Arbetsrapport

Från Skogforsk nr. 828–2014

Evaluation of single tree-based estimates using terrestrial laser scanning in Sweden

Utvärdering av skattningar för enskilda träd baserade på markbaserad laserskanning i Sverige

Andreas Barth, Johan Holmgren, SLU, Lars Wilhelmsson & Maria Nordström

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The Arbetsrapport series comprises background material, descriptions of methods, results, analyses and conclusions relating to both current and completed research.

Titel:

Evaluation of single tree based estimates with terrestrial laser scanning in Sweden.

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Bildtext:

Terrestrial laser scanning based inventory in Österbybruk in 2010. Garret Mullooly from TreeMetrics.

Ämnesord:

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SKOGFORSK

Uppsala Science Park, 751 83 Uppsala
Tel: 018-18 85 00 Fax: 018-18 86 00
skogforsk@skogforsk.se
skogforsk.se

Andreas Barth, SkogD. Researcher at Skogforsk from 2007 to 2014 with focus on forestry planning and inventory.

Johan Holmgren, Associate professor in Forest Remote Sensing at the Swedish University of Agricultural Sciences.

Lars Wilhelmsson, SkogD. Senior researcher in the fields of improved wood utilization including modeling and simulation for characterization of forest resources, Forest Operations and Products and development of industrial integration (since 1995). Tree breeder from 1979 to 1995.

Maria Nordström. TeknLic. Joined Skogforsk in 2008. Primary focus on measurements of diameter and length in harvesters. Also engages in the use of harvester data and information flows in the forestry sector.

Abstract

The aim of this report was to evaluate a method based on Terrestrial Laser Scanning (TLS) data to estimate the tapering of tree diameter, and to calculate the volume of individual trees. Data from felled trees measured by the harvester and manual measurements of diameters of logs was used as reference material in the evaluations. Data from TLS and harvesters was collected from a total of 73 field plots at two test sites, one in southern Sweden (Remningstorp) and one in northern Sweden (Strömsjöliden). Data was collected for a total of 938 trees. Individual stem profiles were compared, and evaluations were carried out at tree level of diameter estimates from first cut until the harvester's final cut. The volume was also calculated and evaluated. For visual comparisons data was also obtained from a number of control stems that were cross-measured manually by the harvester operator (KTR trees). At Remningstorp, the lowest standard deviation for the diameter estimates was between 15 and 20 mm for pine, and just under 12 mm for spruce (Figure 5). At Strömsjöliden, the standard deviation for the diameter estimates was approximately 10 mm (Figure 7). In all cases, the estimates corresponded best with harvester data up to a height of approximately 9 metres. The volume estimates also corresponded very well with the harvester measurements and, in principle, lack systematic errors (Table 1). The standard deviation at Remningstorp was 0.10 – 0.13 m³, depending on tree species. For Strömsjöliden the standard deviation was lower, 0.03– 0.04 m³, but there the trees were much smaller. The conclusion is that TLS gives very good estimates of the stem shape and volume of individual trees, data that will be useful when calculating yield.

Acknowledgements

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Skogssällskapet (*The Swedish Forest Society*) and Sveaskog are acknowledged for providing stands and operational resources for harvesting the stands. TreeMetrics was responsible for the TLS-based inventory and processing of data. We thank Garret Mullooly and Cian Mac a' Bháird for their contributions in the project. Additional thanks to those people who have been involved in the harvesting operation at Strömsjöliden and Remningstorp: Alexandra Frank and her colleagues at Sveaskog in Västerbotten for planning and managing the harvest operations, and Geir Eriksen at Skogssällskapet in Skövde; contractors and machine operators at LA Skog and Tidavads Skog AB for cutting down the trees and manually recording our sample trees in the on-board computer; Lena Jonsson at the Unit for Field-Based Forest Research at SLU for hosting and supporting our project; and Torbjörn Cruse at Cruse Datakonsult for developing a GIS tool for recording trees in the harvester. The authors also thank Kenneth Olofsson at SLU, John Arlinger, Nazmul Bhuiyan, Björn Hannrup, and Johan J. Möller at Skogforsk for valuable guidance, comments, and discussions during the study.

Uppsala, 10 September 2014

Andreas Barth	Johan Holmgren
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Sammanfattning

Tillsammans med SLU och det irländska företaget TreeMetrics har Skogforsk i ett antal projekt utvecklat metoder för skattningar på trädnivå som baserats på markbaserad laserskanning (TLS). En TLS mäter in den omgivande vegetationen genom att skicka ut laserpulser samtidigt som den roterar 360 grader. För varje retur registreras ett avstånd som ger ett 3D-punktmoln på den omgivande marken och vegetationen, inklusive trädens stammar och grenar (Figur 1). Punktmolnen från en TLS ger möjlighet att automatiskt göra detaljerade skattningar av enskilda träd, såsom trädens stamform, kvistighet och krök. Information som kan vara värdefull som indata i exempelvis skogsbrukets utbytesberäkningar.

Syftet med denna rapport var att utvärdera en metod baserad på TLS-data för att uppskatta trädens diameteravsmalning och för att beräkna volym på enskilda träd. Data från avverkade träd som mäts in med skördare och manuella diametermätningar på stockar har användes som referens i utvärderingarna.

Data från TLS och skördare har samlats in på 73 provytor fördelat på två testområden, ett i södra Sverige (Remningstorp) och ett i norra Sverige (Strömsjöliden). Totalt har data samlats in för 938 träd. Varje träd har märkts upp och vid avverkning har skördarföraren registrerat ID-nummer tillsammans med mätningarna från skördaren. 3D-punktmolnen från TLS har processats av TreeMetrics med deras egenutvecklade programvara AutoStem som skattar stamdiameter med ett intervall av 10-cm. Även i stamprofilerna från skördaren lagras diametermätningar med 10 cm längdintervall. Jämförelse har kunna gjorts mellan individuella stamprofiler och utvärderingarna har gjorts på trädnivå av diameterskattningar från trädets fällskär till skördarens sista kap. Även volymen har beräknats för denna del av trädet. Förutom jämförelse med skördarens mätningar fanns också data från ett antal kontrollstammar som korsklavats manuellt av skördarföraren, så kallade KTR-träd. En visuell jämförelse mellan stamprofiler från TLS, KTR (control) och skördare (harvester) finns publicerade i Appendix 1.

På Remningstorp var standardavvikelsen för diameterskattningarna som bäst mellan 15–20 mm för tall och strax under 12 mm för gran (Figur 5). På Strömsjöliden låg standardavvikelsen på diameterskattningarna kring 10 mm (Figur 7). I samtliga fall överensstämde skattningarna som bäst med skördardata på upp till cirka 9 meters höjd. Volymskattningarna överrenstämde också mycket bra med skördarnas mätningar och saknar i princip systematiska fel (Tabell 1). Standardavvikelsen på Remningstorp låg mellan 0,10 – 0,13 m^3 beroende av trädslag. För Strömsjöliden är standardavvikelsen lägre, 0,03 – 0,04 m^3 men där var också träden betydligt mindre.

Slutsatsen är att TLS ger mycket bra skattningar av enskilda träds stamform och volym. Resultaten visar på att TLS ger bra information om de enskilda träden för utbytesberäkningar. Utvärderingarna i studien fokuserar på enskilda träd och säger inget om hur bra metoden kan fungera i tillämpningar på beståndsnivå. För detta krävs bra urvalsmetoder och för inventering av alla träd på provytor krävs oftast att fler TLS-mätningar sker för att få information om eventuellt skymda träd. TLS kan användas för att subjektivt samla in data

om ett bestånds stamform och diameterfördelning. En annan tänkbar metod är att använda TLS tillsammans med information baserad på flygburen laserskanning eller stereobilder som ger stöd för att skatta beståndets totala volym och stamantal.

När data samlades in i detta projekt stamkvistades träden för att ge bra mätningar på trädens stammar och även för att få information om delvis skymda träd. Under projektets gång har dock algoritmer för att filtrerar bort laserreturer i trädens grenar utvecklats och blivit bättre. TreeMetrics har även förbättrade metoder för att skatta trädens avsmalning för områden på stammen som saknar mätdata. Detta är oftast högre upp i träden där grena skymmer sikten.

Summary

Together with SLU and the Irish company TreeMetrics, Skogforsk has carried out a number of projects in which methods were developed to obtain estimates at individual tree level on the basis of terrestrial laser scanning (TLS). TLS records the surrounding vegetation by transmitting laser pulses while rotating through 360 degrees. For each return, a distance is recorded that gives a 3D point cloud on the surrounding ground and vegetation, including tree stems and branches (Figure 1). The point cloud from a TLS enables automatic and detailed estimates of individual trees, such as the stem shape, and degree of branching and bending. This is information that can be valuable, for example, as input data for calculating yield.

The aim of this report was to evaluate a method based on TLS data to estimate the tapering of tree diameter, and to calculate the volume of individual trees. Data from felled trees measured by the harvester and manual measurements of diameters of logs was used as reference material in the evaluations.

Data from TLS and harvesters was collected from a total of 73 field plots at two test sites, one in southern Sweden (Remningstorp) and one in northern Sweden (Strömsjöliden). Data was collected for a total of 938 trees. Each tree was marked and, after felling, the harvester operator recorded its ID number and harvester-based measurements. The 3D point cloud from TLS was processsed by TreeMetrics, using their own AutoStem software that estimates stem diameter at 10-cm intervals. In the stem profiles from the harvester, diameter measurements were also recorded at 10-cm length intervals. This enabled individual stem profiles to be compared, and evaluations were carried out at tree level of diameter estimates from first cut until the harvester's final cut. The volume was also calculated for this part of the tree. In addition to comparisons with the harvester measurements, data was also obtained from a number of control stems that were cross-measured manually by the harvester operator (KTR trees). A visual comparison between stem profiles from TLS, KTR (control) and harvester is presented in Appendix 1.

At Remningstorp, the lowest standard deviation for the diameter estimates was between 15 and 20 mm for pine, and just under 12 mm for spruce (Figure 5). At Strömsjöliden, the standard deviation for the diameter estimates was approximately 10 mm (Figure 7). In all cases, the estimates corresponded best with harvester data up to a height of approximately 9 metres. The volume

estimates also corresponded very well with the harvester measurements and, in principle, lack systematic errors (Table 1). The standard deviation at Remningstorp was 0.10-0.13 m3, depending on tree species. For Strömsjöliden the standard deviation was lower, 0.03-0.04 m3, but there the trees were much smaller.

The conclusion is that TLS gives very good estimates of the stem shape and volume of individual trees, data that will be useful when calculating yield. The evaluations in the study focused on individual trees, but do not indicate how well the method could work in applications at stand level, for which good sampling methods would be needed. In order to carry out an inventory of all trees on a field plot, more TLS measurements would normally be needed to include information about any concealed trees. TLS can be used to subjectively collect data about stem shapes and diameter distribution in a stand. Another possible method is to use TLS together with information from airborne laser scanning or stereo images that help to estimate the total volume and number of stems in a stand.

When data was collected in this project, the trees were pruned to allow good measurements of stems, and also to obtain information about partially concealed trees. However, during the course of the project, algorithms were developed and improved to filter laser returns from tree branches. TreeMetrics has also improved methods to estimate the tapering of trees for areas on the stem that lack measurement data. This is often high up in the trees where branches block the view.

Introduction

In pre-harvest inventories, data on the stocking of the forest, including tree species composition and diameter distribution, is essential for making accurate predictions of forest products. Information about stem taper and stem defects is necessary in order to make accurate predictions of which products can be harvested. In Swedish forest inventories, diameters are typically measured with a calliper at breast height (DBH). Assumptions are then made about stem taper on the basis of DBH and height. However, various factors, such as silvicultural practice and age, cause the shape of the trees to differ not only from forest stand to forest stand, but also within forest stands (Möller et al., 2012). In recent years, technology and methods have been developed to measure diameter of the entire visible parts of stems. Terrestrial laser scanning (TLS) provides forestry planning with information on stem taper, branches, and sweep of the individual trees (Lindberg, 2012).

TLS provides a 3D point cloud with a large number of measurement points on the surface of the trees and other forest vegetation (Figure 1). Based on the 3D point cloud, trees are detected and diameters are estimated for all visual parts of the tree stem. For non-visible parts of the trees, diameters have to be estimated using stem taper functions. TLS data is collected from one sampling point. During the scanning, the TLS rotates 360º and takes measurements from the ground up into the canopy. Typically a scan at a sampling point with an appropriate resolution would take about 5-8 min. Data is assessed from all trees that are not hidden by other trees, so TLS can be used to assess measurements from a sample of trees. If all trees in a sample plot are to be included, more than one scan position is often required.

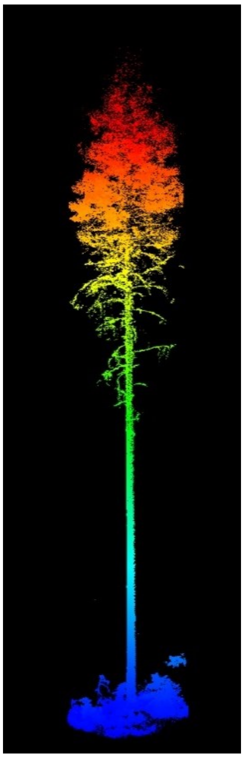

Figure 1.
Example of a point cloud from a TLS data set.

