Towards the Estimation of Tree Biomass Changes in the Sparse Subarctic Forests Using Stereo WorldView 3 Images and Historical Aerial Photographs

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Abstract—**Subarctic forests are open woodlands sparsely populated by small trees having narrow crowns. They cover, in Canada alone, an area of more than 2.5 million km^2. Spread between the 50th and 70th northern parallels, these forests fall within the regions that are experiencing some of the greatest climate change that will likely induce variations in forest biomass. These changes could go undocumented due to the high costs of data acquisition in such remote areas of Canada. Airborne surveys (photo or lidar) are logistically difficult, and conventional remote sensing based on 2D satellite images (e.g., Landsat) lacks accuracy. Our goals are therefore to use new very high resolution satellite stereo images (31 cm pixels) to reconstruct 3D models of subarctic forests, and use historical stereo aerial photos acquired since the 1950s to create similar 3D models representing the structure of these forests in the past. In this study, we have reconstructed a digital terrain model (DTM) using stereo measurements on WorldView 3 images of sparsely wooded areas. We then performed similar stereo measurements on the top of trees and calculated their height by subtracting DTM elevations. These height measurements were in good agreement with reference data, and can afterward be used to estimate tree biomass. Similar measurements will be performed on historical aerial photographs, and the tree biomass changes, as a function of tree height and number of trees, will be estimated.**

Keywords- forest; subarctic; WorldView; height, biomass.

I. INTRODUCTION

Subarctic forests, more specifically the open canopy lichen woodlands of the taiga ecoregions, cover more than 2.5 million km^2 in Canada alone, and occupy a good proportion of other northern nations, such as Russia. They are composed of sparse and rather short trees, and low species diversity (essentially, black spruces and dwarf birch). Roughly located between the 50th and 70th parallels, these environments will experience the greatest climate change. These generally include warming, but may involve an increase or decrease of precipitations. All these variations will likely induce changes in the forest height, density, productivity and species composition [1]. It can be hypothesized that, if growth is not limited by water availability, a significant rise in their productivity caused by the lengthening of the growing season and CO_2 fertilization will increase their biomass density (Mg ha^{-1}), and therefore their capacity to sequester carbon [2]. Such is the case for example in the province of Quebec, Canada, where temperature and precipitation rose [3]. Few resources are however dedicated to the inventory of these vast forests, due to the high cost of airborne and field data acquisition in such remote areas, and because of their low commercial interest. This leaves us with very few precise data on the structure of these forests [4]. Using two-dimensional (2D) remote sensing methods [5], such as regressing forest height, density or biomass against the reflectance of Landsat images, or the backscattered microwave energy of spaceborne radars (e.g., ALOS/PALSAR), leads to prediction models having only moderate accuracy [6]. To calibrate the regression models, numerous field measurements need to be done within 1-2 years of image acquisition, in hardly accessible areas. This calibration is required for any new 2D image. Moreover, upcoming 3D satellite missions (circa 2020), such as BIOMASS (InSAR), or GEDI (lidar), will be on orbits that limit acquisition to 50° N, thus missing subarctic forests [7]. Airborne laser scanning (ALS) is extremely expensive to deploy in these regions because of remoteness, airport rarity, and the required very high laser point density [8]. Indeed, taiga trees are sparse and have very narrow crowns. Many go undetected by low-moderate density ALS because they fall in the gaps between zigzag-patterned laser scan lines [9]. Furthermore, we recently showed that when trees are sparse (discontinuous canopy), the estimation of height becomes ambiguous when using InSAR from TanDEM-X, precluding the use of this sensor for subarctic forests [10].

High resolution imagery (pixel size <=0.3 m) does not suffer from the problems of ALS (inter-scan line gaps) or InSAR (complex scattering behaviour in sparse forests). Stereo measurements performed on aerial images allow the accurate estimation of tree height when ground elevation data is available [11]. Recently, stereo-image acquisition from space, has significantly improved [12]. Notably, the WorldView-3 and 4 imaging sensors from Digital Globe, launched respectively in August 2014 and November 2016, offer an unprecedented resolution from space (0.31 m). They have stereo imaging capacities and their orbit covers the globe up to 80° N, thus encompassing all of the subarctic forests. The photogrammetric quality of WorldView 3 has been shown to be high [13]. Since subarctic forests are sparse, the ground is often visible between trees, thus enabling the reconstruction of a digital terrain model (DTM) without the use of airborne lidar. If the apex of trees, typically narrow black spruces (*Picea Mariana*) in northern Canada, the height of single trees could be measured by stereo measurements performed on tree apices followed by subtraction of the ground elevation. Biomass of single trees can then be predicted using allometric equations. Repeating this operation for all visible trees over given plots then allows the calculation of biomass density. For areas where historical aerial photographs exist, the same operation can be performed, allowing the estimation of biomass change. As a first step towards these goals, we have assessed our capacity to estimate the height of single trees on a stereo-pair of WorldView 3 images in a sparse Canadian forest. The results were compared to the values extracted from an airborne lidar canopy height model (CHM). We have also verified if the manual procedure for measuring tree height could be automated by applying image matching techniques to the WorldView images to create a 3D point cloud.

