Australia's National
Science Agency

Monitoring mangrove rehabilitation with terrestrial laser scanning

CSIRO-EcoScience NT

Kick-Start program collaboration

CSIRO: Dr. Shaun R Levick

EcoScience NT: Dr. Kristin Metcalfe and Mr. Adam Bourke

27 August 2021

Commercial-in-confidence

[Insert ISBN or ISSN and cataloguing-in-publication (CiP) information if required]

[Insert Business Unit specific information if required]

Citation

Levick SR, K Metcalfe and A Bourke (2021) Monitoring mangrove rehabilitation with terrestrial laser scanning. CSIRO, Australia.

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Acknowledgments

We thank Jon Schatz, Stephanie Johnson, Marcus Guderle and Pierre Grandclément for assistance with GPS surveying and LiDAR scanning in the field.

Executive summary

Mangrove rehabilitation success is time consuming and costly to monitor via traditional field-based approaches. Remote sensing technology developments promise to streamline the measurement and monitoring of vegetation status, with potential to provide new insights into revegetation trajectories and rehabilitation strategies. Here we trial the use of time-series terrestrial laser scanning (TLS) for monitoring rehabilitation progress in replanted mangrove assemblages following disturbance.

TLS surveying was conducted in 2017, 2019 and 2020 across an experimental rehabilitation monitoring site in coastal mangroves assemblages of Darwin harbour. Scanning data was analysed over the full spatial extent of the surveyed area, and on a plot basis to align with field monitoring efforts being undertaken at monitoring plot (5 m x 5 m) and recruitment fence (3 m x 0.67 m) scales. The aboveground 3D structure of the mangrove regrowth was well captured in the scanning data, with fine-scale detail (individual leaves, branches, rehabilitation infrastructure) clearly visible in the point clouds. Canopy height and canopy cover estimates derived from TLS showed encouraging rates of growth over time, with median plant height and canopy cover reaching 2.5 m and 70% respectively in the tidal creek assemblage six years after clearing. Canopy metrics derived at the plot scale also provided an avenue for comparing the effectiveness of different rehabilitation treatments, such as the use of nursery grown seedling versus direct propagule implants, and the use of ‘recruitment fences’.

The TLS data collected during this pilot study, however, was not suitable for the automated segmentation of individual plants for the extraction of individual plant attributes. As such, based on TLS alone, rehabilitation progress could only be evaluated in terms of overall height/cover characteristics at the patch scale, rather than as a percentage survival score relating to the number of planted individuals. Consequently, the density and rate of natural seedling recruitment could not be distinguished from planted seedlings within monitoring plots. TLS data collected across this site over multiple years provided valuable insights into how the use of this technology might be optimised in future studies and monitoring strategies.

1 Introduction

1.1 Project background

A linear strip of vegetation in Darwin Harbour was cleared during the construction phase of the INPEX operated Ichthys LNG Project Gas Export Pipeline project in 2013. The disturbed area primarily impacted coastal mangrove and salt flat habitats and involved the removal of 1.6 ha of dense mangrove forest for construction of a trench and a temporary access road. The clearing is approximately 20 m wide and traverses four main mangrove assemblages and an extensive salt flat. Mangrove communities can take an extremely long time to recover from disturbance (McGuinness 1992, Ellison and Farnsworth 1996) with particularly slow natural regeneration of clearings and clear-cut strips (Blanchard and Prado 1995, Kaly and Jones 1998). EcoScience NT was contracted in 2013 to design and implement a rehabilitation program to fast-track the reforestation of mangrove assemblages within the pipeline corridor.

Using techniques that were trialled during the PhD of Dr. Kristin Metcalfe (Metcalfe 2007), a network of ‘recruitment fences’ were constructed to assist the process of natural seedling recruitment. In the macro-tidal conditions in Darwin Harbour plastic mesh fences effectively hinder strong tidal currents, trapping organic debris including mangrove seeds and propagules, encouraging their establishment.

Regeneration of the clearing was also facilitated by replanting of nursery-grown mangrove seedlings and direct-sowing of propagules in selected areas. Long-term monitoring plots were established to assess seedling survival, while also comparing the success of direct implants versus nursery seedlings. Control fences were established to quantify the effectiveness of the recruitment fences. Following the initial establishment of the rehabilitation project in 2014, mangrove survival and growth was monitored annually until 2020 with traditional field-based techniques. Field-based monitoring is very time intensive, and certain attributes of plants are challenging to measure in the field through traditional techniques.

In 2017, terrestrial laser scanning (TLS) was trialled at a portion of the site to test its potential for monitoring change over time. TLS is a proximal remote sensing technique that has the advantage of capturing the 3D structure of vegetation in its entirety and provides georeferenced benchmarks for monitoring change through time (Calders et al. 2020, Levick et al. 2021). The application of TLS in ecological studies is growing across the globe, but its potential to contribute to rehabilitation monitoring still needs to be explored. Previous studies utilising TLS in mangrove habitats have focused on structural quantification and biomass estimation (Owers et al. 2018, Rouzbeh Kargar et al. 2020), but to the best of our knowledge there have been no prior assessments of mangrove growth and rehabilitation with TLS.

2 Aim and approach

2.1 Study objectives

The aim of this project was to explore the potential for terrestrial laser scanning (TLS) to facilitate the spatial and temporal monitoring of mangrove rehabilitation outcomes. Specific project objectives were to:

- determine how well 3D point clouds from terrestrial LiDAR scanning could be used to quantify structural parameters of mangroves in rehabilitated sites
- assess the utility of time-series LiDAR data for monitoring rates of individual plant growth and mortality

2.2 Study site and experimental design

Construction of the Gas Export Pipeline (GEP) required the clearing of aboveground mangrove vegetation within a 20 m wide x 1000 m long corridor running east-west from the landward zone to the seaward zone (Figure 1). Rehabilitation efforts focussed on four mangrove assemblages – the hinterland margin (*Avicennia marina* and *Lumnitzera racemosa*), the tidal flat (*Ceriops australis* and *Avicennia marina*), the tidal creek (*Rhizophora stylosa*) and the seaward zone (*Sonneratia alba*). Planting of seedlings and propagules occurred only in the tidal flat and the tidal creek assemblages. Recruitment fences were established in straight rows at 10 m intervals throughout the four main assemblages. Monitoring of fences in the seaward zone was abandoned in 2017 due to fence instability in the unconsolidated sediments in this dynamic habitat. Designated 'recruitment fences' consisted of plastic mesh supported by four wooden stakes, attached between two marker poles. Each fence was 3 m long and up to 1 m high. Control fences consisted of only the marker poles, with no fencing material. Ten replicate fences per assemblage were randomly selected for monitoring of assisted recruitment. Each monitoring fence was established within 4 marker posts defining a 2 m^2 quadrat (3 m long x 0.67 m wide) within which the total number of seedlings was recorded, noting height and species (Figure 2).