Accurate prediction of forest products can improve forestry planning and result in more precise deliveries to the customer. Punctual deliveries of the right products increases the value for the forestry customer and reduces the cost of logistics (Sonesson et al., 2008). Accurate predictions prior to harvest enable operations to be planned on the basis of customer requirements. Accurate prediction of products is based on bucking simulations (Arlinger et al. 2002). Using individual tree information, including tree species, stem taper, and stem defects, the bucking is simulated using the same requirements as in the harvester.

TLS provides more detailed information about individual trees than has previously been possible in forest inventories. Measurements from harvested trees can be used to evaluate the accuracy of the new technology. The harvester continuously measures the diameter from a height of approximately 80 cm up to the final cut in the tree, using the pruning knives in the harvester head. The diameter measurements of a modern and well-calibrated harvester typically have a standard deviation of 4.5 mm (Möller et al. 2008). To calibrate the measurements of the harvester, the operator carries out manual measurements on a sample of the harvested trees, using a calliper and measuring tape, and makes cross measurements typically at each metre of height (Arlinger & Möller, 2006).

The aim of this report was to evaluate a method based on TLS data to estimate stem taper and volume on single trees. Data from harvested trees measured with harvesters and manually calipered trees were used as references for comparison with the TLS data.

Material and methods

TEST SITES

Forest data from two test sites was used in the project: Remningstorp (N 58° 27', E 13° 40') in southern Sweden and Strömsjöliden in northern Sweden (N 64° 6', E 19° 11').

The Remningstorp test site provided data from 10 forest stands dominated by Norway spruce and Scots pine. The 1 500-ha estate is managed by the Swedish Forest Society. Up to three field plots within each forest stand were systematically placed on a grid with a 50 m inter-nodal distance. TLS data was collected at 28 field plots. Additional field measurements were taken on all trees in the plots: harvester-measured stem data was collected, including manual measurements from harvested control logs.

The Strömsjöliden test site provided data from 8 forest stands dominated by Norway spruce and Scots pine, and are managed and owned by the forest company Sveaskog. Four field plots within each forest stand were systematically placed on a grid with a 50-m inter-nodal distance. TLS data was collected at 45 field plots. Additional field measurements were taken on all trees in the field plots. All trees were harvested and measurement data from the harvester was collected.

FOREST DATA

TLS data

The TLS inventory was carried out by TreeMetrics in August 2008 using a scanner from FARO. A first scan was performed at the centre of each plot. The scanner was then moved to a new position for a second scan and, if necessary, for a third scan, to ensure that all trees in each field plot were included. Each single scan was processed in the TreeMetrics software Autostem in October 2012. For each tree on the plot the best scan was selected to represent that tree. The selection was only based on the informtion from the scanning data. Before scanning, each plot was pruned to facilitate better measurements on the stems. During the project, filtering algorithms were developped by TreeMetrics Ltd to remove branch points, thereby reducing the need for pruning.

Additional field measurement data

The field plot inventory was carried out from June to August 2008. All tree stems in a 10-m radius field plot were callipered 1.3 m above ground level (DBH), tree species were recorded, and stem position was measured relative to the field plot centre using ultrasonic triangulation with three transponders. An identification number was painted on each tree in the sample plots. The plot centre position was measured using DGPS, which is expected to produce sub-metre accuracy under optimal conditions. The addition field measurements were only used to validate the link between the harvested trees and the TLS measurements.

Harvester data

At Strömsjöliden the trees were harvested with a CTL harvester during January and February 2009. At Remningstorp the trees were harvested during autumn 2008. In order to connect the trees measured in the field plots with harvester measurements at tree level, a special module of a harvester GIS program was used. GIS software was developed in the project to allow recording of the identification of the harvested trees. The positions of the harvester and the field plots were visible on a digital map. If a tree was harvested within a field plot, the operator was requested to enter the tree identification number painted on the stem. The stem data was recorded according to the StanForD standard (Anon. 2013) and the tree identification number was saved in an associated stem file. Stem diameters along the processed part of the stem were continuously measured by the harvester and recorded at 10-cm intervals.

At Remningstorp 34 felled trees were manually measured with a calliper by the operator using common procedures for KTR trees (Arlinger & Möller, 2006). All logs were callipered twice at each metre of length, and the average diameters at all measuring points were recorded in the on-board computer.

EVALUATION

The harvester data was considered to be the true diameter measure of the tree. The standard deviation of the diameter measurements from a calibrated harvester is typically around 4.5 mm (Möller et al. 2008). The harvester uses sensors to measure the diameter; these are placed in the delimbing knives and the first actual diameter measurement from the harvester head is at a height of approximately 0.8 metres, so comparisons of the first metre of the stem are in most cases not reliable. The study involved 295 harvested trees at Remningstorp and 643 harvested trees at Strömsjöliden. In some of the analysis the 34 felled and manually measured trees were also used in the evaluation and were regarded as the true diameter of the stems.

Volume was estimated on the basis of diameter measurements. The volume of the stem was considered as equal to small cylinders with a height of 10 cm. The same method was used to estimate the volume, based on both the TLS measurements and the harvester data. Comparisons were made from first cut of the tree until the last common diameter measurement, normally the final cut of the harvester, which corresponds to the top diameter of the last log. In the TLS data the first cut was considered to be at a height of 10 cm.

Results

ACCURACY OF DIAMETER ESTIMATES

KTR trees at Remningstorp

In most cases the 34 estimated stem profiles corresponded well to the measurements from the harvester and manual cross measurements by the operator. There were a few exceptions where the diameters were biased. Two good examples from stand 343 at Remningstorp are presented in Figures 2 and 3. Stand 343 was a mixture of both spruce and pine (Figure 4). Comparisons for all 34 trees are presented in Appendix 1.

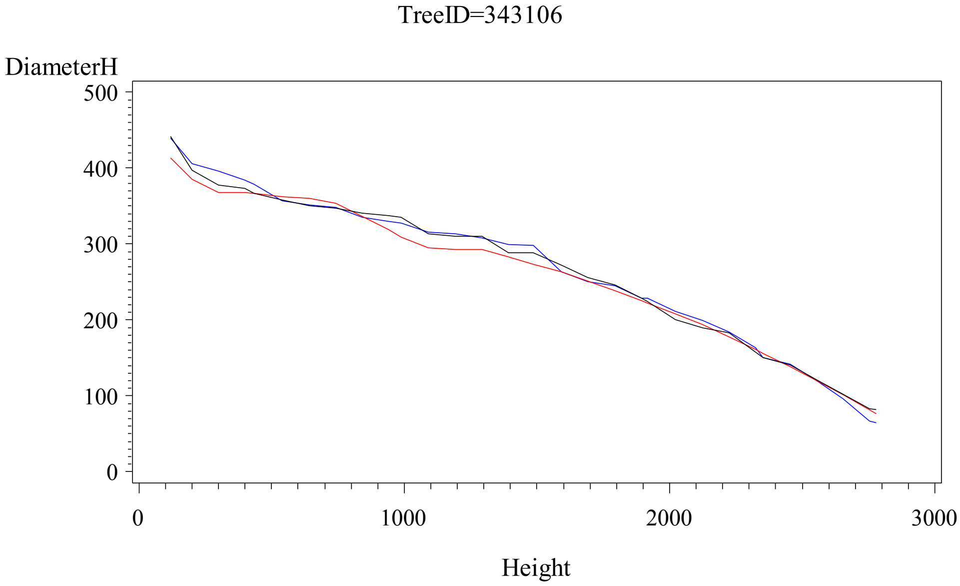

Figure 2.
Stem taper for a Norway spruce tree at plot 1 in stand 343 at Remningstorp. The blue line is harvester-measured diameter, the black line is from manual measurements with calliper, and the red line is diameter based on TLS.

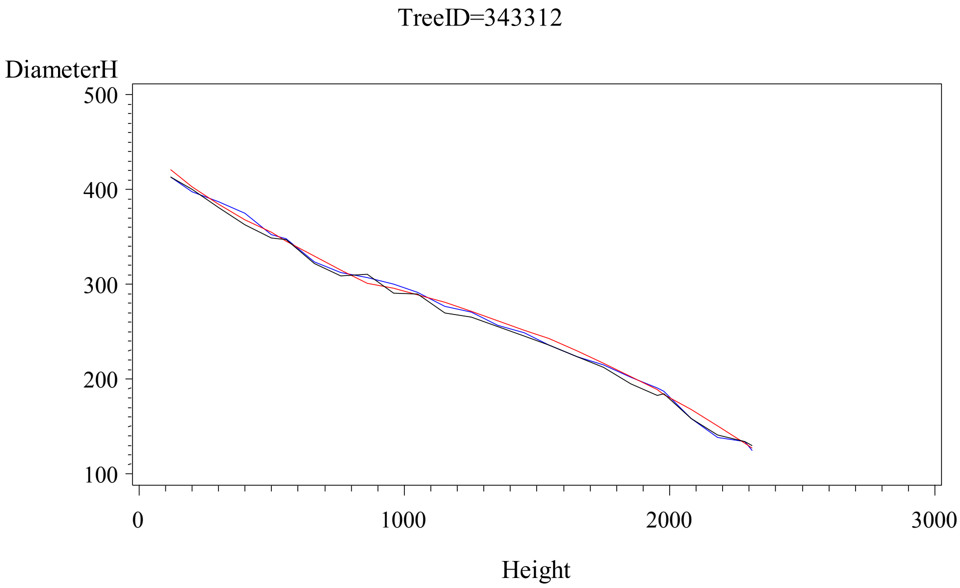

Figure 3.
Stem taper for a Scots pine tree at plot 3 in stand 343 at Remningstorp. The blue line is harvester-measured diameter, the black line is from manual measurements with calliper, and the red line is diameter based on TLS.

Figure 4.
Picture from stand 343 (unknown Plot ID) at Remningstorp with some of the sample trees (coloured markings).

All harvested trees at Remningstorp

Diameter estimates from TLS were compared with harvester measurements of 257 trees. The standard deviation was lowest for heights between 2 and 9 metres (Figure 5). The standard deviation was slightly lower for spruce than for pine. The diameters were slightly underestimated except for pine between 5 and 7 metres high (Figure 6).

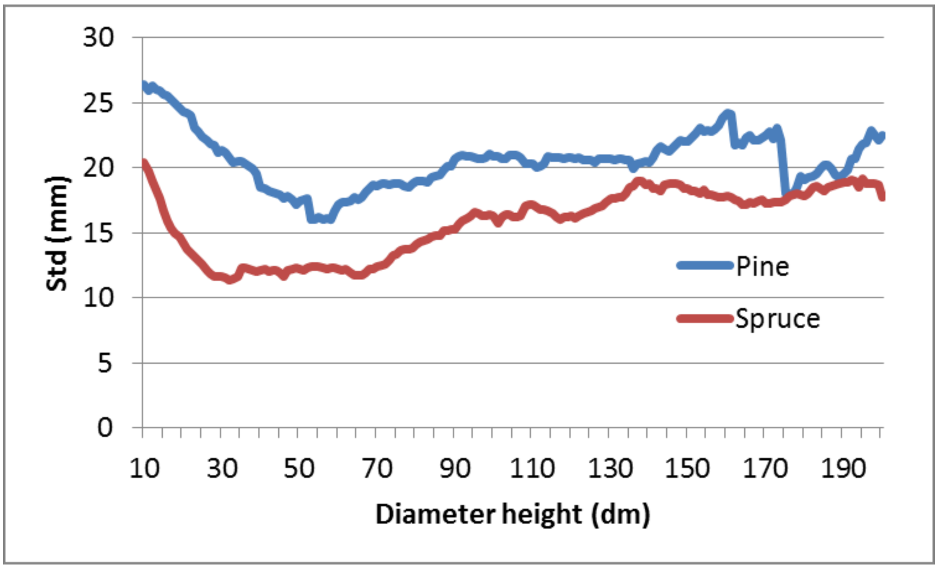

Figure. 5.
Standard deviation (Std) of diameter estimates based on TLS data. Comparisons are made with the diameter measurements from the harvester. Data from the Remningstorp test site in southern Sweden. The statistics are based on measurements from 257 trees.

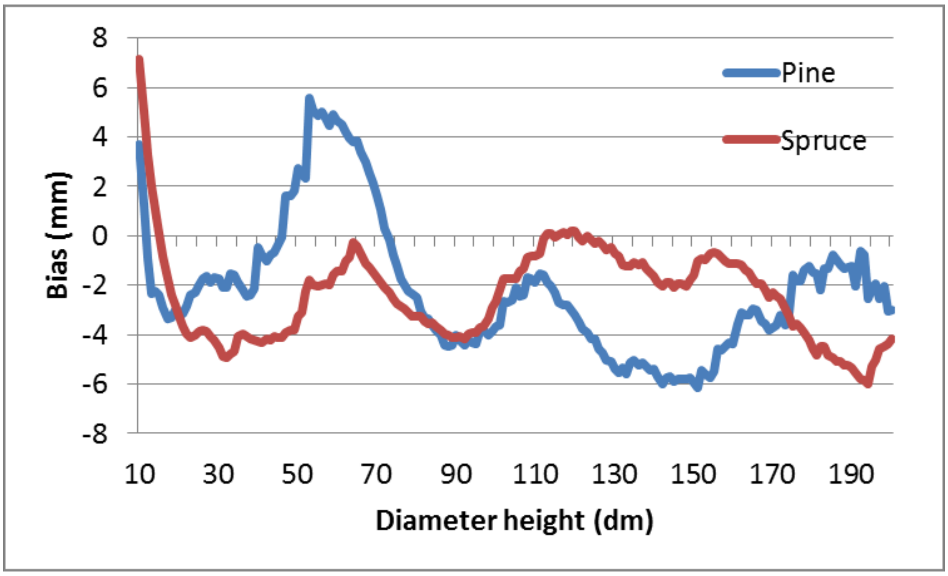

Figure 6.
Biases of diameter estimates based on TLS data. Comparisons are made with the diameter measurements from the harvester. Data from the Remningstorp test site in southern Sweden. The statistics are based on measurements from 257 trees.