We first explain the methods used for measuring tree heights on the WorldView stereopairs and how we compared these measurements to corresponding lidar heights (section II). In the following section, we present quantitative as well as image-based results. Finally, we discuss these results and provide an outlook of future research (section IV).

II. METHODS

A. Study region and data

Pending the acquisition of WorldView 3 or 4 imagery in true subarctic forests (planned for summer of 2017), we have used available data (imagery and lidar) in an area of the Canadian boreal forest centered at 49°54' N, 71° 34' W. The area has a gentle topography, and is populated mostly by black spruces growing in closed or open canopies. Sparsely wooded subareas were selected for this study.

A WorldView 3 stereo-pair acquired on June 6th 2015 in ortho-ready format, with rational polynomial coefficients (RPC), were used. View angles were respectively 12.7 and 24.3 degrees off-nadir, and sun elevation was 61.5 degrees at the time of acquisition. While nominal pixel size at nadir is 31 cm, the obliquity of the images caused this size to be slightly larger.

An airborne lidar CHM was retrieved from the province of Quebec's (Canada) open lidar archive. This data was captured in summer of 2013, and transformed to a 1 m resolution raster CHM by the provider. The initial lidar point clouds had a density of at least 2 points per m^2 (first or single returns). The 2D coregistration between the WorldView stereo-model and the lidar models was checked visually and found to be very good. The RPCs were therefore not adjusted.

B. Measurements

An interpreter performed stereo-measurements on the WorldView pair viewed in stereo using liquid crystal shutter glasses, and checked his pinpointing of tree tops using a monocular split screen strategy. The elevation of 30 tree apices were thus measured in 3D. For each tree, a similar measurement was made of ground elevation in the immediate vicinity of the tree. All stereo-measurements were performed using the Summit Evolution software application (DAT/EM Systems International, U.S.A.). The stereo height of trees (H_S) was computed by simply subtracting the ground elevation associated to the tree from the elevation of its apex. The lidar tree height (H_L) was extracted by reading the CHM value of the highest lidar pixel within each crown corresponding to the stereo measurements. The set of H_S and H_L values were compared by computing the bias (average of H_S - H_L), root mean square error (RMSE), and r^2. The ground elevations at the XY position where terrain level stereo measurements were made (GE_S) were compared to the elevations of the lidar DTM at these positions (GE_L). The set of GE_S and GE_L values were compared using the method used for H.

Three image matching algorithms were tested: Correlator 3D (Simactive, Canada), MapMatrix (VisionTek, China), and OrthoEngine (PCI Geomatics, Canada). The number of available matching algorithms is limited by the fact that solutions applicable to (pushbroom) WorldView imagery are still few, compared to those using (full frame) airborne imagery. In our trials, the 3D models produced by Correlator 3D were the best, so results are presented only for this algorithm. Subtracting the ground elevations of the lidar DTM from the surface elevations automatically extracted from the stereo WorldView images produced a stereo-lidar CHM (CHM_{SL}). Alternatively, low photogrammetric points within local neighborhoods were classified as ground points and interpolated into a stereo DTM (DTM_S). An entirely stereo-photogrammetric CHM (CHM_S) was generated by subtracting the WorldView surface points from the DTM_S. These models (CHM_{SL}, CHM_S) were each compared pixel-wise to the lidar CHM (CHM_L) using, again, bias, RMSE and r^2 (i.e. CHM_{SL} - CHM_L , CHM_S - CHM_L).

III. RESULTS

Figure 1 shows corresponding excerpts from each of the WorldView image forming the stereo-pair. In can be seen that individual trees can be well resolved, even in the case where trees are short and crowns are narrow.

