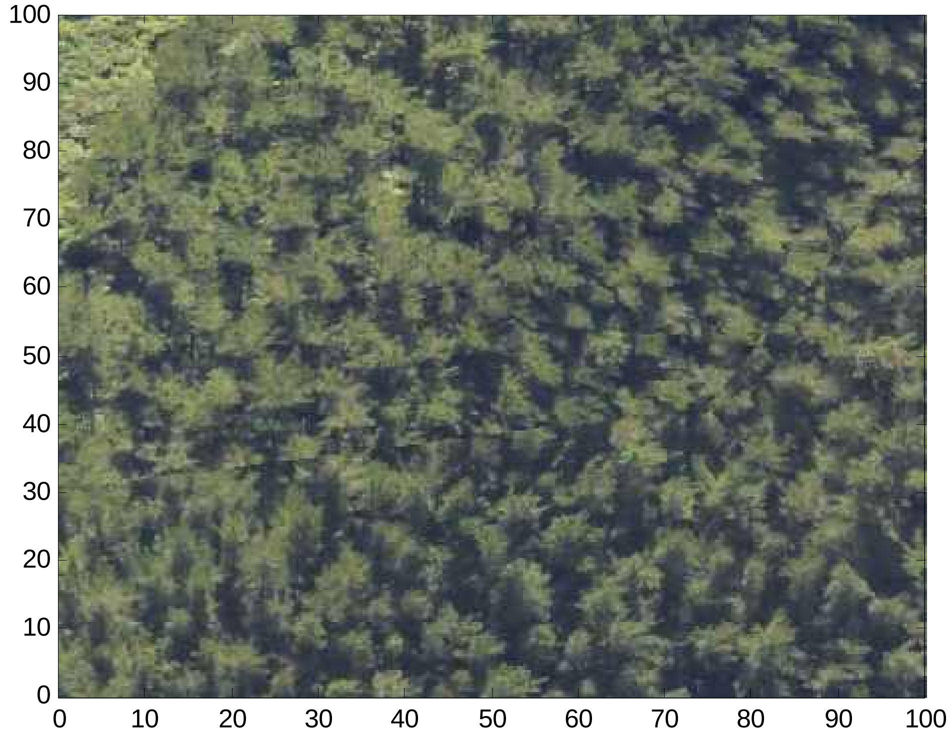


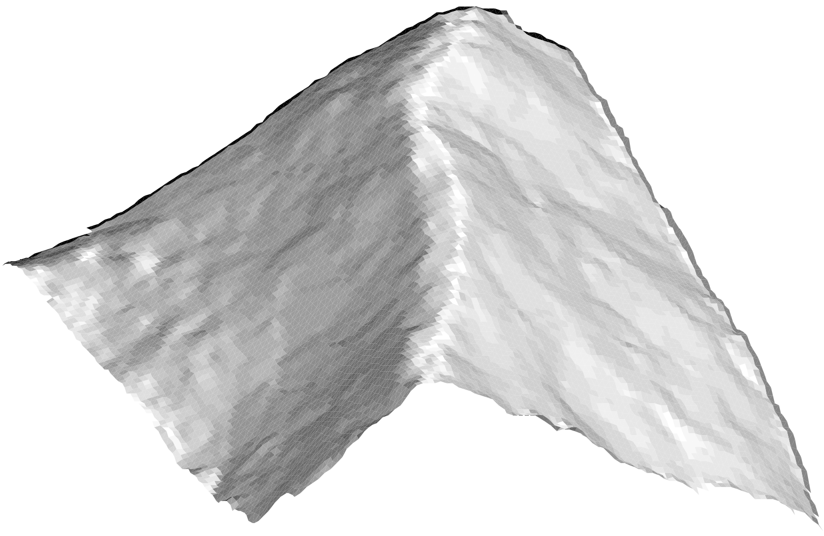


4 - Ridge end by steep face