All harvested trees at Strömsjöliden

Diameter estimates from TLS were compared with harvester measurements of 586 trees. The standard deviation was rather stable for the pine trees while the standard deviation increased with height for the spruces (Figure 7). For both pine and spruce the diameters were overestimated by 2–4 mm from height of 7–9 metres (Figure 8).

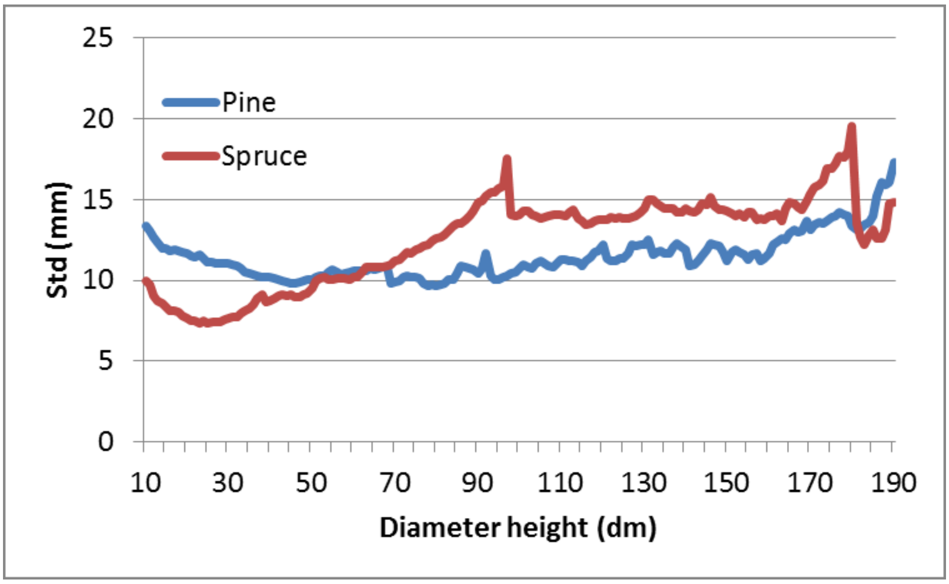

Figure 7.
Standard deviation (Std) of diameter estimates based on TLS data. Comparisons are made with the diameter measurements from the harvester. Data from the Strömsjöliden test site in northern Sweden. The statistics are based on measurements from 586 trees.

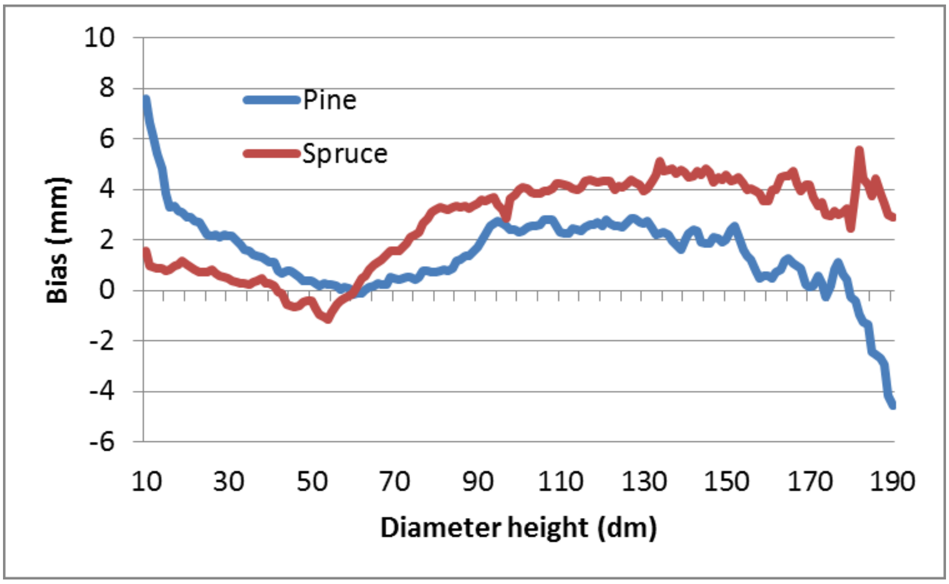

Figure 8.
Biases of diameter estimates based on TLS data. Comparisons are made with the diameter measurements from the harvester. Data from the Strömsjöliden test site in northern Sweden. The statistics are based on measurements from 586 trees.

ACCURACY OF VOLUME ESTIMATES

Volume estimates based on the TLS diameter data were compared with volume estimates based on diameter measurements from the harvesters. The bias was close to zero for all tree species and standard deviation was greater at Remningstorp due to larger trees (Table 1).

Table 1.
Accuracy of volume estimates at the single-tree level. Comparisons made between volumes estimated based on TLS diameter data and harvester data (reference).

Site	*Spices*	*n*	*Mean volume (m^3)*	*Bias (m^3)*	*Std Dev (m^3)*	*RMSE (m^3)*
Remningstorp	Pine	94	1.12	0.00	0.13	0.13
	Spruce	185	1.01	– 0.01	0.11	0.11
	Birch	16	0.44	– 0.01	0.10	0.10
Strömsjöliden	Pine	275	0.47	0.02	0.04	0.05
	Spruce	339	0.27	0.01	0.04	0.04
	Birch	29	0.21	0.01	0.03	0.03

Discussion and conclusion

Comparisons between TLS diameter estimates and diameter measurements from harvesters show that TLS can provide accurate estimates of stem taper and volume at single-tree level. However, in estimation of product recovery at stand level, TLS is dependent on accurate sampling methodology and/or remote sensing data to provide accurate predictions. Airborne laser scanning (ALS) is one example of such a method, and can provide information on diameter and height distributions at stand level. Consequently, the combination of information from TLS and ALS could give detailed information at tree level, but also accurate descriptions of the tree-size distributions at stand level.

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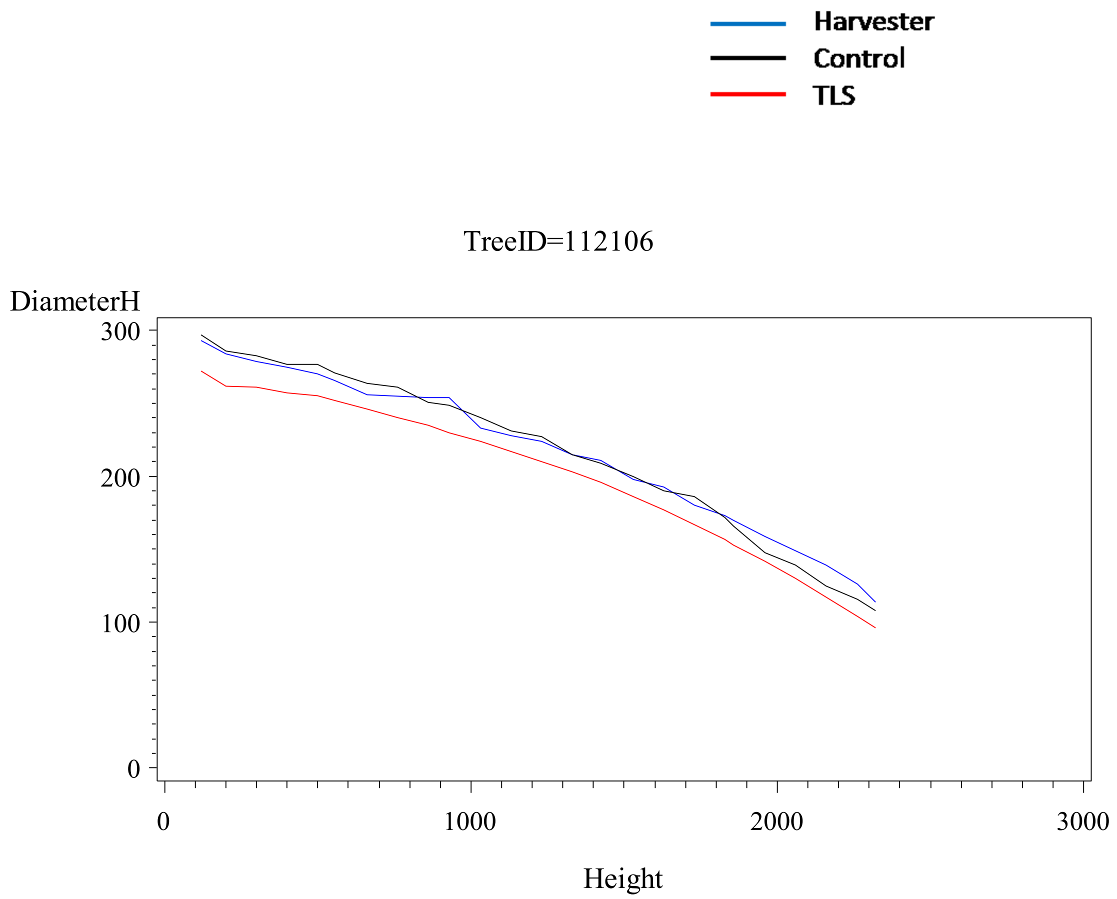
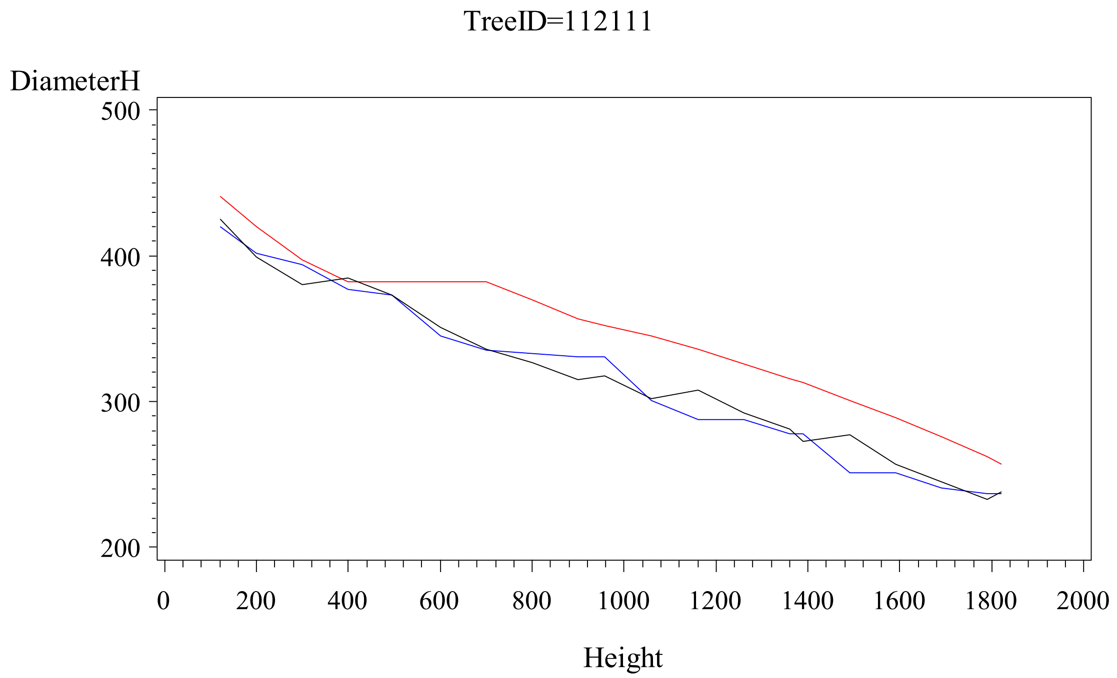
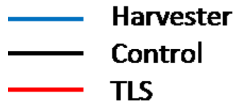
Appendix 1