H_S values ranged from 3.7 m to 14.7 m, with a standard deviation of 2.7 m. Compared to lidar, a bias of 0.19 m, a RMSE of 2.11 m, and a r^2 of 0.63 was obtained. Figure 2 presents a scatter plot of the H measurements. A clear outlier caused by a tree that was likely most entirely missed by lidar led to a +7.7 m difference (top-left data point in Figure 2). When this observation was removed, the bias and RMSE dropped to -0.07 m and 1.62 m respectively, and the r^2 increased to 0.77. In the case of ground level measurements, these values were respectively -0.73 m, 1.06 m, and 0.98.

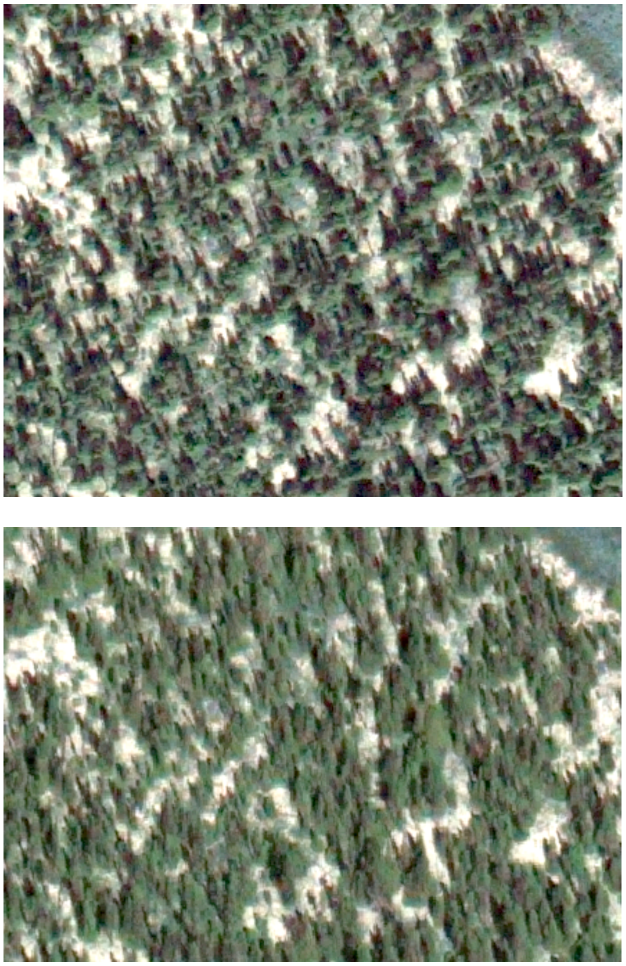

Figure 1. Corresponding excerpts of the WorldView 3 stereo pair.

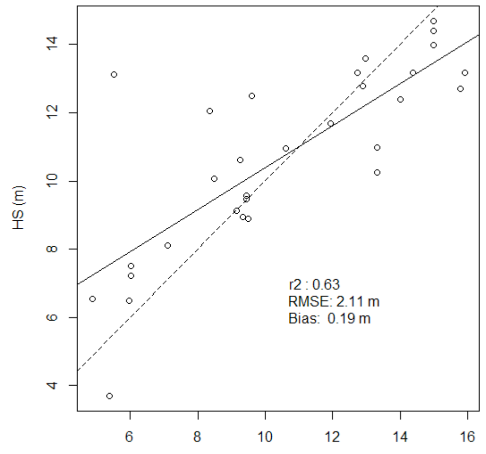

Figure 2. Scatterplot of the stereo (H_S) vs lidar tree heights (H_L).