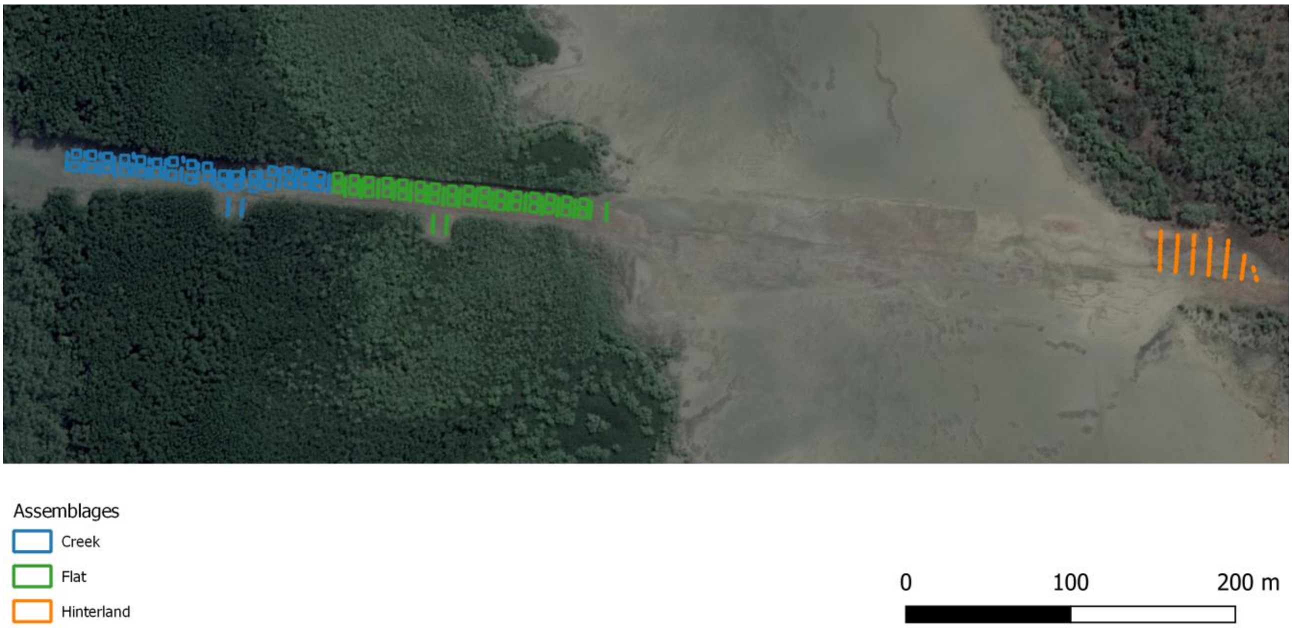

Figure 1 - Study site layout. The gas export pipeline runs east to west, and a 20 m wide corridor was cleared through the mangroves to accommodate it. Rehabilitation progress is being monitored in three community assemblages – tidal creek, tidal flat, and hinterland. A 330 m wide salt flat separates the hinterland and tidal flat assemblages.

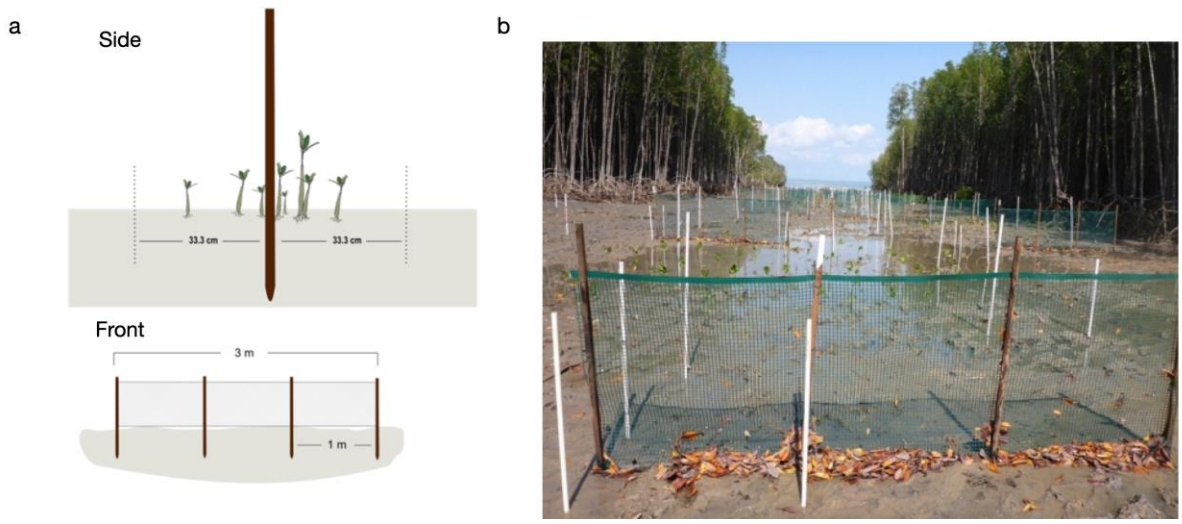

Figure 2 - Diagram showing design of recruitment fences comprising wooden stakes supporting 3 m x 1 m plastic mesh. Natural recruitment of seedlings was recorded within a 2 m^2 quadrat surrounding each monitoring fence and control plot (a). Recruitment fences after establishment in pipeline corridor in 2014 (b).

2.3 Field based-monitoring

Permanent 5 m x 5 m monitoring plots were established in the tidal creek and tidal flat during initial planting in 2014 (e.g., Figure 3a). Paired plots were placed at 10 m intervals, one containing nursery grown seedlings (N) and the other implanted propagules (T). Only two mangrove species were planted, *Rhizophora stylosa*, dominant in the tidal creek and *Ceriops australis*, which is the dominant species in the tidal flat. A regular planting arrangement ensured consistency amongst plots with each 5 m x 5 m plot containing 57 seedlings planted at 0.5 m spacing, at the commencement of the program. Planting was not attempted in the seaward or hinterland assemblages due to extreme environmental conditions and anticipated low survival rates.

Survival of *R. stylosa* was recorded by counts of planted nursery cultivated seedlings and directly implanted propagules within 16 replicate study plots for each treatment in the tidal creek assemblage. Growth (height and nodes) was recorded by random sub-sampling within three replicate 2m^2 quadrats per study plot (Figure 3b). Node counts were discontinued in 2017 due to time constraints, but field measurements of seedling height continued until 2020. Natural recruitment has been closely monitored since program commencement by recording the species and height of all seedlings that established naturally within the 64 monitoring plots as well as within these three replicate quadrats.

Natural recruitment associated with recruitment fences was recorded at 10 monitoring fences and 10 adjacent controls per assemblage (Figure 4). The species and height of each seedling that established within the 2 m^2 quadrat surrounding each monitoring and control fence was recorded for the hinterland, tidal flat and tidal creek assemblages. Field monitoring also included detailed photo- monitoring of each study plot and monitoring fence, and images taken from central marker posts in each of the four main assemblages. Photo-monitoring has been conducted annually as part of field-based monitoring for seven years since establishment in 2014.

A Lecia G16 GNSS, with real-time correction (RTK) via precise point positioning (SmartLink PPP), was used to stake out the corners of the monitoring plots, the control, monitoring, and recruitment fences, and the locations of individual plants within with monitoring plots. Positions were collected in the WGS84 UTM52S coordinate system, and the AusGEOID model was applied. Positional accuracy was < 0.05 m across x,y and z dimensions.