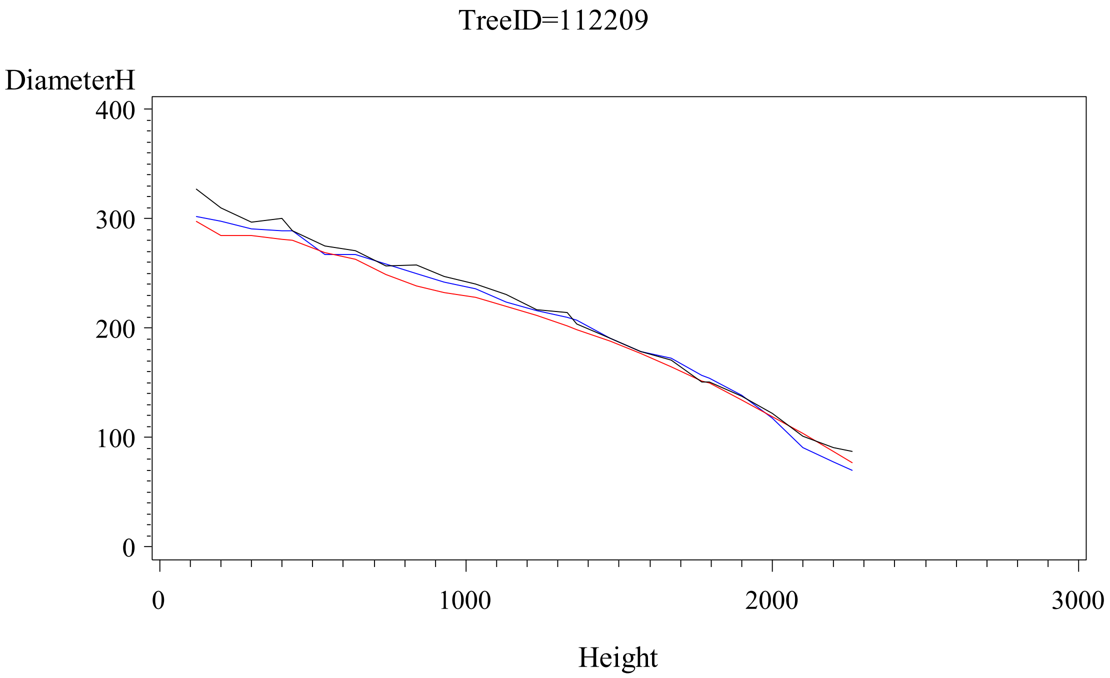
Appendix 1





Appendix 1


Harvester
Control
TLS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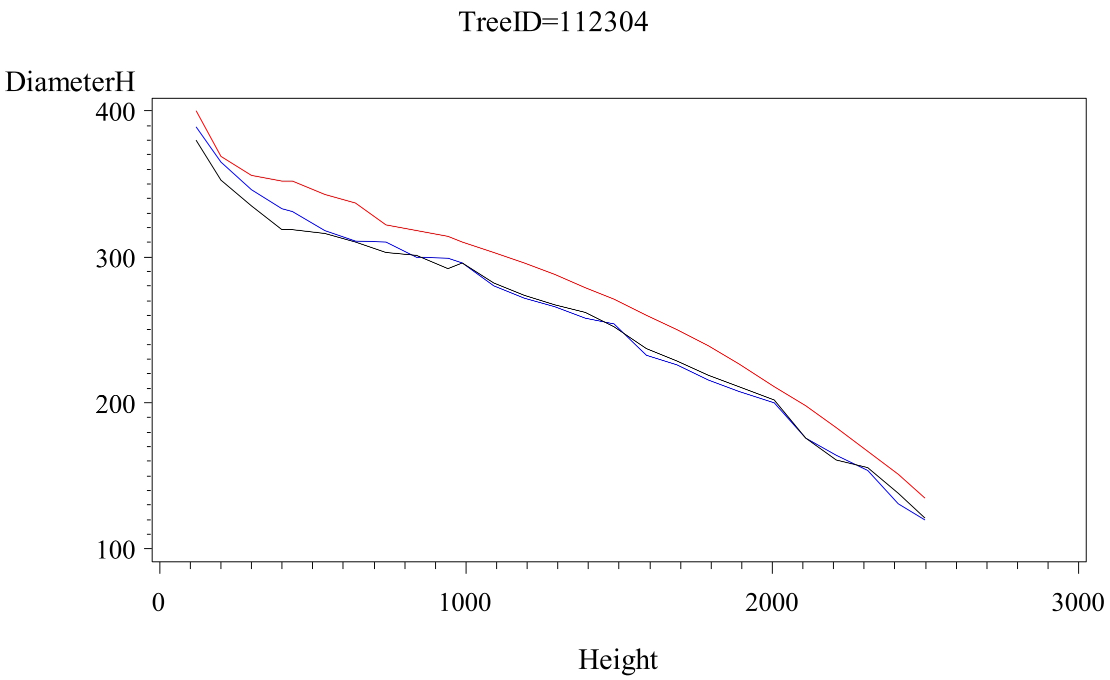
DiameterH
400
300
200
100
0
0
1000
2000
3000
Height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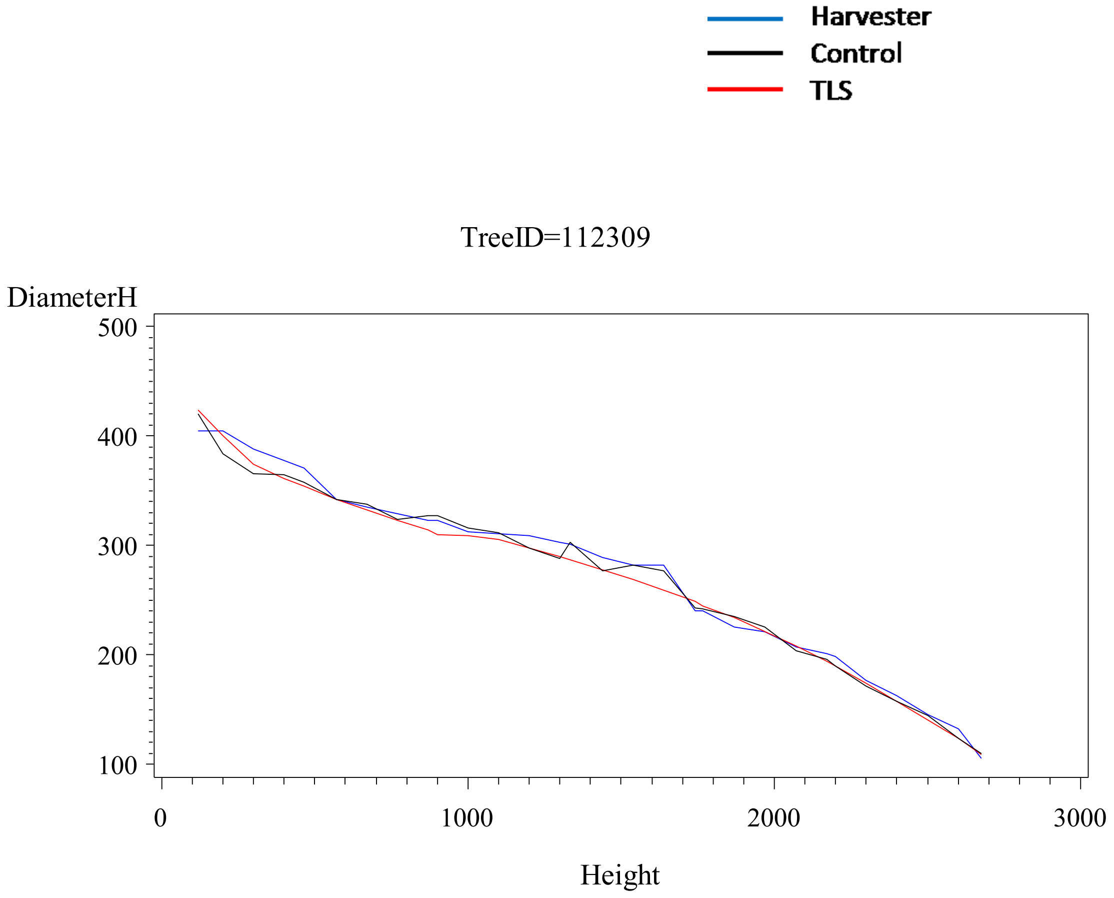
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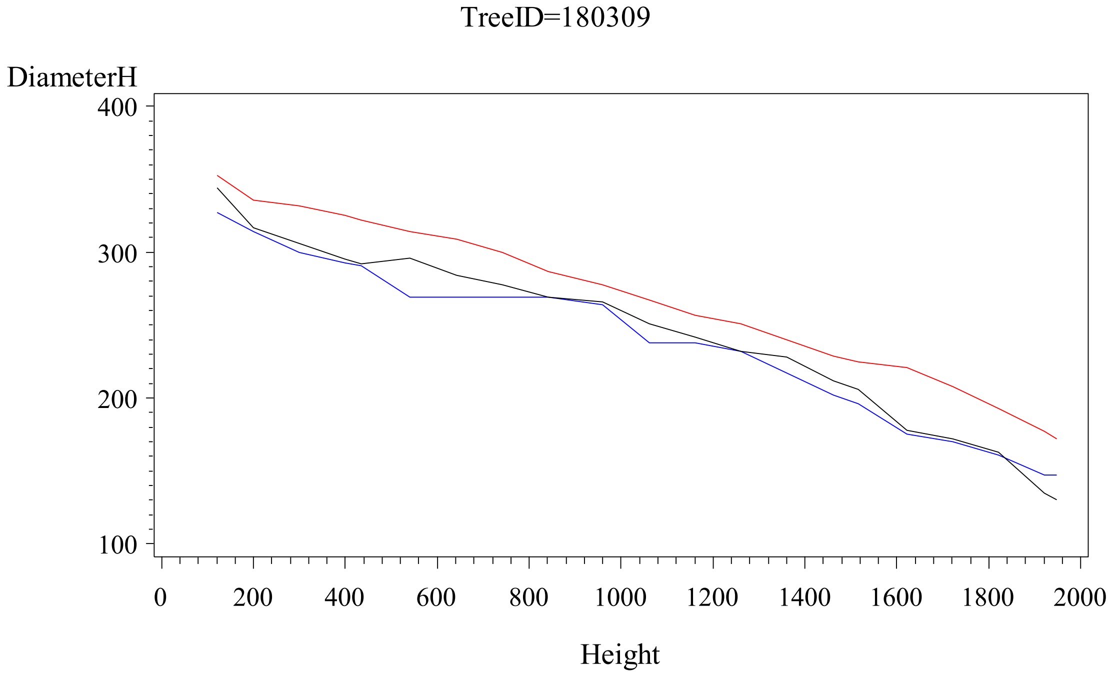
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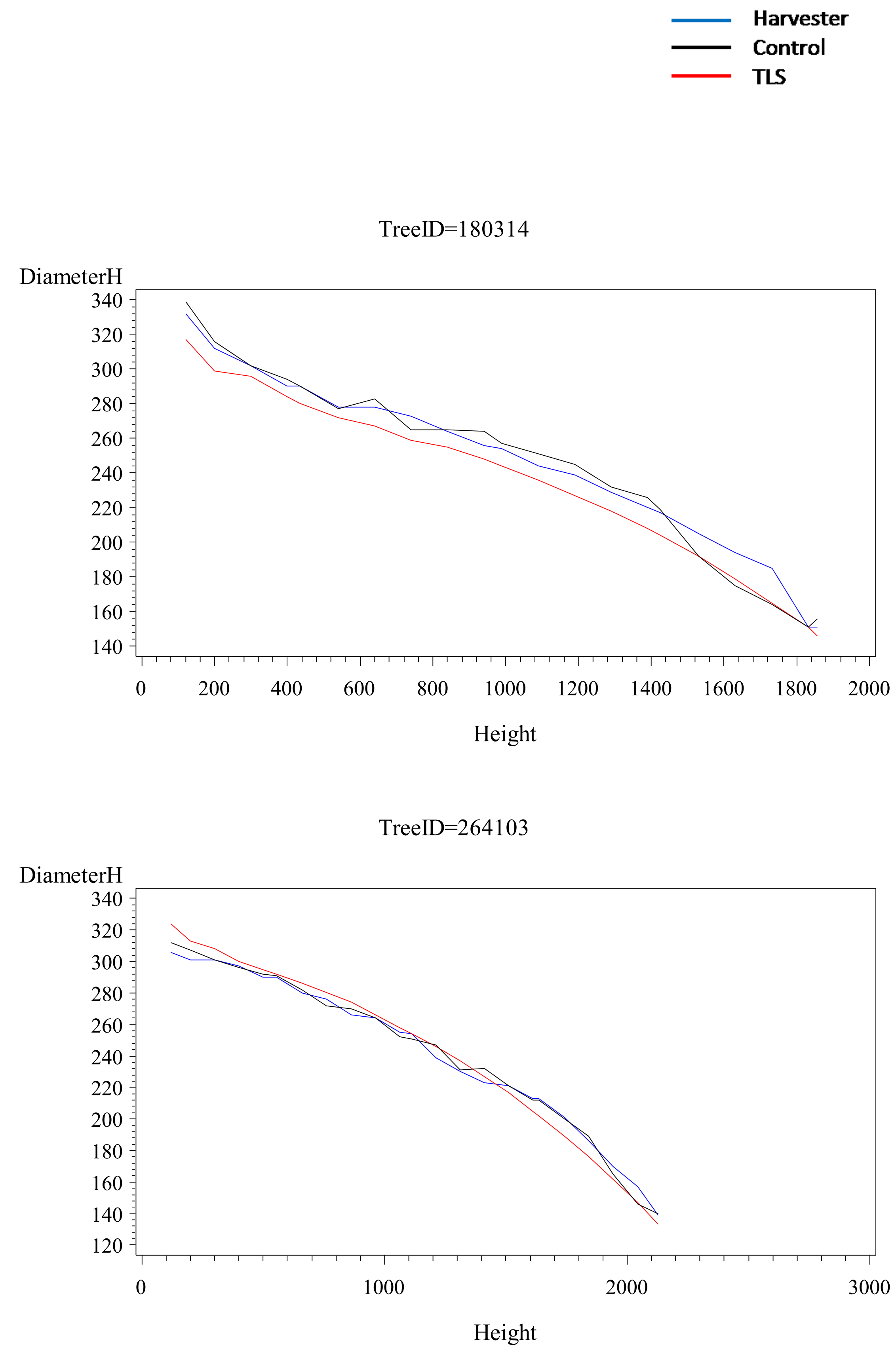
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Appendix 1