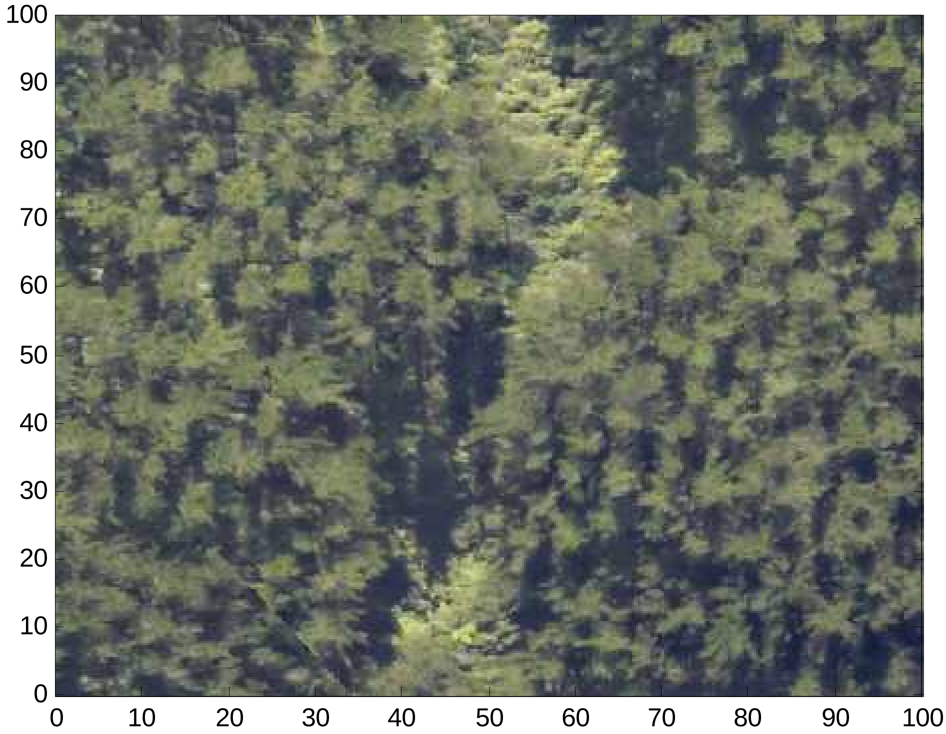


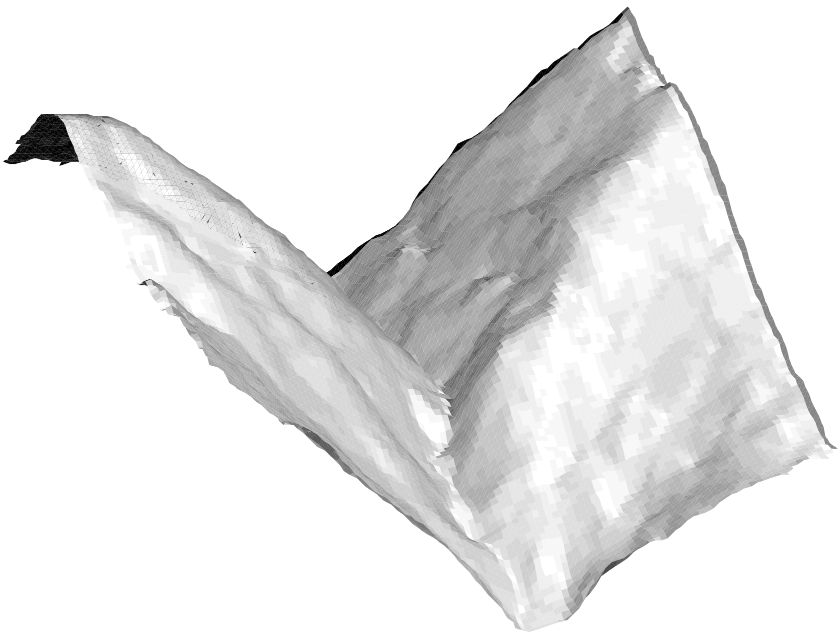
5 - Ridge with steep drop off to west