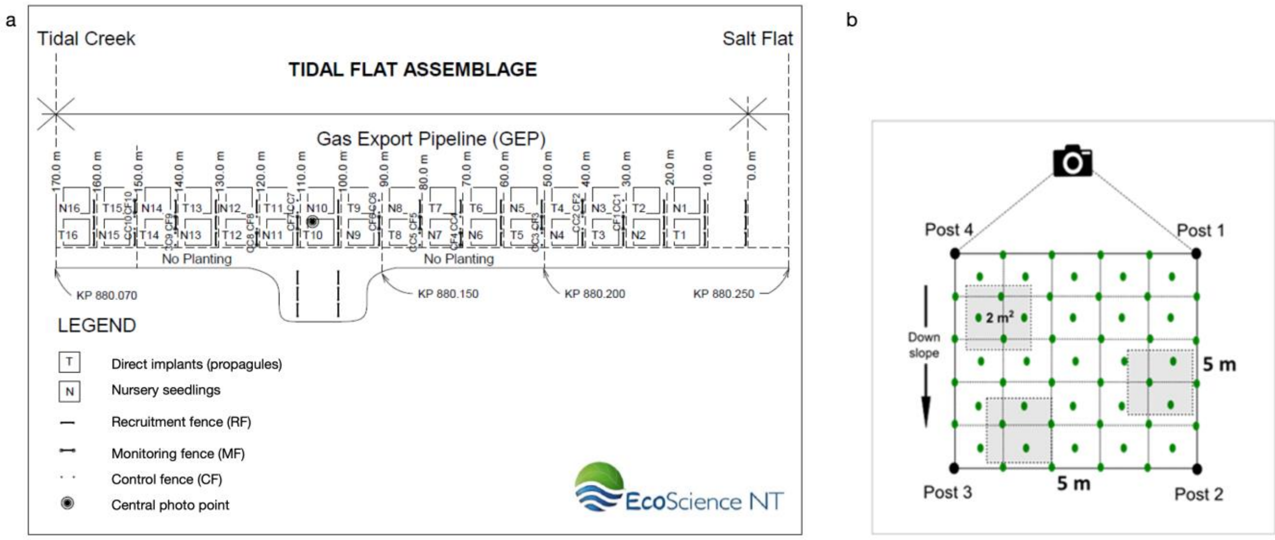

Figure 3 - Layout of 32 study plots and 20 rows of recruitment fences with the tidal flat assemblage. Ten fences were monitored (MF) with 10 adjacent controls (CF) per assemblage (a). Planting configuration within permanent 5 m x 5 m study plots to monitor the survival and growth of 57 planted or nursery grown propagules (green dots). Randomly placed 2 m^2 quadrats were used during field-based monitoring to measure growth (height) and natural recruitment (b).

Figure 4 - Field monitoring of survival and growth of planted seedlings and natural recruitment in 2016 (a). Measurement of seedling height and density of natural recruitment at tidal creek fence in 2016 (b).

2.4 Terrestrial laser scanning

Terrestrial laser scanning was conducted at the rehabilitation site on three separate occasions. The first pilot survey was conducted in October 2017 and focussed on the tidal creek assemblage. A light-weight Leica BLK360 scanner was used and a total of 18 scans were collected in a linear pattern with 10-15 m between scan positions. The BLK360 has a wavelength of 905 nm and was operated at the 'high-resolution' point cloud setting.

Two more comprehensive surveys which covered all three assemblages were conducted on 3 July 2019 and 21 July 2020, using a longer-range Riegl VZ-2000i laser measurement system. The scanner was mounted on a survey tripod at 1.6 m agl, and communicated with an Emlid Reach RS2 base station via LoRa for RTK corrections. A total of 32 scan positions were captured on each occasion. Traditional grid-based scanning was not possible due to the challenging field conditions (waterlogged mud), so the scan positions were aligned linearly along the southern edge of the rehabilitation site, with an average distance of 15-20 m between scan locations. The Riegl VZ-2000i scanner has a wavelength of 1550 nm and a maximum range of up to 2000 m. Scans were conducted at 600 kHz with an angular spacing of 0.03 mrad, using a scan pattern of 360° x 100°.

Each scanning survey was timed to align with the outgoing spring low tide to minimise the presence of standing water in the tidal flat and tidal creek assemblages.

Figure 5 - Terrestrial laser scanning at the GEP rehabilitation site. a) Scanning with the light-weight Leica BLK360 in the tidal creek assemblage in 2017; and b) scanning with the long-range Riegl VZ-2000i in 2019 in the hinterland margin assemblage.

2.5 LiDAR point-cloud processing

Raw scan data from the Leica BLK360 (.blk files) was imported into Leica's Infinity software suite, and each scan position was exported in standard x,y,z,i ascii format. The BLK360 has no GPS capability, so all scans were output in the scanner's own coordinate system (SOCS). Raw scan data from the Riegl VZ-2000i (.rxp) were imported into Riegl's RiSCAN Pro software suite, with the embedded GNSS, compass and inclination corrections applied. Points were filtered for noise (reflectance > 5, reflectance < -25, deviation > 60) and outliers (air and below ground points) prior to further processing.

The 2019 dataset was chosen as the reference frame against which to co-register the 2017 and 2020 scans, as it was the closest temporally to the other datasets and was the year in which the GPS surveying was conducted. The GPS locations of the monitoring plot corners and recruitment fences were imported in RiSCAN Pro, to provide a refence backdrop during the co-registration of the induvial scan location data. First, the individual 2019 scan were co-registered with each other using the Multi-Station Adjustment (MSA) module, which is a form of Iterative Closet Point (ICP) registration (Bergstrom 2016). Second, the 2020 scans were co-registered to each other and then to the 2019 reference data using the MSA approach. The Leica BLK360 ascii files were imported into the RiSCAN Pro project in the scanner's own co-ordinate system (SOCS). The manual transformation and adjustment tools were used to place each Leica scan in the project co-ordinate system (PCS) and roughly align them to the Riegl scans. Following that the MSA tool was applied to finely co-register the 2017 scans to each other and to the 2019 reference dataset. Co-registered scans for each year were merged together using an octree filter with a 0.01 m voxel size. The single files representing 2017, 2019 and 2020 were then exported in the industry standard .las format (v1.4) in geographic coordinates (WGS84 UTM52S) for further analysis with LAStools and CloudCompare scripts.

The merged clouds for each year were classified into noise, ground, and vegetation points using the *lasground* script within LASTools (-step size = 0.02, -ultra-fine and -not_airborne flags applied). Point clouds were then normalised to height above ground level with the *lasheight* (-replace_z) tool. The normalised point clouds representing each surveyed year were then queried with *lascanopy* to extract canopy metrics for different treatment plots and fence quadrats (full list in Table 1).

Table 1 - Canopy metrics derived from the normalised LiDAR point clouds for each year.