Harvester
Control
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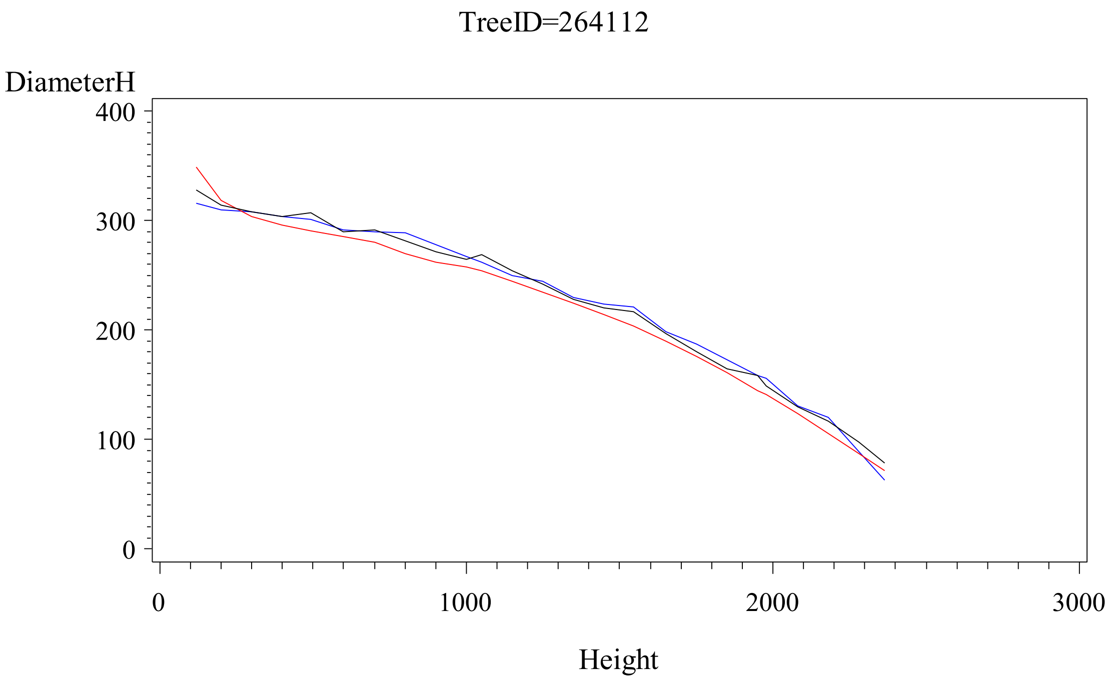

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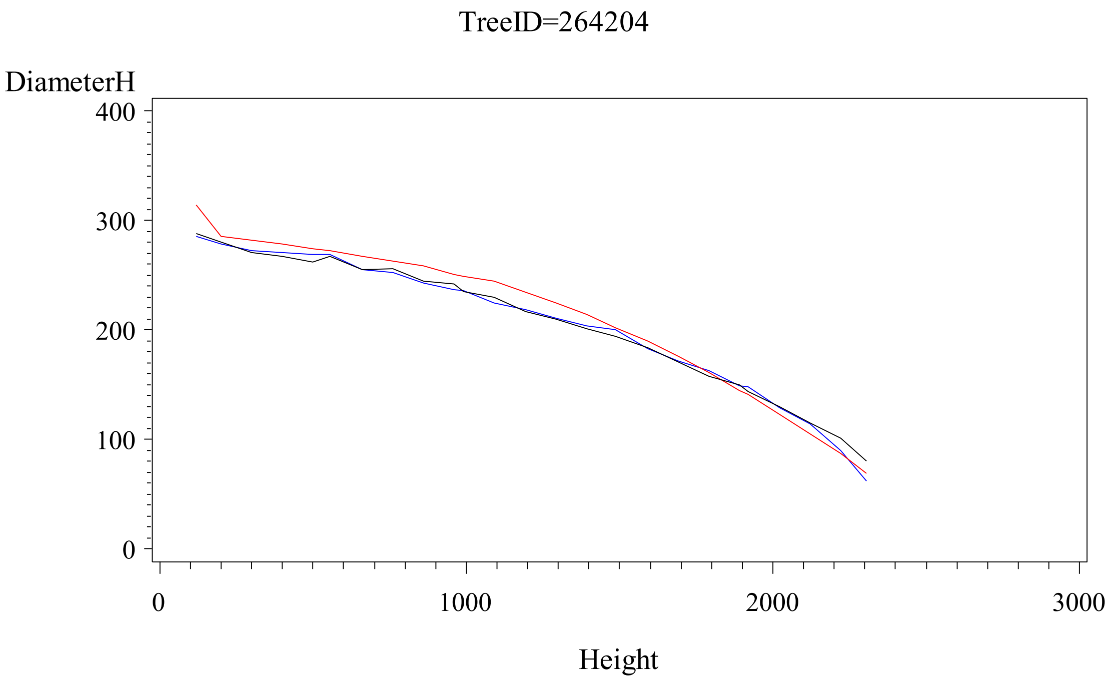

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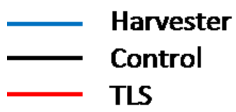

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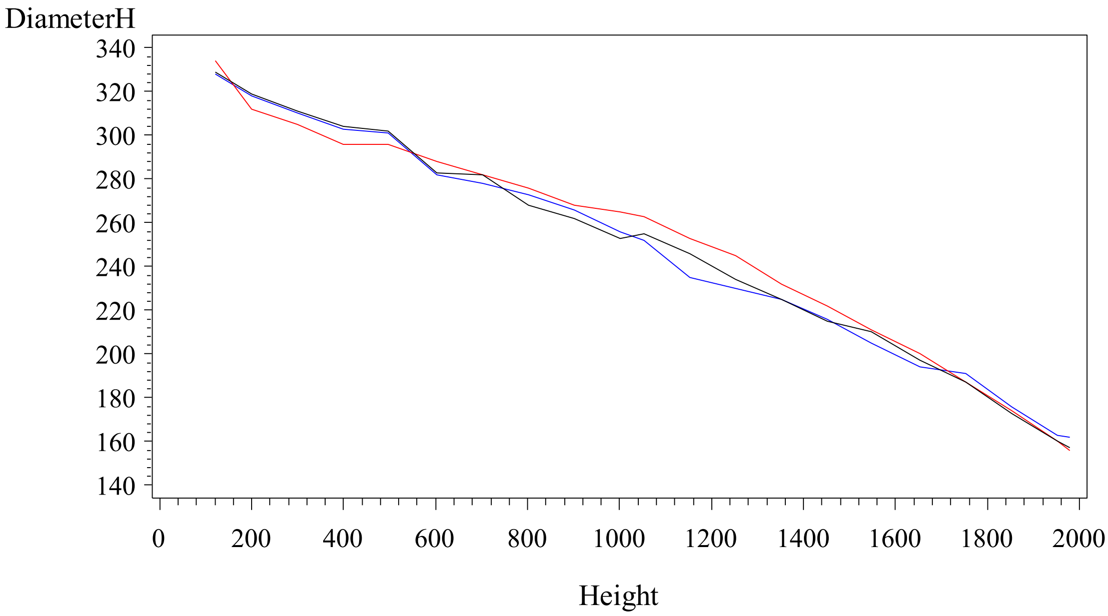

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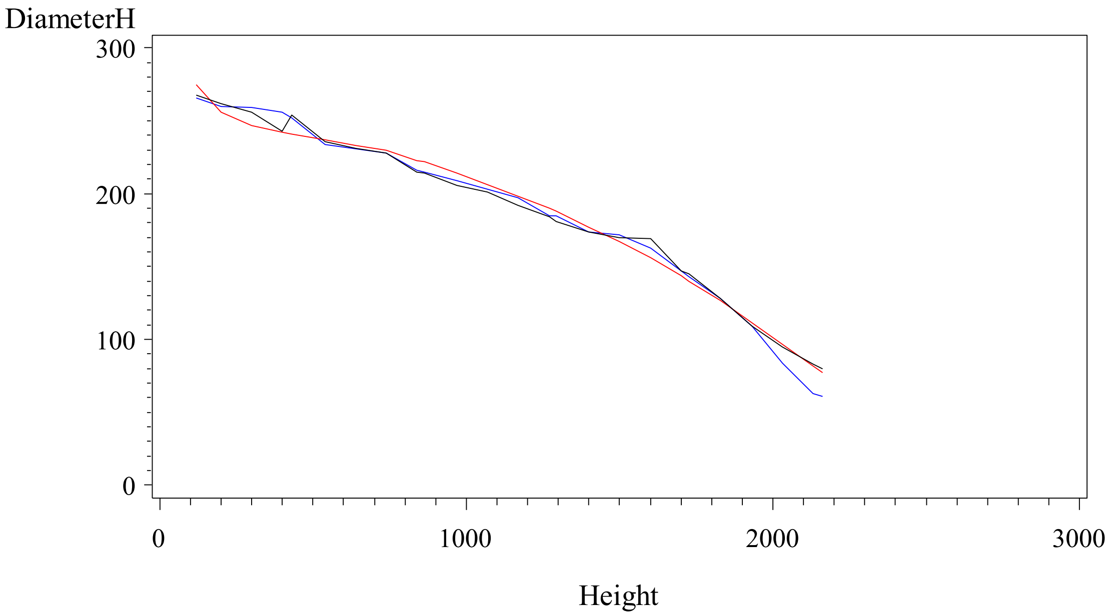

