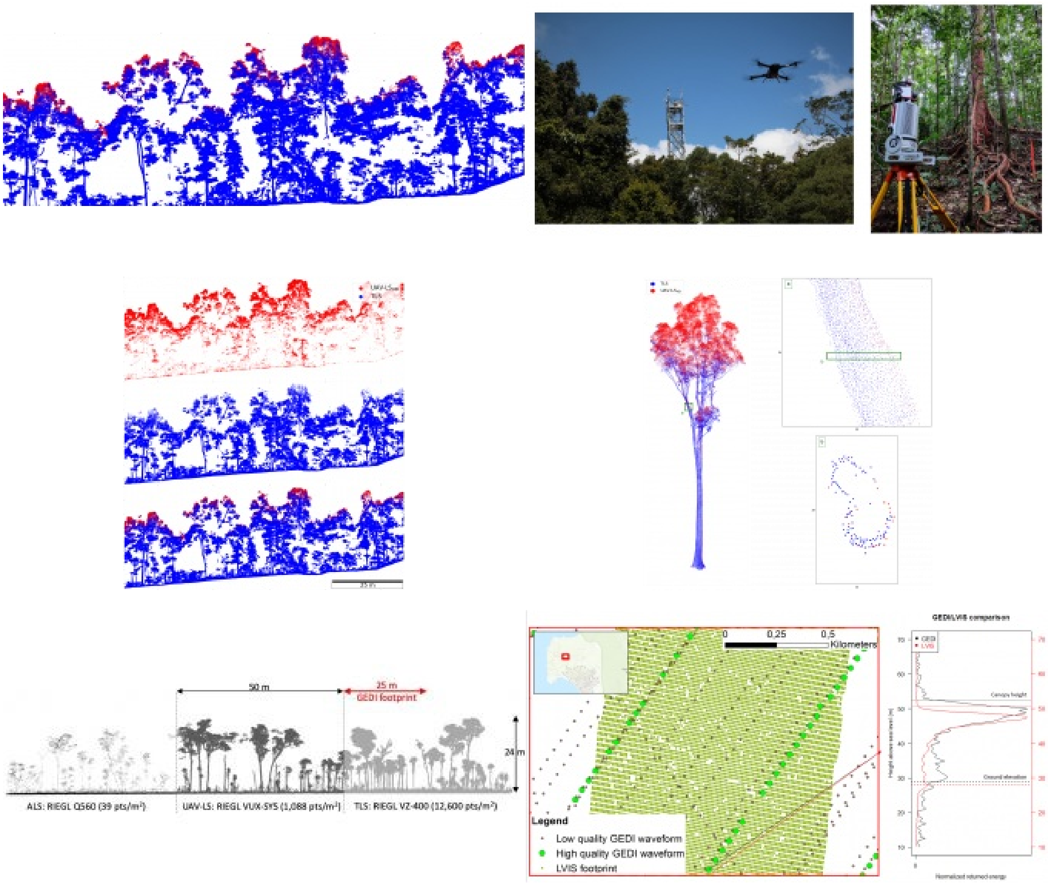
EXPLORING 3D INFORMATION ACROSS SPATIAL SCALES IN FOREST ECOSYSTEMS

Upscaling of terrestrial laser scanning through fusion with remote sensing data



Terrestrial laser scanning is increasingly being fused with air/spaceborne Lidar to characterize vegetation structure across a range of forest ecosystems. This article explores the potential of this approach to support scaling up for larger areas in practice.

Terrestrial laser scanning (TLS) is an important tool for plot-scale measurements of tree and forest structure. These local measurements are meaningful to support quantification of a forest's carbon balance and long-term forest monitoring. Typically, the upscaling from individual trees to local plot measurements to regional or national estimates is facilitated by the coupling of TLS data with airborne and spaceborne Lidar. There has recently been an increase in the fusion of TLS data with air/spaceborne Lidar to characterize vegetation structure across a range of forest ecosystems.

TLS data can already provide accurate estimations of tree volume and biomass. This is crucial to monitor carbon changes as a result of climate change, as well as for forestry and forest management. Moreover, the rich 3D datasets that TLS can provide are becoming ever-more widely used in environmental science in general, and ecology in particular. Specifically, there are many open and important science questions regarding the relationship between tree form and function that 3D information is helping to unpick. In addition, a range of other areas relating to biodiversity, habitats and movement of birds, insects and small mammals are also a function of forest structure. Next, branch architecture traits could further be related to leaf and wood properties at the whole tree level. Unfortunately, the upscaling to larger areas in practice is limited to the amount of resources that can be allocated to the collection of TLS data over larger areas (>10ha). In this context, the potential of other laser scanning platforms (spaceborne, airborne, unmanned aerial vehicles) is interesting in the context of fusion with TLS data.