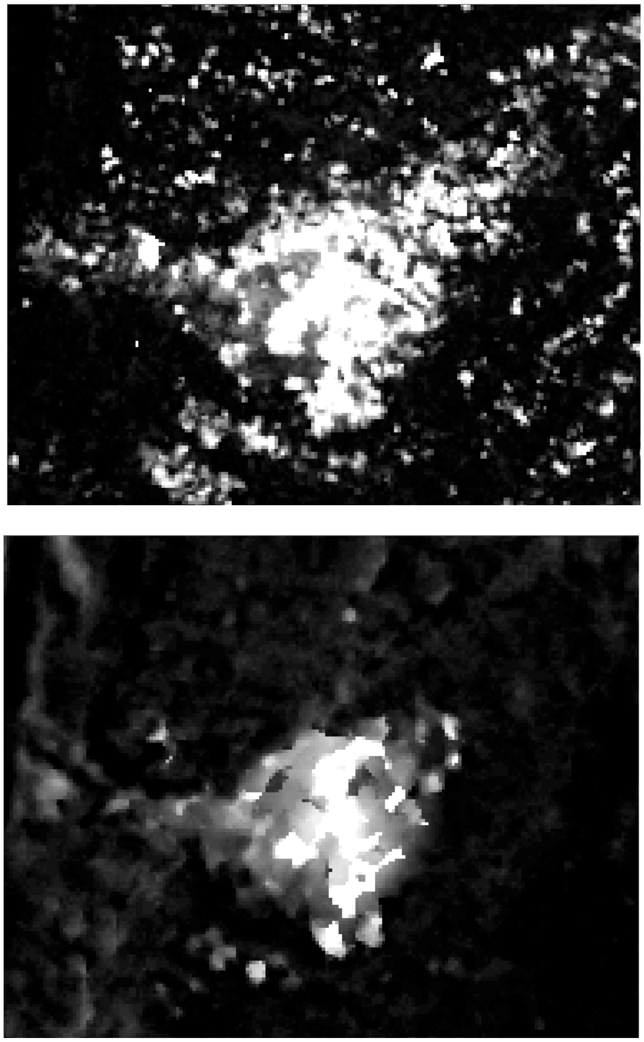

Figure 3. Lidar (top) and stereo CHM excerpts (unrelated to Figure 1).

Excerpts from the lidar and stereo-lidar CHMs appear in Figure 3. The CHM_{SL} is clearly lower and less resolved than the CHM_L. The bias, RMSE and r^2 between the different types of CHM are respectively, for CHM_{SL} - CHM_L, -0.51 m, 2.98 m, and 0.29, and for CHM_S - CHM_L, -1.2 m, 3.13 m, and 0.28.

IV. DISCUSSION AND CONCLUSION

The discrepancy between the H_S and H_L measurements must be interpreted with care. At this phase of our study, lidar was used as reference for tree height, despite shortcomings. The lidar point density was rather low for ensuring that the top of the narrow crowns be hit in such a way that they would have generated a return at an elevation close to the tree apex. Furthermore, the rather large pixels size of the CHM (1 m) may have introduced more uncertainty. In this context, it appears that the manual measurements are quite accurate (conservative estimate of RMSE = 1.62 m). In general, we may expect the height measurement to be slightly underestimated, both in the stereo and lidar measurements. The presence of shrubs on the ground may have elevated the perceived terrain level, while lack of resolution of the apex of the crown may have diminished the top elevation. The larger ground level bias, at -0.73 m, accompanied with a lower RMSE (1.06 m) suggests that there might have remained a slight Z misregistration (negative bias) but that stereo measurements are actually very precise when the object is easily scannable by lidar (lower G_S - G_L RMSE).

Automating the creation of tree height data through stereo-matching will represent a significant challenge in light of the results we have presented. The coefficient of determination (r^2) did not exceed 0.29, while they reached 0.77 for manual measurements. This is not entirely surprising for these types of sparse forests. Because the trees do not form a closed carpet-like canopy, the surface to be reconstructed is very complex. It is formed by a smooth base layer (terrain) over which sharp isolated peaks (trees) protrude. In many circumstances, the side of a tree is visible in one image, and the opposite side in the other (Figure 1). Also, tree leaning caused by obliquity occurred in different directions. The relatively high level of obliquity of the stereo pair that we have used probably aggravated this situation. It seems unlikely that current image matching algorithms will be able to produce usable photogrammetric points clouds for subarctic forests before significant improvements are made to their matching strategies.

Nevertheless, we have shown that using a manual stereo measurement approach, the accuracy of the individual tree heights is at least 1.62 m. Once this is ascertained in a true subarctic forest using precise field measurements of tree height, it signifies that we could easily measure the height of single trees of any plot, however remote and inaccessible it may be. This method would probably not be applied wall-to-wall over the vast subarctic forests of the world on the short term due the high cost of the imagery. However, it can be used as a dense sampling tool across large regions. This would greatly enhance our capacity to create new knowledge on the current state of these forests. Time series of these measurements, whether pastward using historical images, or forward by repeating similar measurements in the future, will allow a better understanding of the dynamics of height, density, and therefore biomass of sparse but vast subarctic forests.

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