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Harvester
Control
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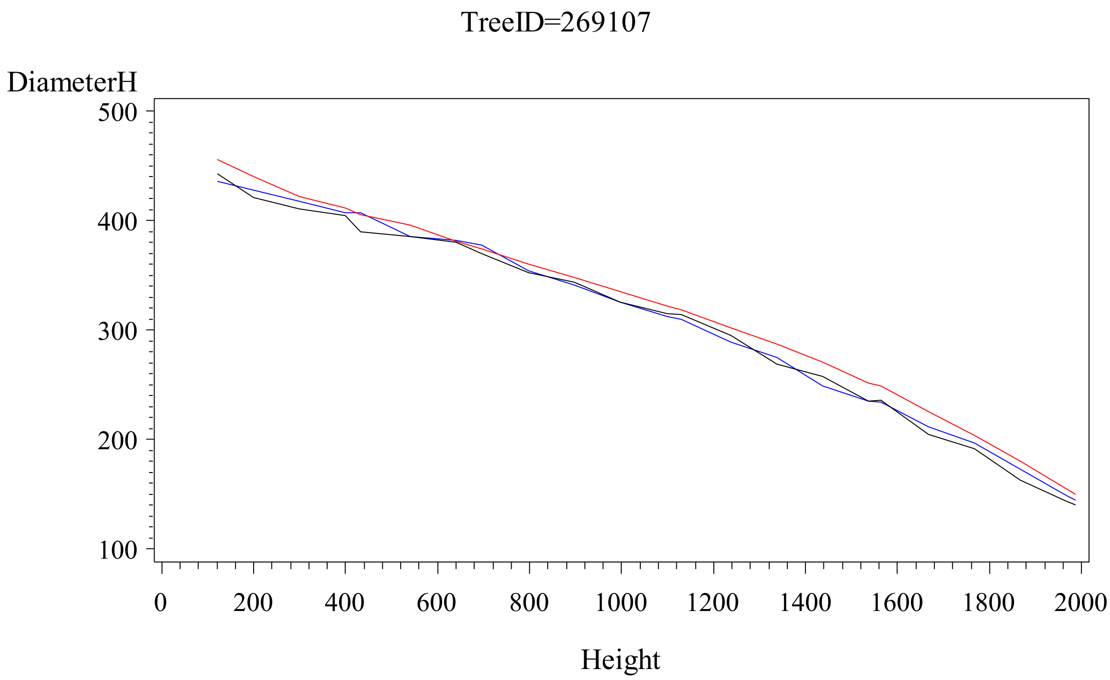
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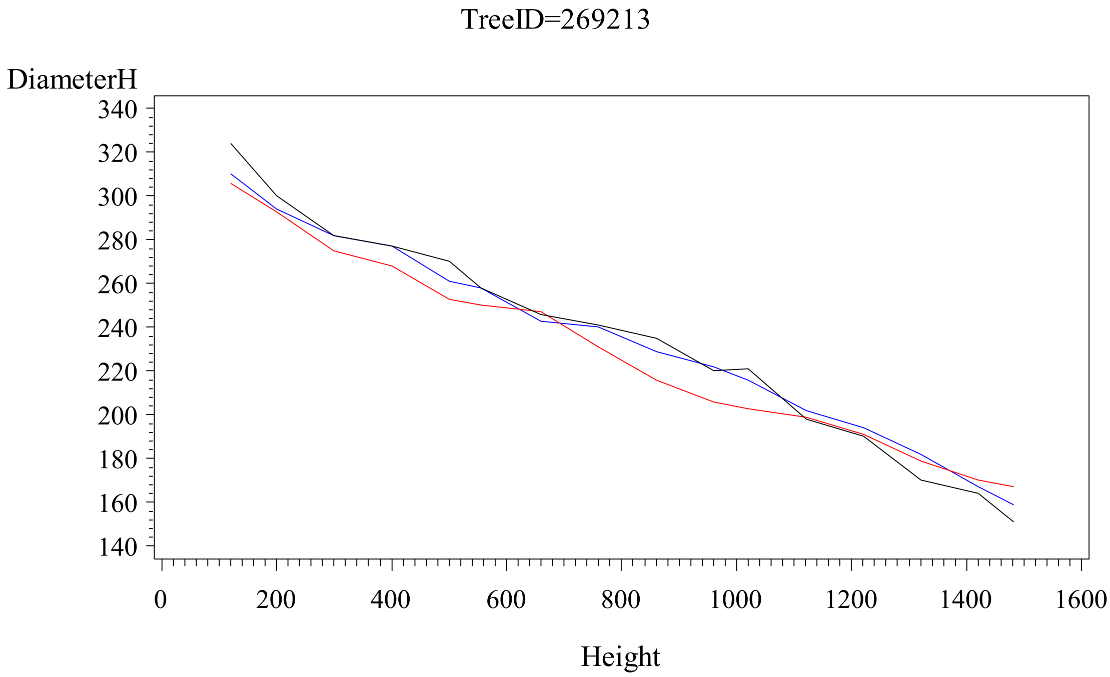
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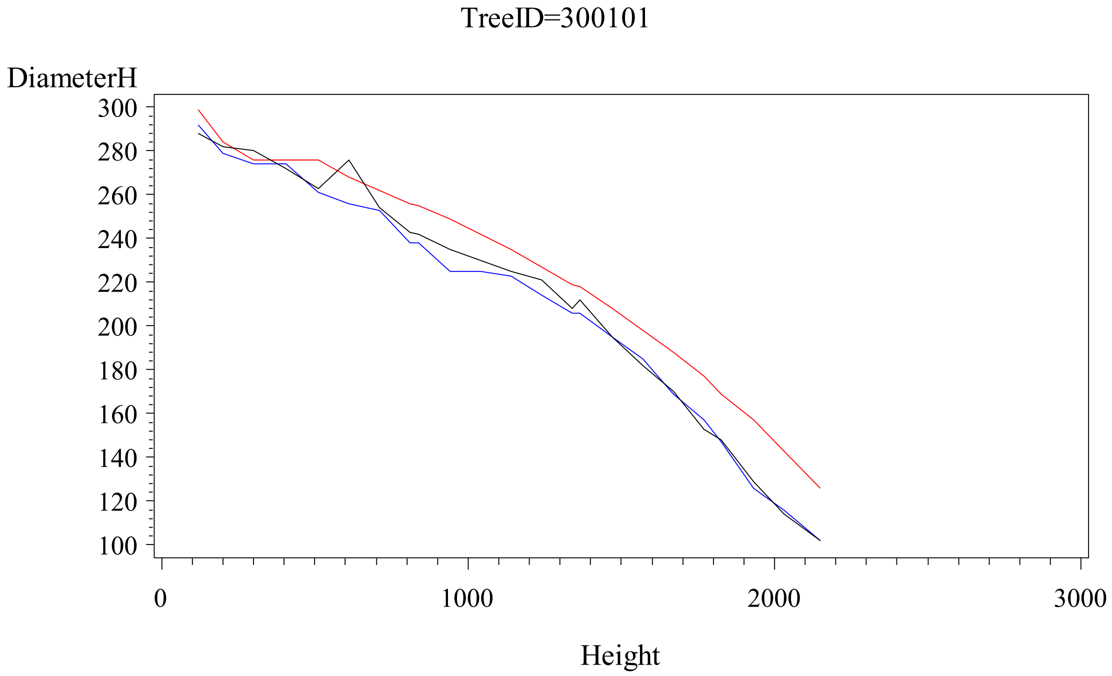
Height

Appendix 1


Harvester
Control
TLS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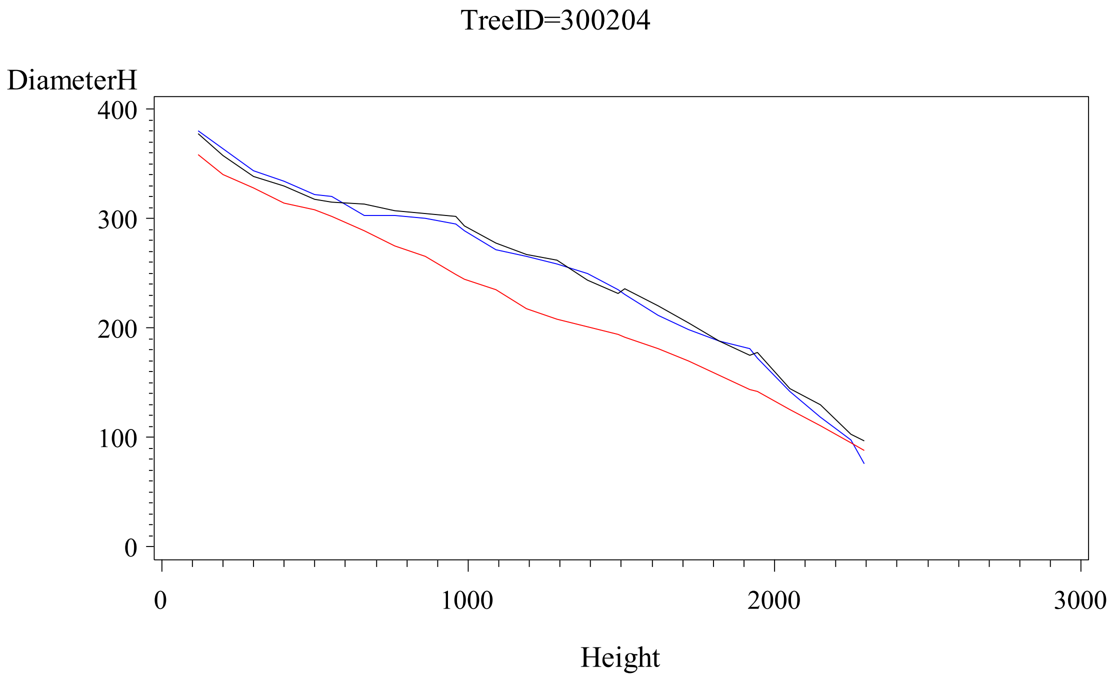
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Appendix 1


Harvester
Control
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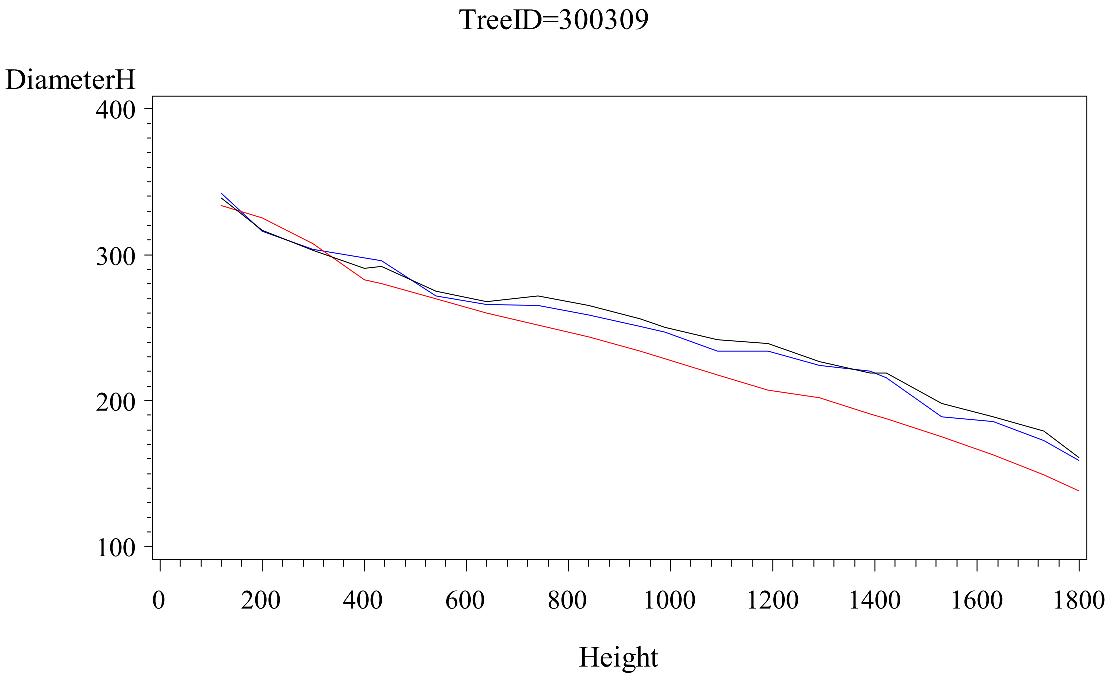
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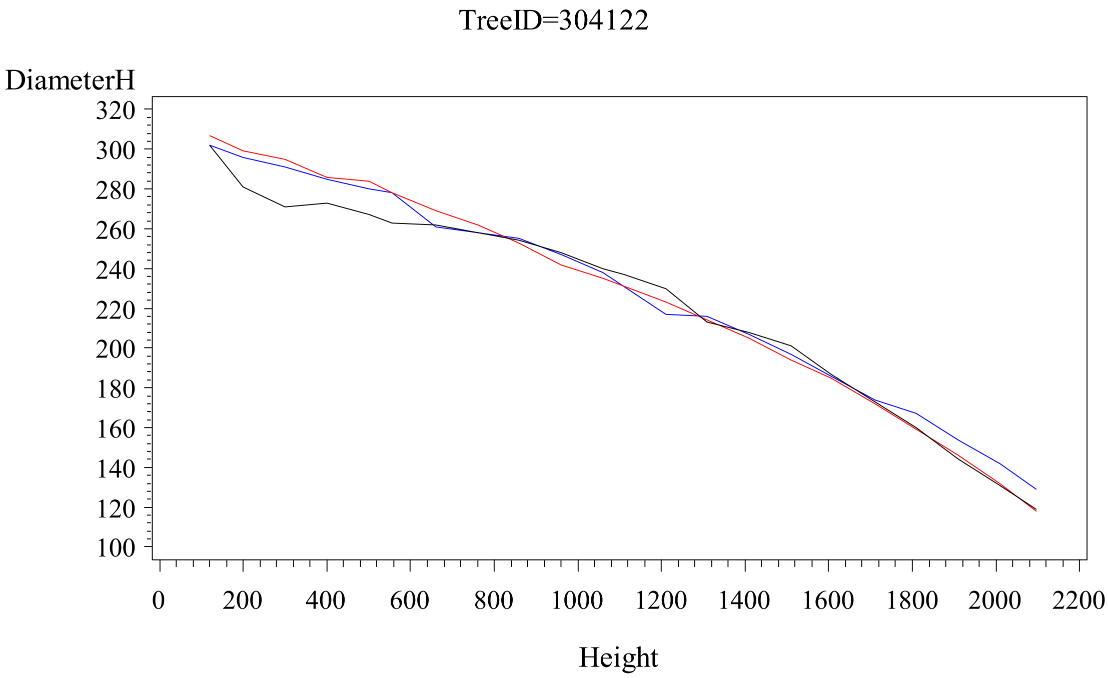
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Appendix 1