Figure 1: The left-hand image shows a RIEGL RiCOPTER with RIEGL VUX-1UAV laser scanner flying over a wet tropical forest plot in Australia. The right-hand image shows a RIEGL VZ-400 terrestrial laser scanner mounted on a

tripod in a wet tropical forest plot in Australia.

In general, data fusion can be regarded in two different ways. On the one hand (type 1), fusion can refer to the combination of two individual datasets into one unique new dataset. In this case, the resulting (fused) dataset builds on the strengths of each sensor and gives a more complete view of the sampled object. Two datasets with a different point of view are co-registered and combined into one point cloud in order to reduce the occlusion which is present in both separate point clouds. This type of fusion is typically interesting when both individual datasets are representing the same level of spatial detail. On the other hand (type 2), separate datasets can be spatially aligned (co-registration) but not converted into a single unique dataset. This is typically the case when the individual datasets have very different levels of detail. However, due to the complementary spatial extent, this type of fusion is not only interesting to study changes of structure over time, but is also crucial in the context of calibration and validation for spaceborne remote sensing products.

Terrestrial and UAV Lidar fusion

To cover larger areas while maintaining a comparable level of detail compared to TLS, unmanned aerial vehicles (UAVs) equipped with laser scanners (UAV-LS) are being explored as a possible solution to speed up the scanning process over larger areas (>1-100ha). Currently there are multiple commercial UAV systems available, with a large variation in data quality. Recent UAV-LS systems have produced point clouds with point densities ranging from 50 to >4,000 points per square metre. UAV-LS demonstrates significantly higher point density at lower cost and with higher flexibility, but with significantly smaller spatial coverage when compared to traditional airborne laser scanning (ALS).

The fusion of TLS and UAV-LS into a single fused dataset is particularly interesting as these two techniques capture different parts of the forest (Figure 1). Due to its above-canopy view, UAV-LS could account for the canopy parts which are occluded in TLS and improve structural metrics derived on plot and tree level. Therefore, high-density UAV-LS data is preferred, especially for dense and structurally complex tropical forests. A good spatial alignment of the UAV-LS and TLS point cloud can be achieved when a critical number of common spatial features are present to act as tie points (Figures 2 and 3).

Figure 2: Illustration of fusion results at plot level for TLS and multiple returns of a high-density UAV-LS flight in a wet tropical forest plot.

The fused point cloud can not only be used to improve structural metrics, but also as a reference to investigate the potential and limits of the standalone TLS and UAV-LS. Moreover, the fused point cloud could be applied as a local calibration tool to improve standalone UAV-LS structural estimations at the landscape scale.

Terrestrial and airborne Lidar fusion

As outlined above, a key challenge in making the best use of these new sources of 3D information lies in combining them in such a way as to bring the best, most useful information of each source together into a single dataset. The major advances in measurements of individual tree structure from TLS and UAV-LS are in part limited by scale. ALS is embedded in forestry management and practice, as well as in environmental science, in part because it can cover large areas rapidly.

Figure 3: Illustration of fusion results at tree level for TLS and multiple returns of a high-density UAV-LS for a tropical tree. Subplots â€˜aâ€™ and â€˜bâ€™ represent different zoom-ins on the tree.

The relatively long heritage of ALS means that there are a wide range of established tools and workflows for extracting tree and forest information, and currently more so than for TLS and UAV-LS. ALS typically provides estimates of canopy height, stem density and potentially vertical structure. Needless to say, the trade-off is the detail: ALS provides less than a hundred points per square metre, compared to potentially thousands from UAV-LS (and more from TLS), and generally with much lower canopy penetration and larger footprint size (Figure 4). But ALS is, and will remain, a vital bridging tool, particularly in linking plot-scale measurements to spaceborne ones. ALS underpins many local, regional and national estimates of canopy cover (particularly in urban environments), carbon stocks, growth and yield, as well as habitat types, forest change maps, etc. As a result, there is a hugely important time series of ALS going back several decades in some places.