Canopy metric	Description
cov	Percentage canopy cover > 0.1 m
p99	99^{th} percentile canopy height
p95	95^{th} percentile canopy height
P75	75^{th} percentile canopy height
P50	50^{th} percentile canopy height
P25	25^{th} percentile canopy height
P10	10^{th} percentile canopy height
std	Standard deviation of canopy height
VCI	Vegetation complexity index
skew	Height distribution skewness
kur	Height distribution kurtosis

3 Project findings

3.1 3D characterisation of the rehabilitation site

Terrestrial laser scanning with both the Leica BLK360 and the Riegl VZ-2000i was effective in capturing above ground 3D structure in high-resolution detail. Scans from the two sensors exhibited a degree of noise, visible as points in the air and below the ground surface, which arose due to the scattering effects of standing water and wet soil across the site. Nonetheless, after filtering for statistical outliers, individual plant stems and leaves were clearly visible in the resulting point clouds, as was the fine-scale micro-topography of the terrain surface. Rehabilitation infrastructure in the form of plastic marker poles and meshed fencing material were also well represented, and were useful for co-alignment with field collected GPS survey data (**Error! Reference source not found.**).

Co-registration between the point clouds collected in 2017, 2019 and 2020 was successful, achieving an overall RMSE of 0.08 m. This robust alignment through time enabled growth patterns to be observed at the scale of an individual plant, as illustrated in Figure 7. Direct comparison of field-measured heights and LiDAR-derived heights showed similar distributions, but were not directly comparable since the field data are point measurements at sub-sets of the monitoring plots, and the LiDAR data capture the full canopy surface (Figure 8).

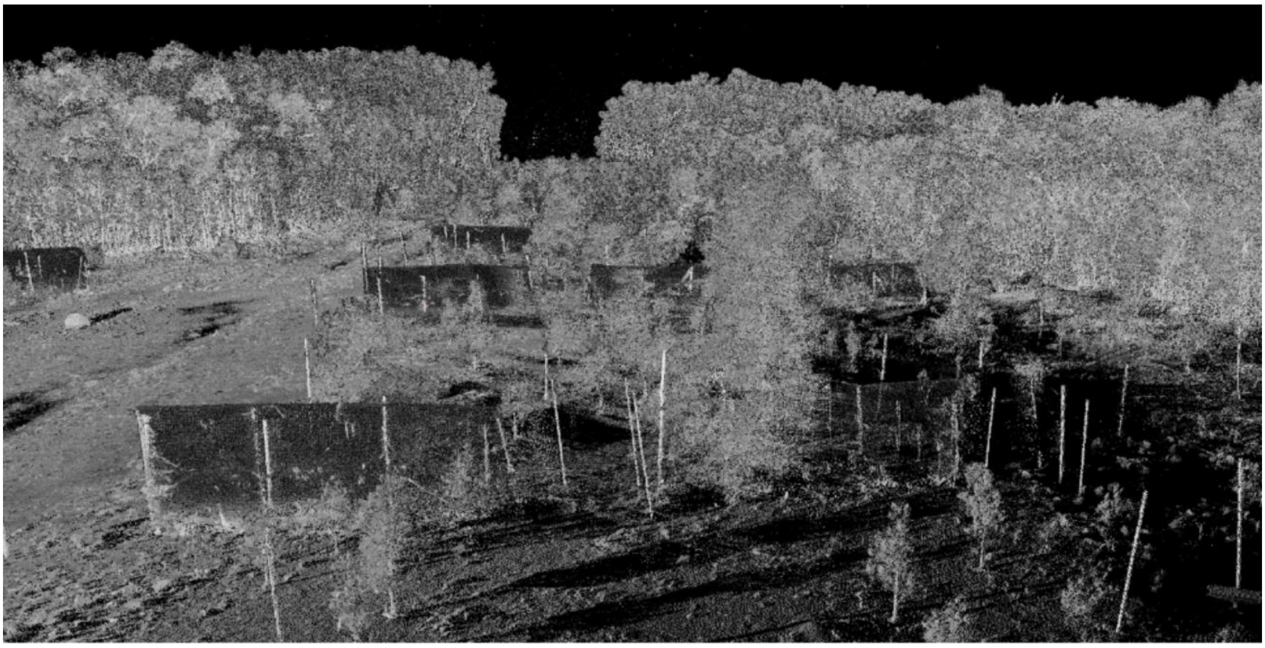

Figure 6 - Oblique reflectance view of the rehabilitation zone. Grayscale image shows the reflectance of the laser beam. The sky and wet soil show no reflectance (black) whereas the stems and leaves of mangroves show up in whiter shades. Recruitment fences are visible in the laser reflectance data with the support poles in white and the fencing mesh in darker shades.

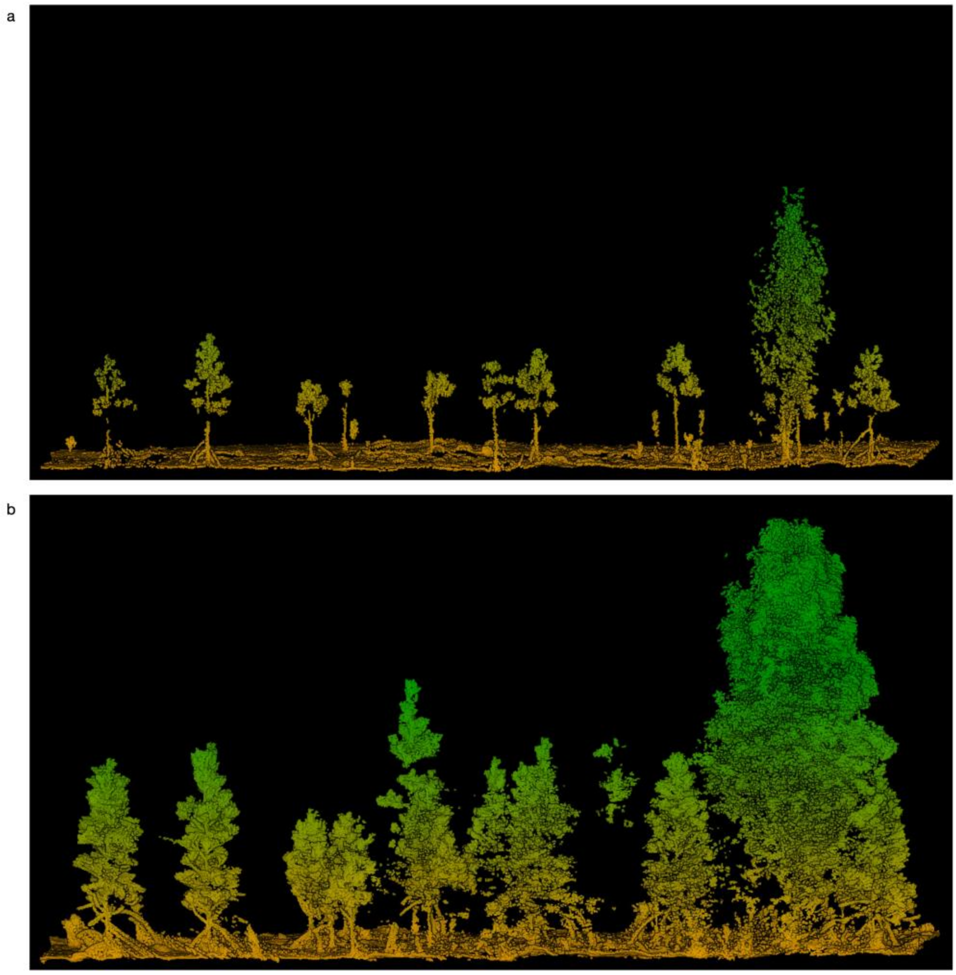

Figure 7 - Visualising change in seedling height and cover from 2017 (a) to 2020 (b). Colour scale indicates height above ground.