Harvester
Control
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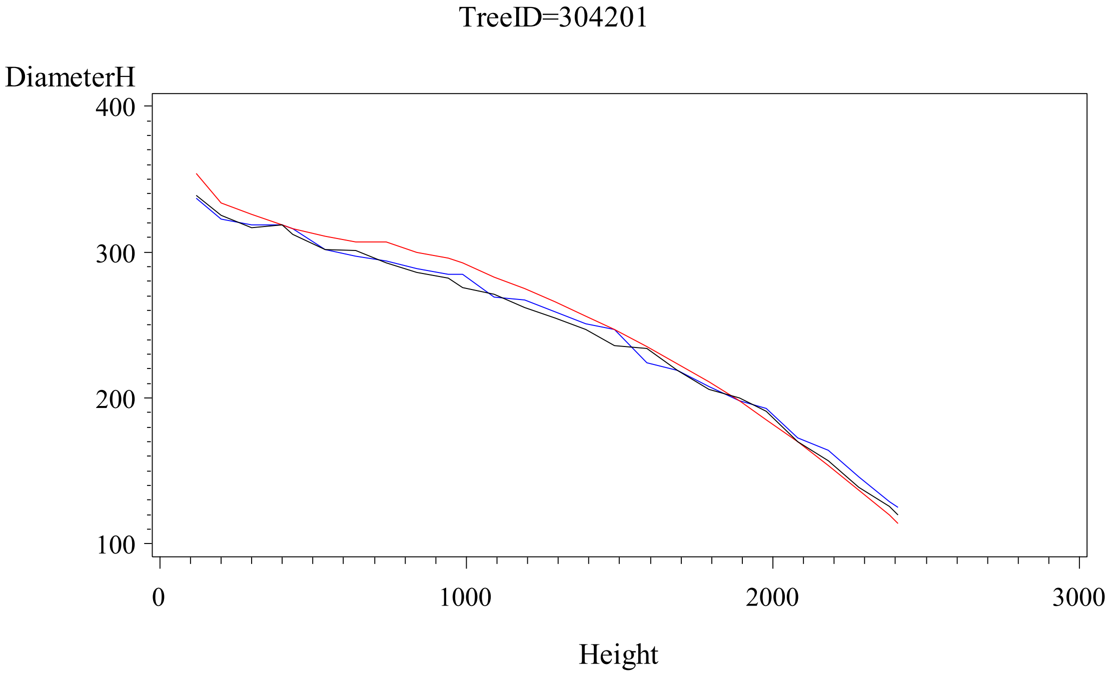
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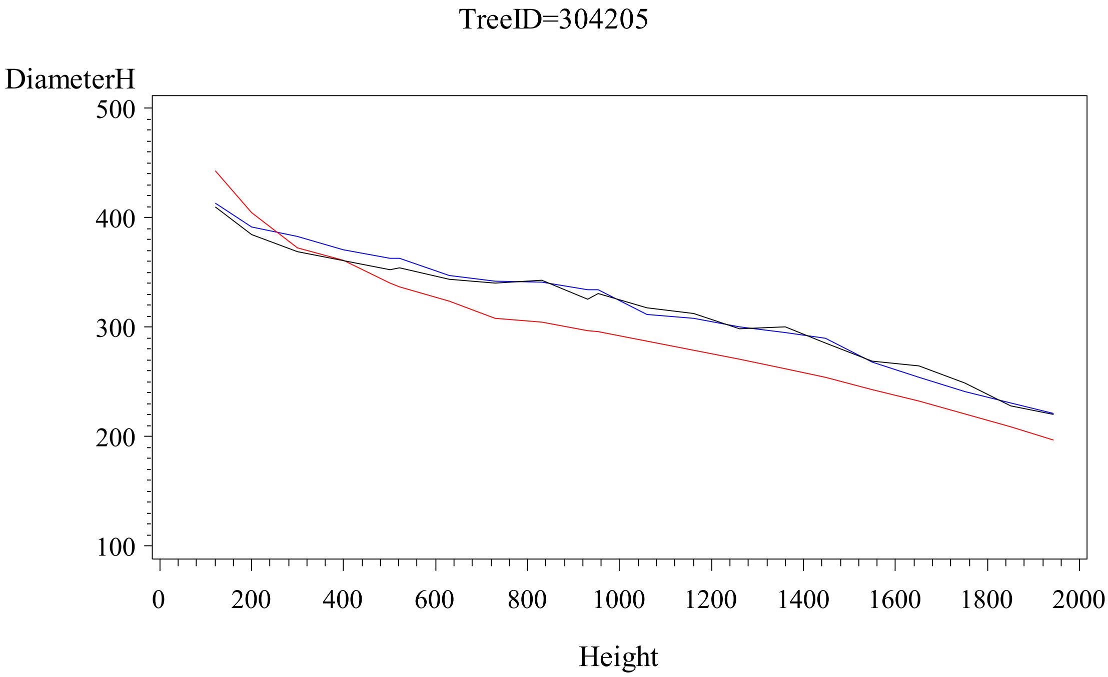
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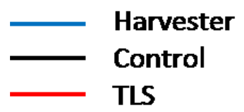
Appendix 1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Control
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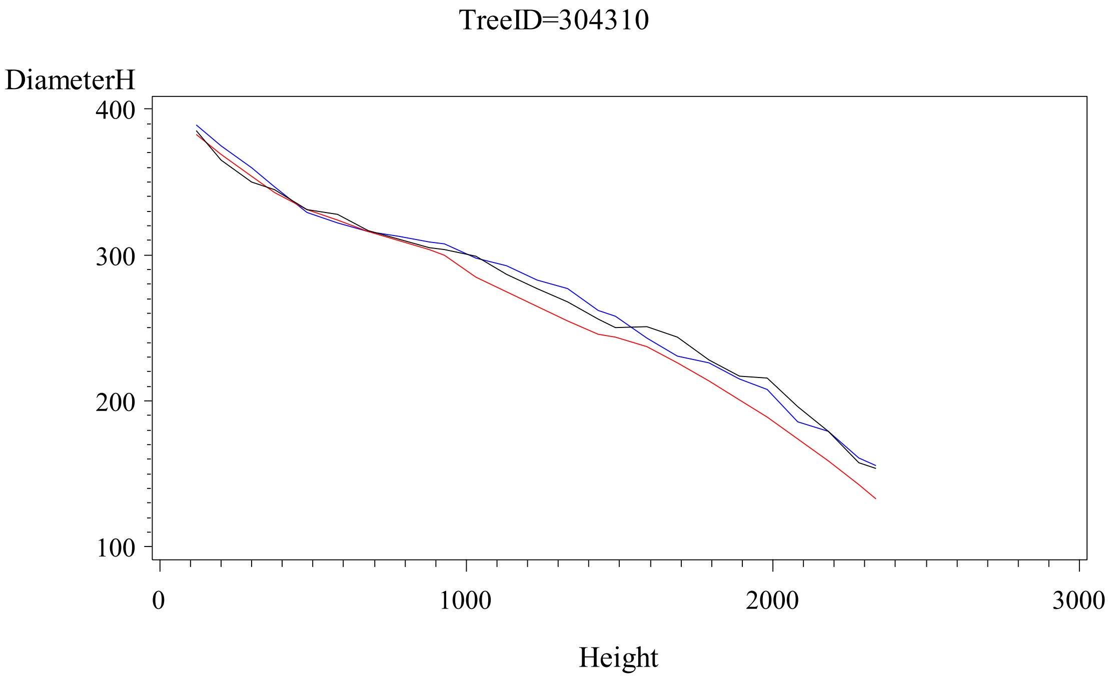
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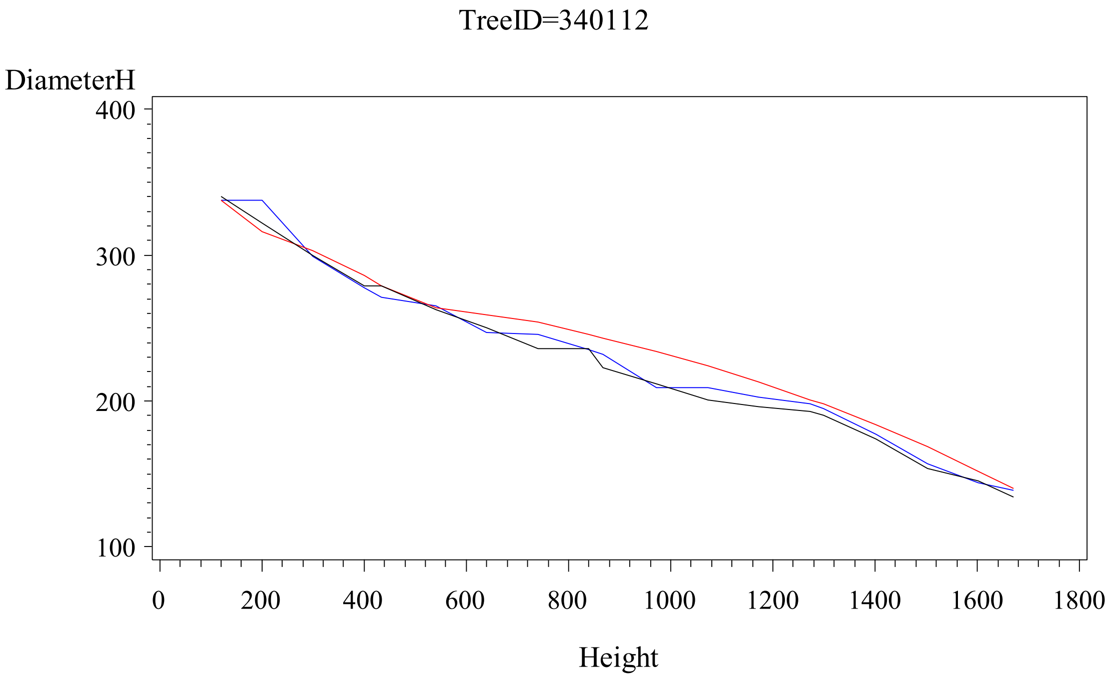
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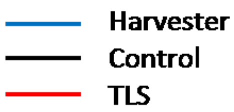

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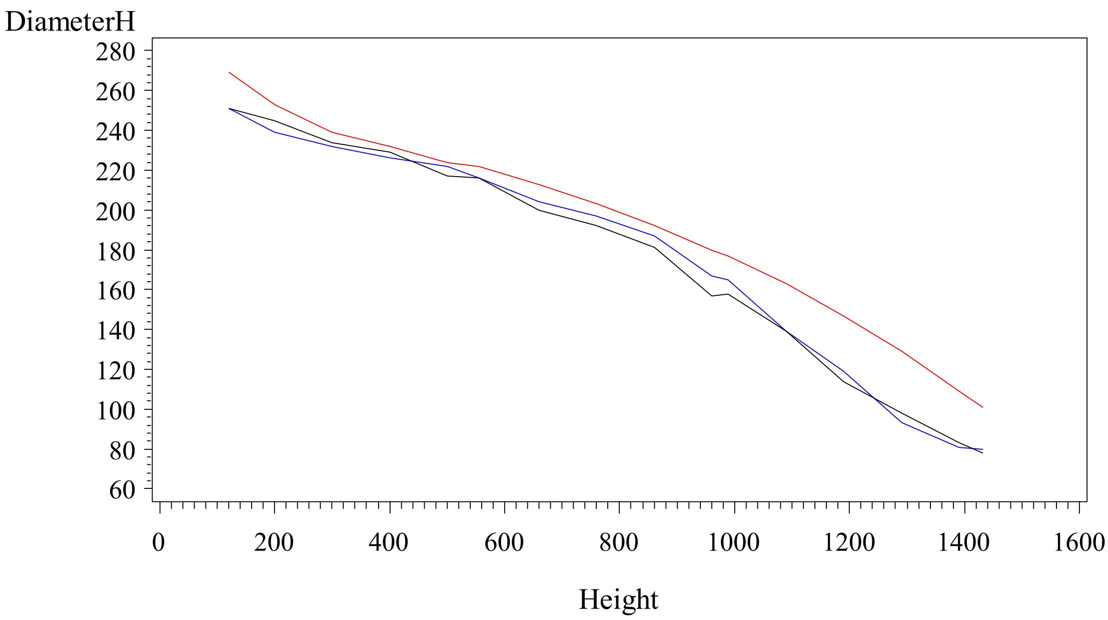

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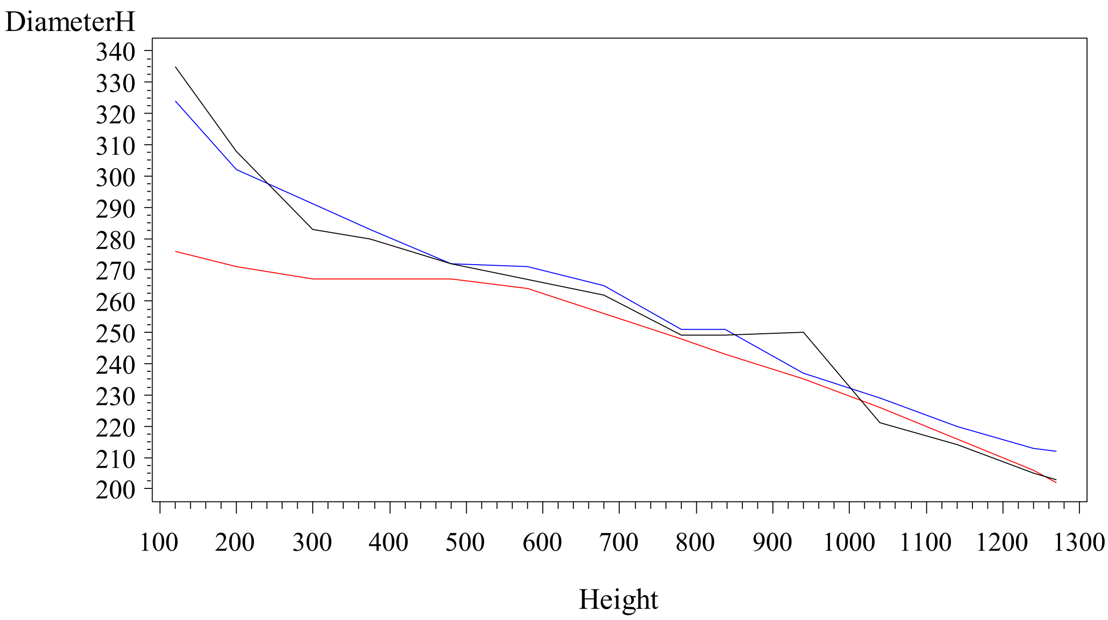