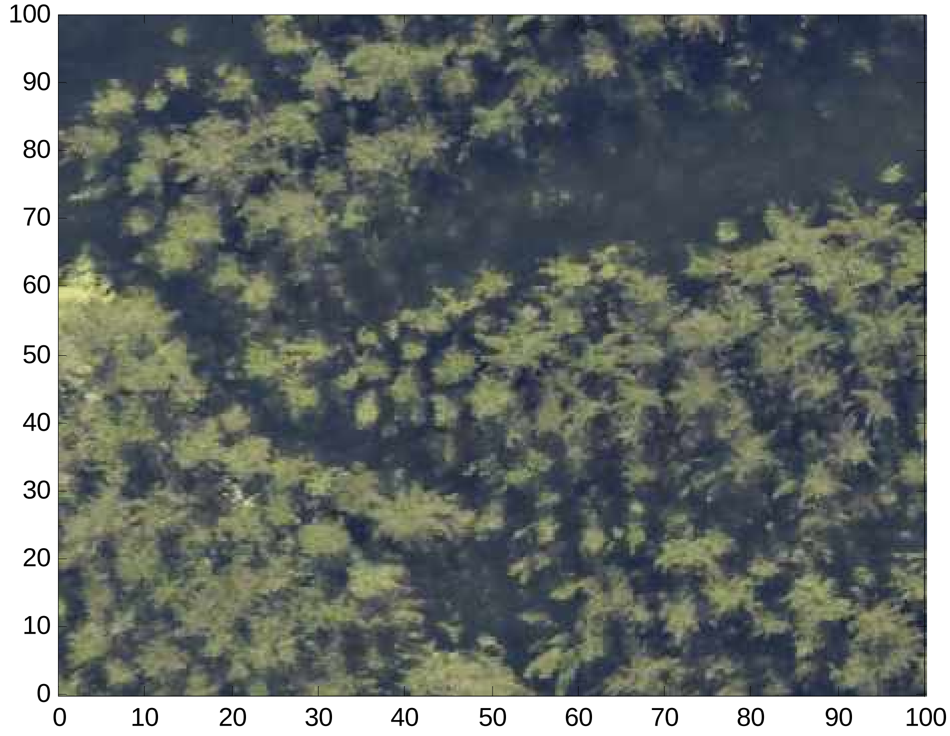


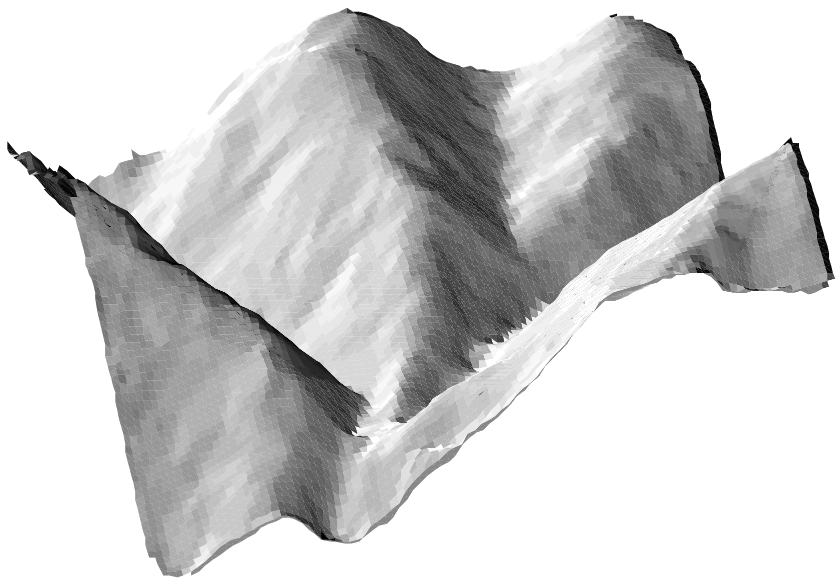
6 - Old road above river



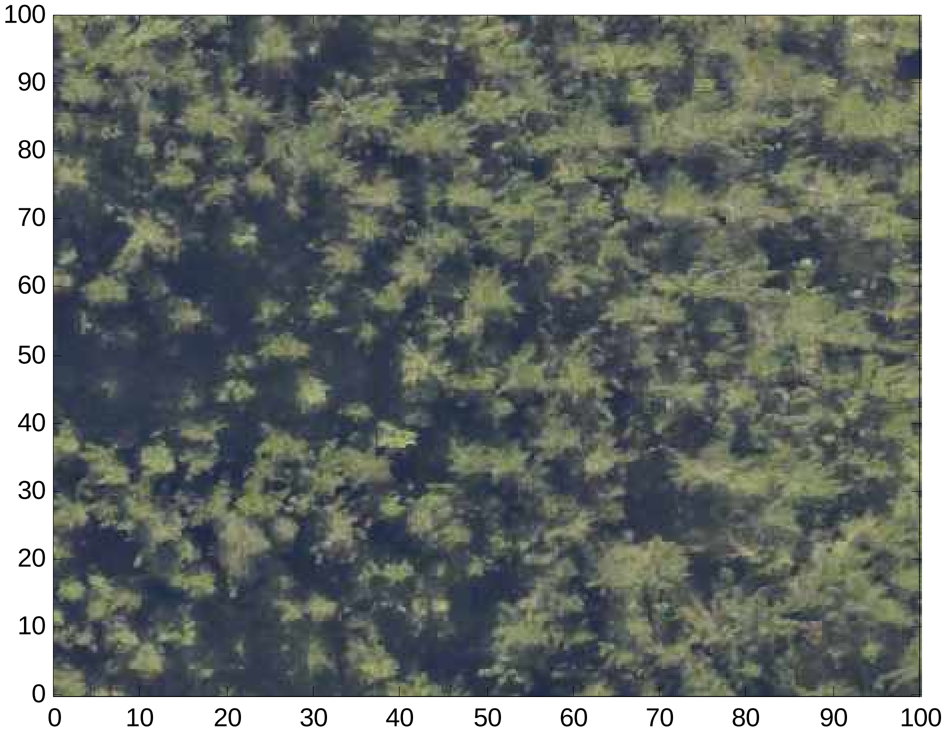