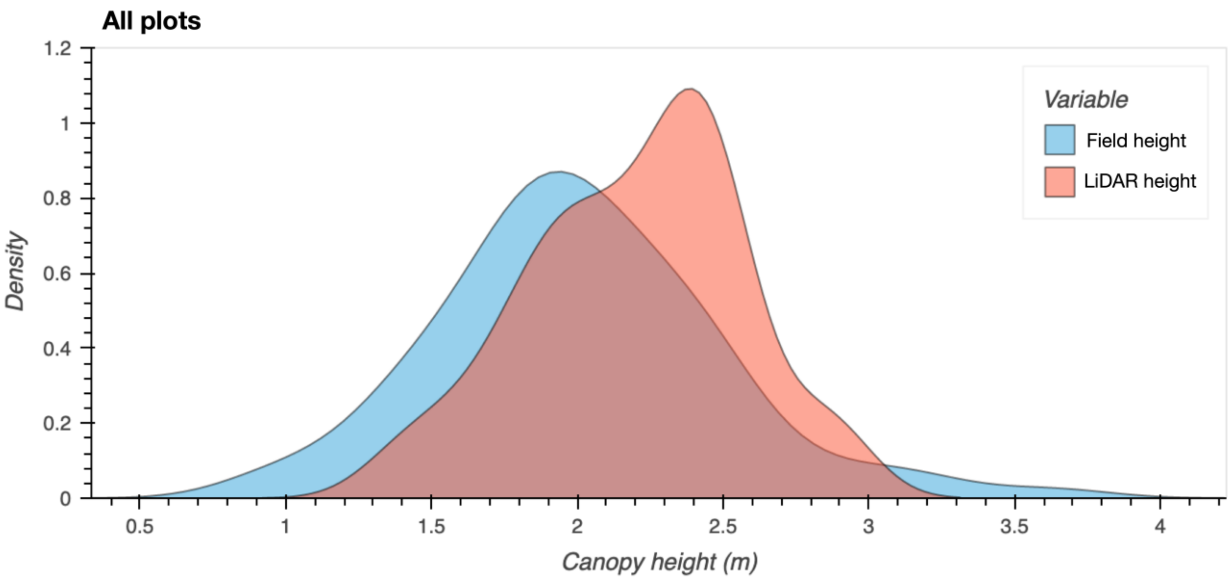

Figure 8 - Comparison of field measured versus LiDAR estimated canopy height at the plot scale. Note that direct comparison is not possible since field data are for a spatial subset of the monitoring plots.

3.2 Patterns of rehabilitation success across different assemblages

Rehabilitation success, measured in terms of canopy 3D structural change, varied as a function of length of rehabilitation (year) and the mangrove community type (assemblage). Median canopy height (95th percentile height of all canopy returns) measured across the full area surveyed increased markedly in the tidal creek assemblage from 2017 to 2019, and showed a further 25% increase from 2019 to 2020 (Figure 9). These rapid changes in canopy vertical growth were not reflected in the tidal flat and hinterland margin assemblages, where median canopy height increased marginally from 2019 to 2020 (no data collected in these assemblages for 2017). Average seedling heights are characteristic of the dominant species in each assemblage, with *R. stylosa* is intrinsically taller than *Ceriops australis* seedlings (tidal flat) and *Lumnitzera racemosa* (hinterland margin).

Canopy cover (proportion of laser returns > 0.1 m) showed similar patterns to canopy height in the tidal creek assemblage, with a large gain in horizontal cover during the two-year period from 2017 to 2019 and a smaller expansion from 2019 to 2020. However, in the tidal flat assemblage the increase in cover from 2019 to 2020 was more marked that that of height, while only a minor increase in cover was observed in the hinterland margin (Figure 10). Despite exhibiting less canopy height and cover than the tidal assemblages (and noting that no planting was done in this assemblage), the hinterland margin still shows signs of recovery as median canopy height is approaching 1 m and cover is greater than 30%. Canopy complexity (represented by the VCI index) was considerably higher in the two tidal assemblages than in the hinterland margin, indicating greater variation in vegetation 3D structure in these zones (Figure 11).

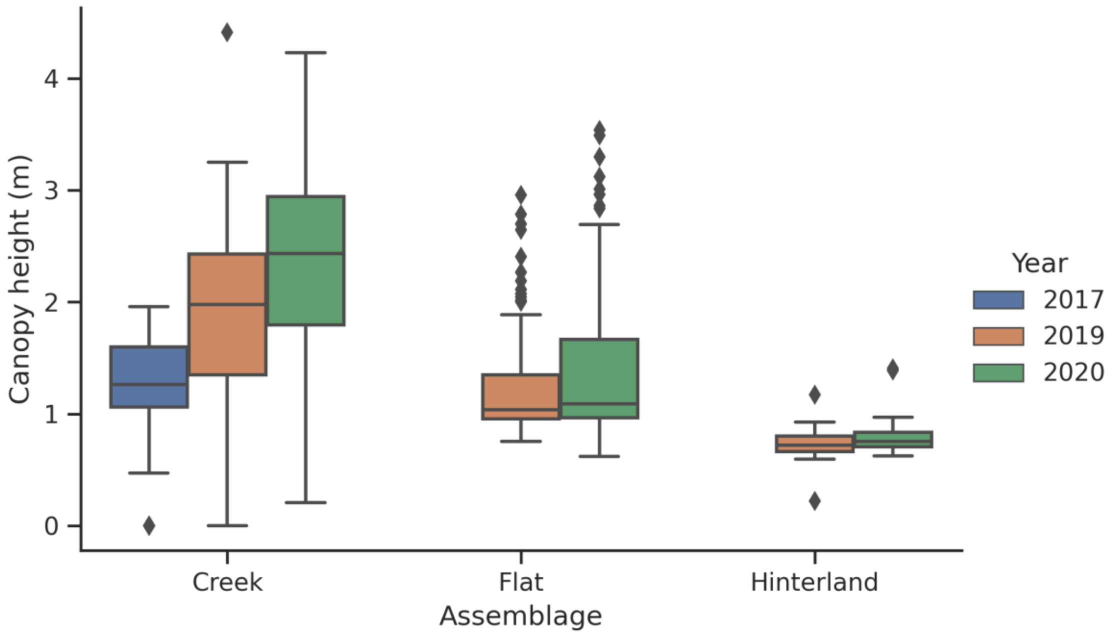

Figure 9 – Terrestrial laser measured temporal change in canopy height across different assemblages of the rehabilitation site.