A lot of development in combining ALS with TLS has been focused on how to relate these more aggregated ALS-derived canopy properties to tree-scale detail from TLS. The challenge of co-registering TLS and ALS point clouds is even greater than for TLS to UAV-LS, mainly due to the much greater area covered. While technological improvements in platform location and attitude are certainly helping, the next steps in integration may be algorithmic, i.e. a SLAM-like approach but at larger scales, based on the datasets themselves. There has already been significant development in identifying and delineating individual tree crowns from large-area ALS coverage, including via machine learning/deep learning. Combining this with the information from TLS is already allowing improved matching at the individual tree scale, particularly in less dense forest areas.

An alternative approach is to go the other way, relating plot-scale aggregate estimates of height and vegetation density from TLS to ALS (potentially via UAV-LS). This has the advantage of not requiring co-registration at the tree scale, and so is a very attractive pragmatic approach. The drawback is the loss of the detailed tree-level information. The importance of establishing links between ground and airborne data is widely recognized. New Committee on Earth Observation Satellites (CEOS) activities make this explicit for applications relating to above-ground biomass and carbon stocks. For example, the GEO-TREES initiative seeks to establish a network of a hundred or more permanent 1 ha biomass reference sites across the globe, which are urgently needed to improve calibration and validation of satellite and airborne estimates of forest carbon.

Figure 4: Illustration of different Lidar datasets at the tropical savanna Litchfield TERN supersite in Australia. All point clouds are down-sampled to 0.02m voxels (from Calders et al. 2020).

Airborne and spaceborne Lidar fusion

Spaceborne Lidar datasets providing information on forest/canopy structure are limited to three different missions: ICESat-1 (2003-2009), ICESat-2 and Global Ecosystem Dynamics Investigation (GEDI). As the names suggest, ICESat 1 and 2 were primarily designed to measure the growing and shrinking of ice sheets and only GEDI was specifically designed to map canopy structure. GEDI was launched late 2018 and is currently orbiting the Earth from its vantage point on the International Space Station. GEDI collects full-waveform Lidar data, so instead of the detailed point clouds resulting from TLS measurements, the instrument collects a ‘waveform’ containing information on ground elevation, canopy height and vertical canopy structure at each sampling location, whereby the sampling location spans an approx. 25m-diameter circle. Given the vantage point from space, the sampling pattern is much less dense than from airborne Lidar data, but the advantage of GEDI is that it collects consistent Lidar measurements across nearly all temperate and tropical forests (between roughly 51.6 degrees North and South latitude).

Data fusion involving spaceborne Lidar data is exclusively of the second type mentioned above; two datasets are spatially aligned (co-registered) but not converted into a single unique dataset. High-resolution airborne Lidar datasets, spatially aligned with spaceborne data, can be used to validate the spaceborne measurements of canopy height and the vertical profile (Figure 5). Spaceborne and airborne fusion can also be used to assess changes in canopy structure over time, for example, using the time lag between data collection. Differences in canopy structure as measured by the two instruments can potentially be attributed to natural and human-induced processes. Additionally, airborne reference datasets can be used to train models to extract more information from the spaceborne Lidar datasets than is currently possible. Going even further, spaceborne and airborne Lidar datasets could even be fused with other spaceborne remote sensing data products at high resolution to train advanced machine learning models to estimate canopy structure over vast areas at higher resolution than is possible with spaceborne Lidar data alone.

Figure 5: The left-hand image shows an illustrative scanning pattern of an airborne full-waveform Lidar system (LVIS) and GEDI in Gabon. The right-hand image shows a comparison between a Lidar waveform collected by LVIS (red) vs GEDI (black); the retrieved ground elevation and canopy height are indicated with dotted lines for both instruments. Note that these datasets were collected roughly three years apart, which may add to the observed differences in canopy structure.

Conclusion

3D information on the Earth’s forest ecosystems is essential to support long-term carbon monitoring, especially now that the world’s climate is under increased pressure. TLS data can already provide accurate estimations of tree volume and biomass, but in practice the spatial coverage is limited to just a few hectares. Larger areas can be mapped with UAV, airborne and spaceborne Lidar and this article has described how such data can be fused with TLS in two different ways to support upscaling.

Further reading

Calders, Kim, et al. Terrestrial laser scanning in forest ecology: Expanding the horizon. *Remote Sensing of Environment* 251 (2020): 112102.