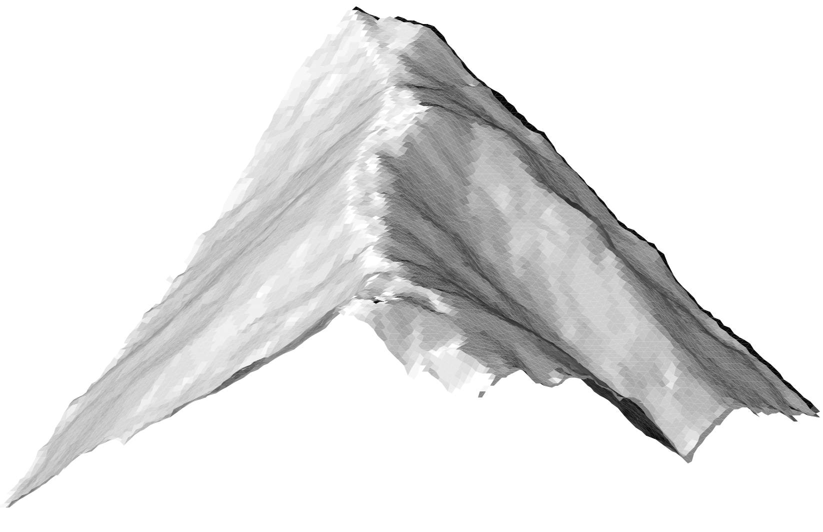
7 - Nose of ridge





8 - Top of a ridgeline





9 – Hairpin road in cutover