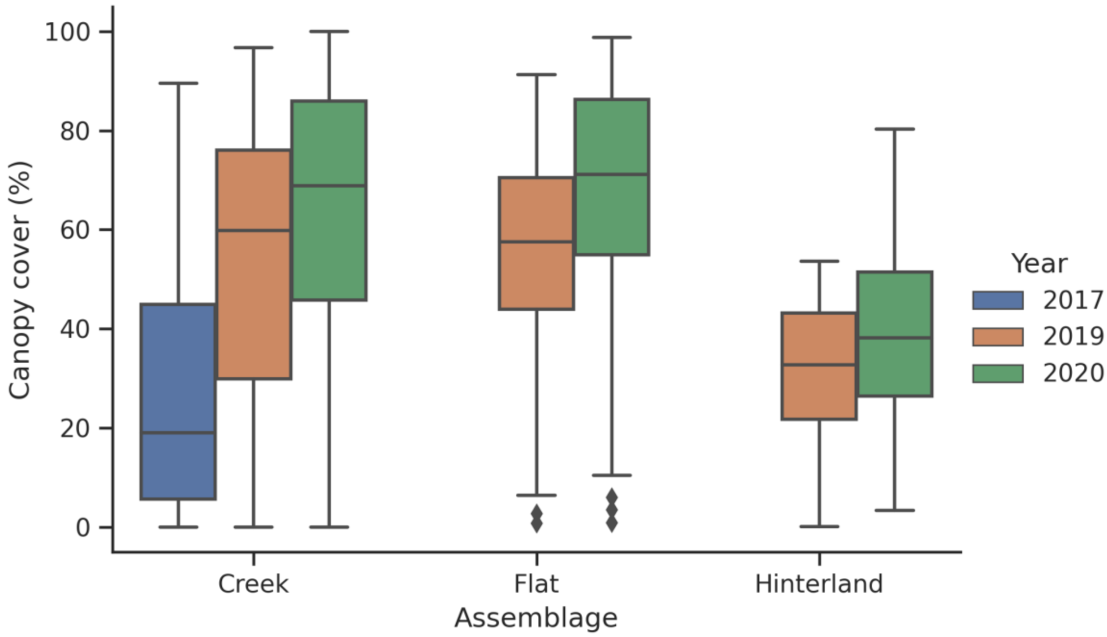

Figure 10 – Terrestrial laser measured temporal change in canopy cover across the rehabilitation site.

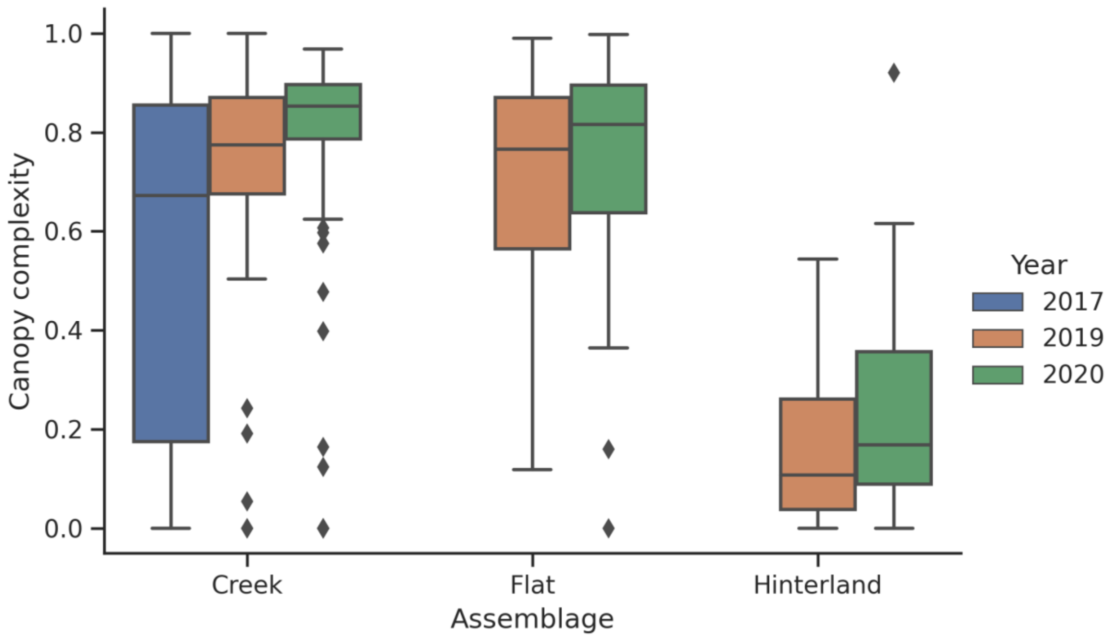

Figure 11 – Terrestrial laser measured temporal change in canopy complexity across the rehabilitation site.

3.3 Patterns of rehabilitation success across different treatments

Field data collected since the inception of the rehabilitation monitoring experiment showed that monitoring plots (5 m x 5 m) in the tidal creek assemblage containing seedlings grown under nursery conditions initially had greater plant height on average than those that were revegetated with direct propagule implants (Figure 12). This pattern was maintained through to 2019, but by 2020 the median value was equal to that in the propagule plots. These differences are very marginal however and are not statistically significant. As such, the field data indicate that no long-term benefit appears to be derived from planting established mangrove seedlings which have been cultivated in a nursery environment.

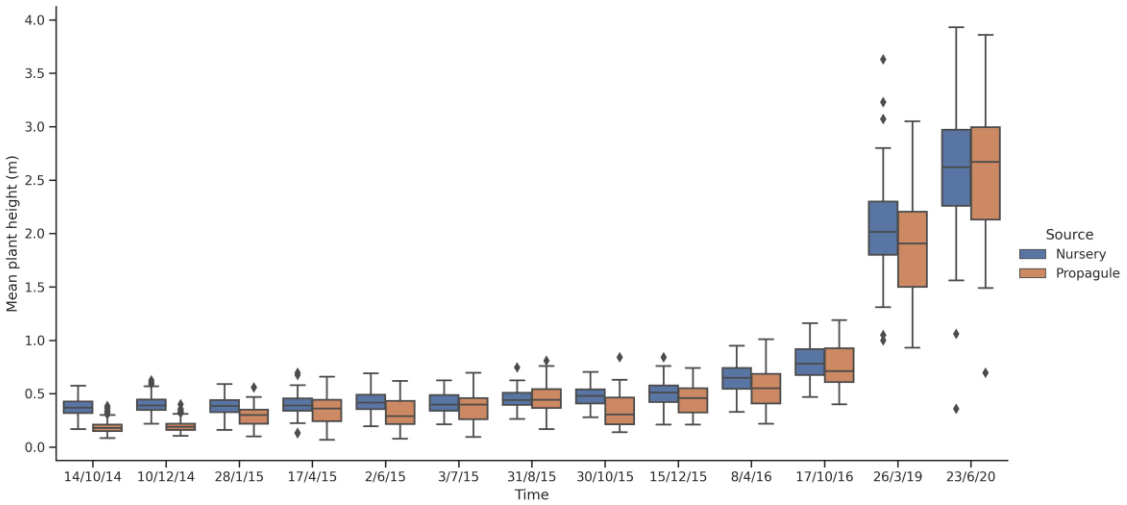

Figure 12 – Field measured change in plant height during the course of the rehabilitation experiment. Data shown are from the tidal creek assemblage. Note that there are missing data points for the 2017/18 season, growth is more gradual than it appears.

Minor differences in canopy height and cover between nursery grown and direct propagule implant plots were also detected in the terrestrial laser scanning data (Figure 13). The tidal creek assemblage showed higher canopy height for both planting techniques than the tidal flat, and the values obtained from point-cloud analysis were very similar to those obtained from the field measurements (Figure 13a). Canopy cover was consistent across both the treatment types and the two tidal assemblages (Figure 13b).

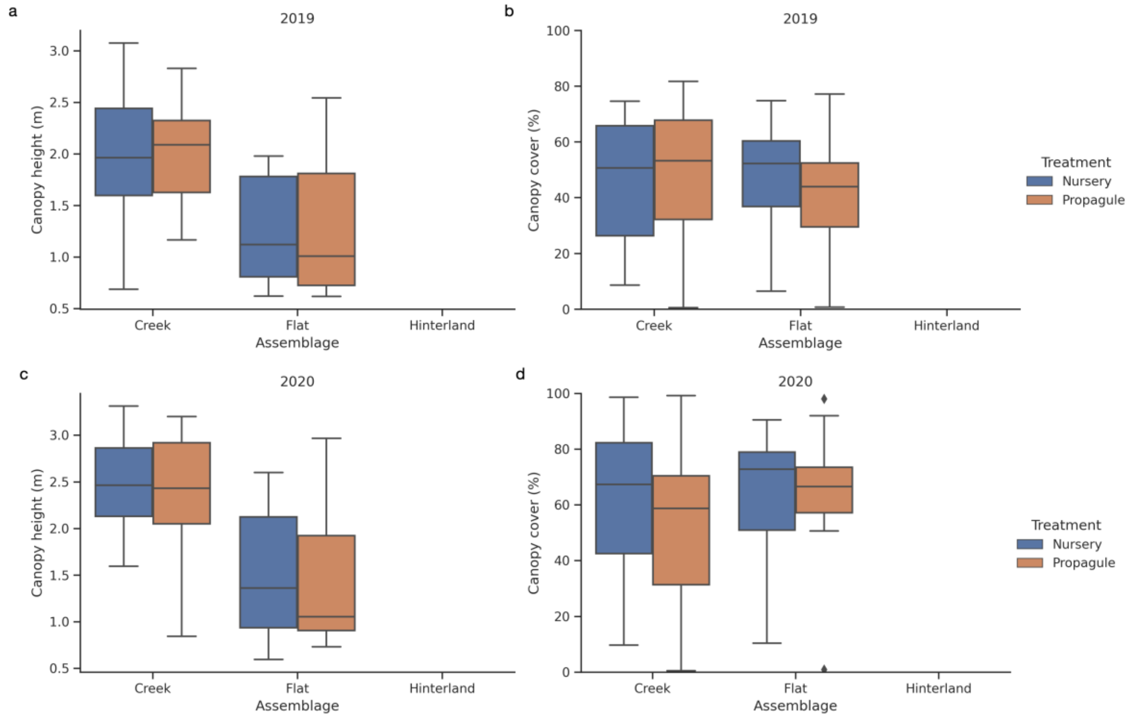

Figure 13 – Terrestrial laser scanning measured variation in canopy height (a,c) and canopy cover (b,d) between monitoring plots established to track the success of nursery seedlings and direct propagule implants. No data for the hinterland margin as this assemblage was not replanted.

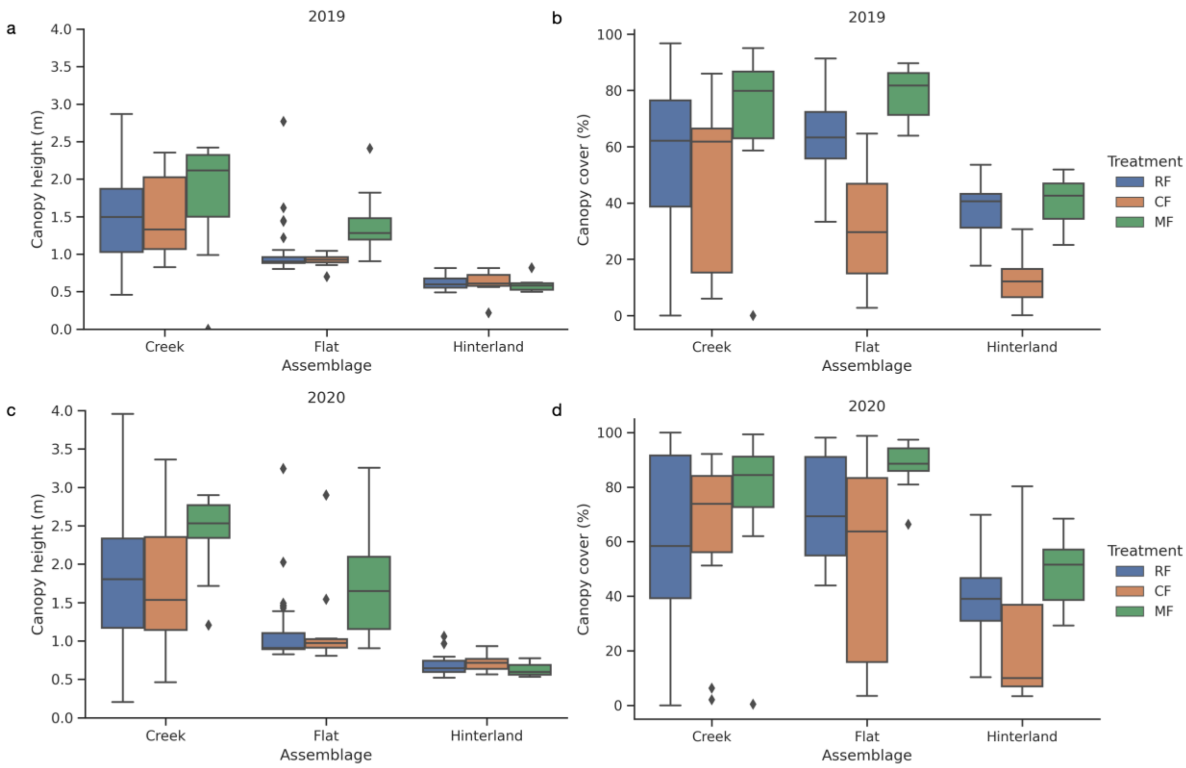

Figure 14 - Terrestrial laser scanning measured variation in canopy height (a,c) and canopy cover (b,d) between recruitment, control, and monitoring fences.

4 Project implications

Terrestrial laser rapidly measured canopy height distribution across different assemblages of the rehabilitation site. It provided an effective assessment of the success of natural recruitment at the 10 pairs of rehabilitation and control fences, as well as broader assessment of seedling establishment at the 83 other recruitment fences installed within the corridor. Patterns of temporal change in canopy height, canopy cover, and growth were also measured between 2019 and 2020 with the TLS instrument. Laser measured height data generally corresponded closely to values measured in the field (Figure 8).. The TLS approach provided insights into canopy cover and cover change, which deviated from the height patterns. Canopy cover is very challenging and time-consuming to measure in the field, and its quantification by TLS provides a more holistic measure of structural state and dynamics. However, the TLS data collected during this pilot study was not suitable for the automated segmentation of individual plants the extraction of individual plant attributes. As such, based on TLS alone, rehabilitation progress could only be evaluated in terms of overall height/cover characteristics at the patch scale, rather than as a percentage survival score relating to the number of planted individuals nor could rates of natural recruitment outside of fence plots be determined. TLS data collected across this site over multiple years provided valuable insights into how the use of this technology might be optimised in future studies and monitoring strategies.

4.1 Optimising terrestrial laser scanning sampling design

The TLS surveys on all three occasions were conducted in a linear scan position configuration. Ideally, scans would have been collected with a grid-based design which reduces occlusion and ensures a more homogenous distribution of laser returns across the study site (Wilkes et al. 2017). Grid-based scanning was not possible due to time-constraints associated with the low-tide window, difficulty in moving through site (waterlogged mud), and reluctance to disturb the rehabilitating vegetation (trampling/compaction). Preliminary analysis of the linear scan position data showed that plant canopies were still well represented in the scan data as the time-of-flight nature of the scanner and its very narrow beam divergence enabled it to pass through tiny gaps in foliage and sample the full canopy extent of individual plants. However, the degree of occlusion (obstruction of the laser beam by vegetation/terrain casting shadows) in the datasets increased in each year of surveying, as the vegetation grew taller and denser. The canopies of individual plants were still well captured in the 2019 and 2020 datasets, despite considerable thickening, but the degree of occlusion of the terrain surface is likely to continue increasing through time.

Terrain occlusion is in itself not a critical limitation for the monitoring of vegetation canopies, however it becomes important when creating and working with normalised canopy height data, i.e., when transforming point-clouds into height above ground level as opposed to height above sea level (Stobo-Wilson et al. 2021). As the vegetation at the site grows denser, it becomes harder to receive terrain points through them at oblique scanning angles, preventing accurate height normalisation of plants furthest away from the scanner. Potential avenues for alleviating these issues when grid-based designs are not possible include: i) elevating the scanner higher to ensure more acute scanning angles of the terrain surface; ii) complimenting TLS surveys with airborne LiDAR for high-quality terrain model generation; and/or iii) utilizing the terrain surface generated from earlier surveys to gap-fill missing terrain points in the more recent surveys.

4.2 Point-cloud processing improvements

The 3D visualisations of the rehabilitation study site created from TLS surveying highlight the rich level of detail that is possible to capture with this approach (**Error! Reference source not found.** - Figure 7). However, translating these 3D point-cloud into ecologically meaningful metrics remains a challenging task (Calders et al. 2020). Although the measures of canopy height and cover that were extracted in this study are very informative for understanding the restoration progress – extraction of individual plant status would be very beneficial and would have enabled more direct comparison with field-measured variables. Individual tree segmentation algorithms that have been successfully applied in a variety of ecosystems settings from point-cloud data (Tao et al. 2015, Burt et al. 2019, Liu et al. 2021), but these established techniques were not able to segment the young mangroves reliably. Additional research effort would be required to adapt existing segmentation techniques to the fine-scale structure of young mangrove plants with their complex above ground rooting structures. Furthermore, the presence of the rehabilitation infrastructure in the site, such as the recruitment fences (Figure 15), added complexity to the point-cloud classification and height normalization steps (page 13). Manual removal of these features from the point-cloud would be possible, but would be a time-consuming undertaking, complicated by the close proximity of mangrove recruits to the fences. Automated classification and extraction of these features may benefit from the adoption of Machine Learning algorithms. A large number of training samples would need to be digitised for calibration and validation, but emerging use of Deep Learning for point-cloud classification shows much promise (Widyaningrum et al. 2021).

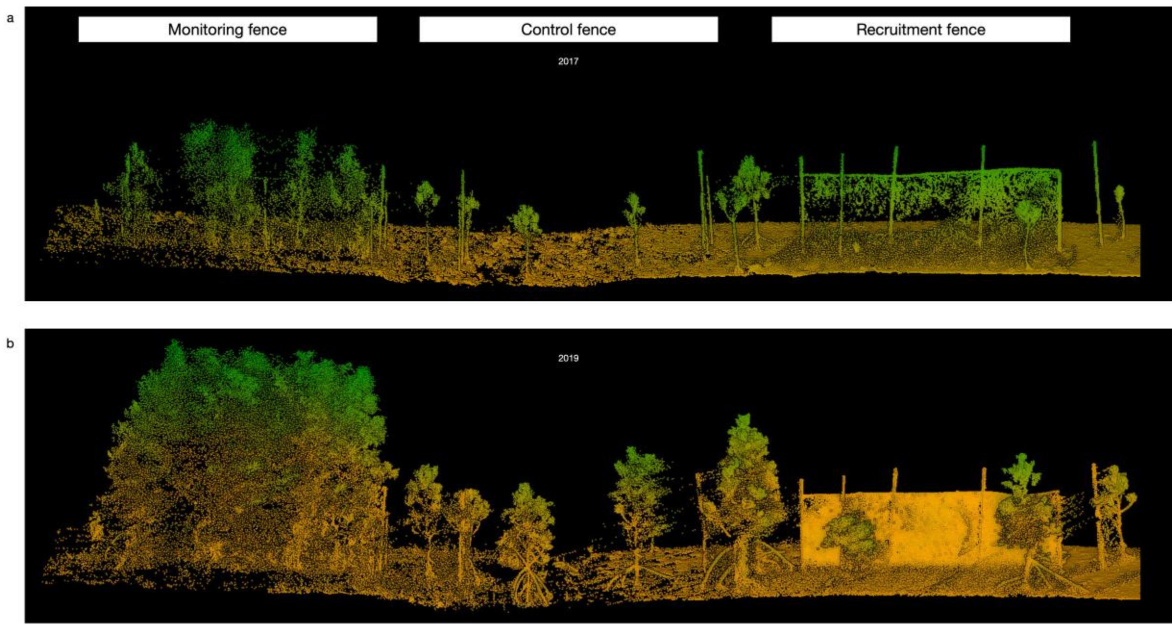

Figure 15 - Side view of terrestrial laser scanning data collected across a monitoring, control and recruitment fences in 2017 (a) and 2019 (b).

5 Conclusion

Terrestrial laser scanning (TLS) proved to be a viable option for the measurement and monitoring of mangrove canopy height and cover within the rehabilitation experiment. It provided comprehensive spatial coverage of the full rehabilitation zone, in addition to complimenting field-based measurements collected in the monitoring plots and fence quadrats. The data collected during this pilot study was not suitable for automated individual plant segmentation and characterisation, but this could be achieved in future studies through the use of comprehensive grid-based scanning designs and the inclusion of Machine Learning point-cloud classification techniques. We anticipate that as the vegetation covers more fully, the density and height of mangroves in some assemblages will reach a point where occlusion of the TLS instrument's laser will be prohibitively high for reliable 3D characterisation. The delayed reforestation observed in the hinterland and seaward zones (< 30% cover after 6 years) indicates that TLS could be used to reliably document recovery in these assemblages over the longer term. High-resolution airborne scanning from a drone-based system may offer a suitable alternative in coming years for continued tracking of 3D structural changes.

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For further information

CSIRO Land and Water
Shaun R Levick
+61 475 884 038
shaun.levick@csiro.au
csiro.au/land-and-water