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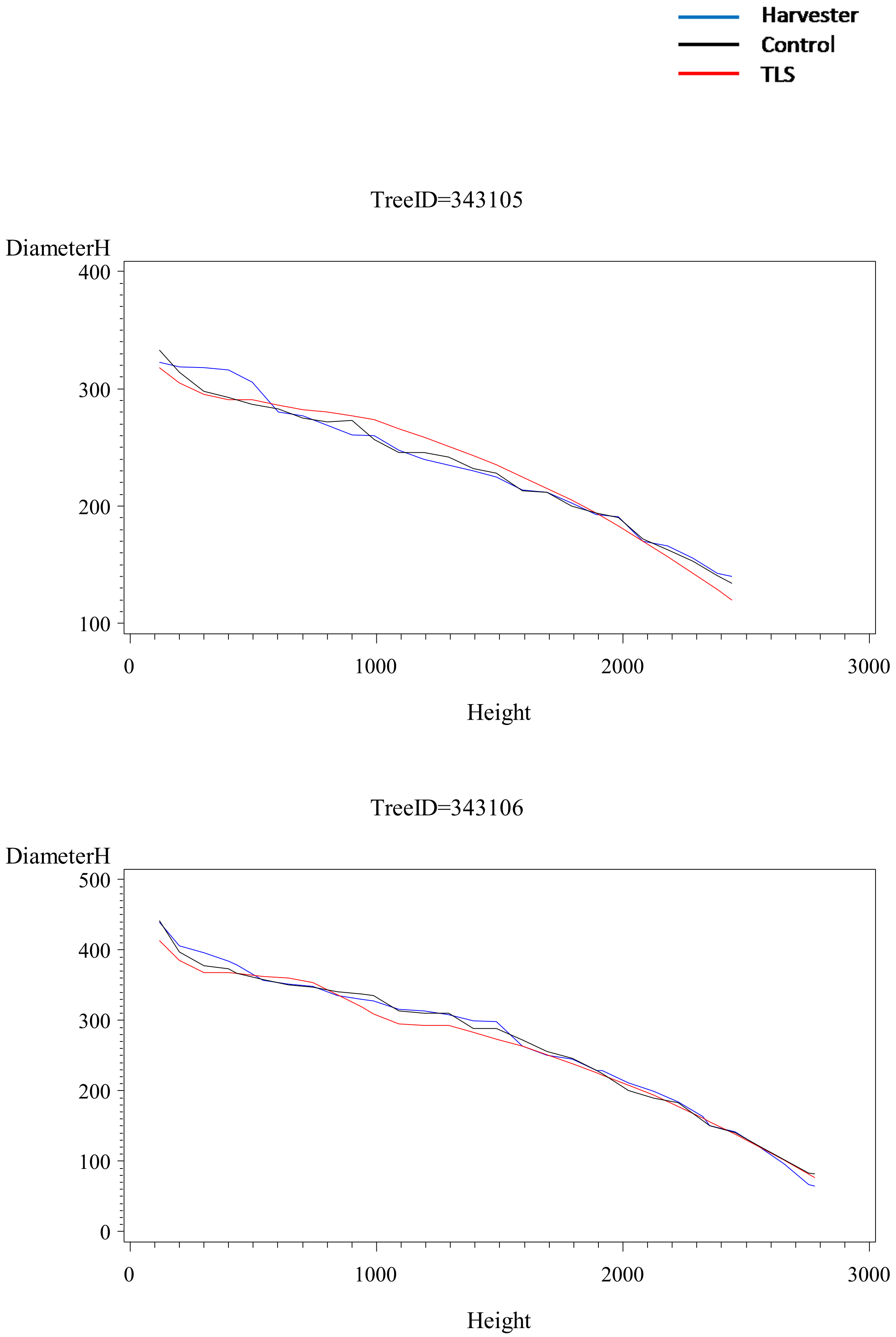

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Height

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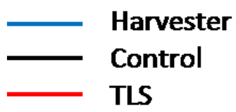
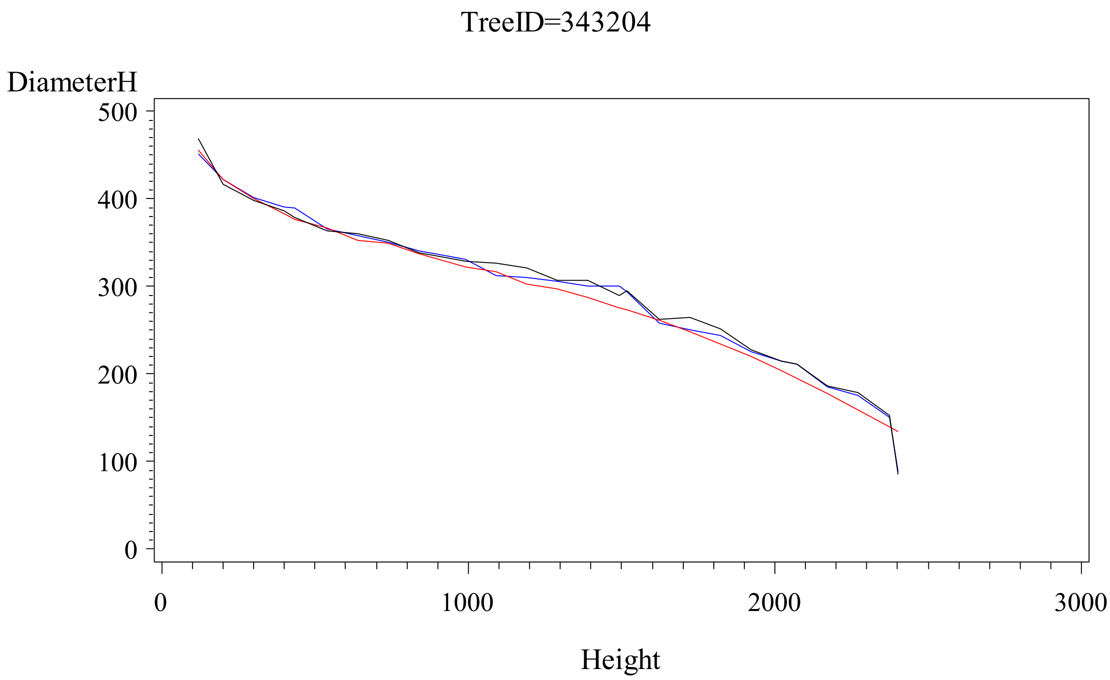

Harvester
Control
TLS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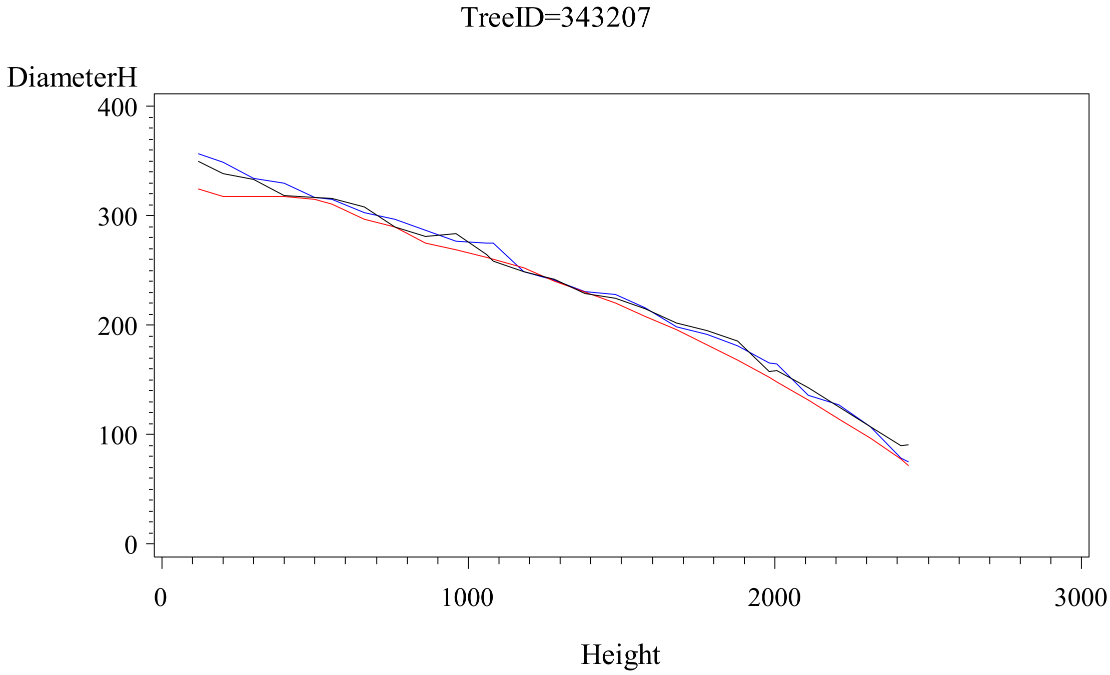
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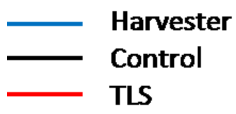
Appendix 1



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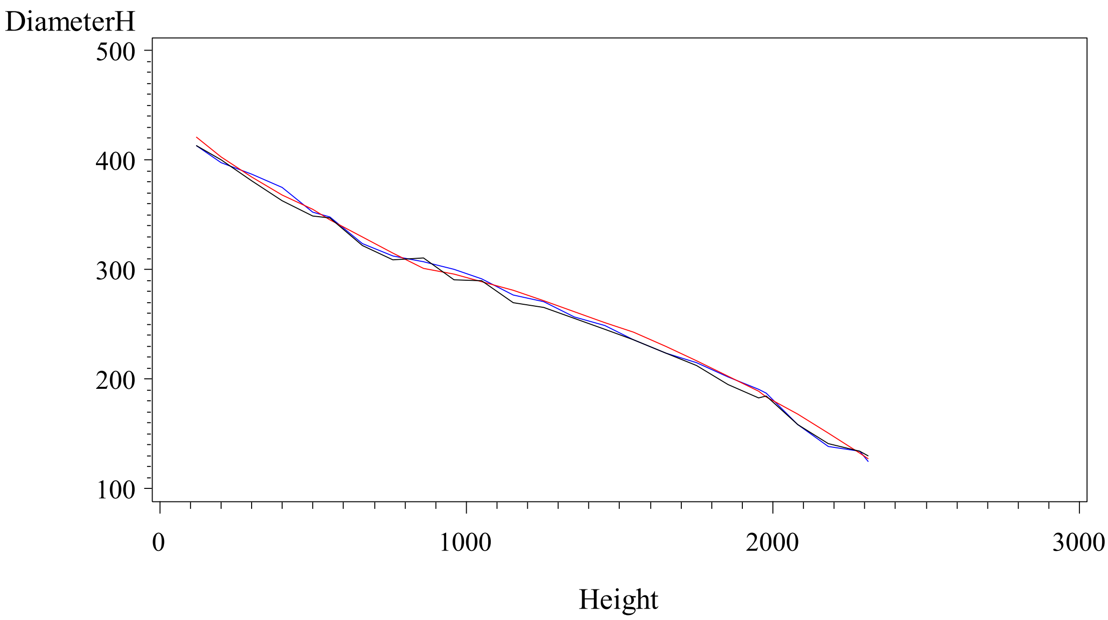

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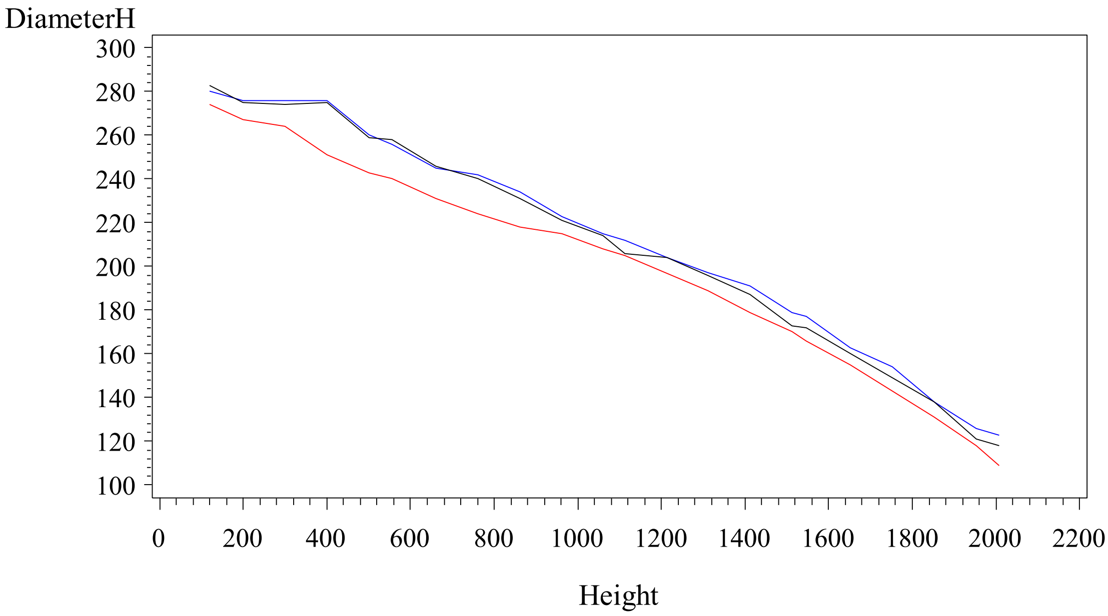

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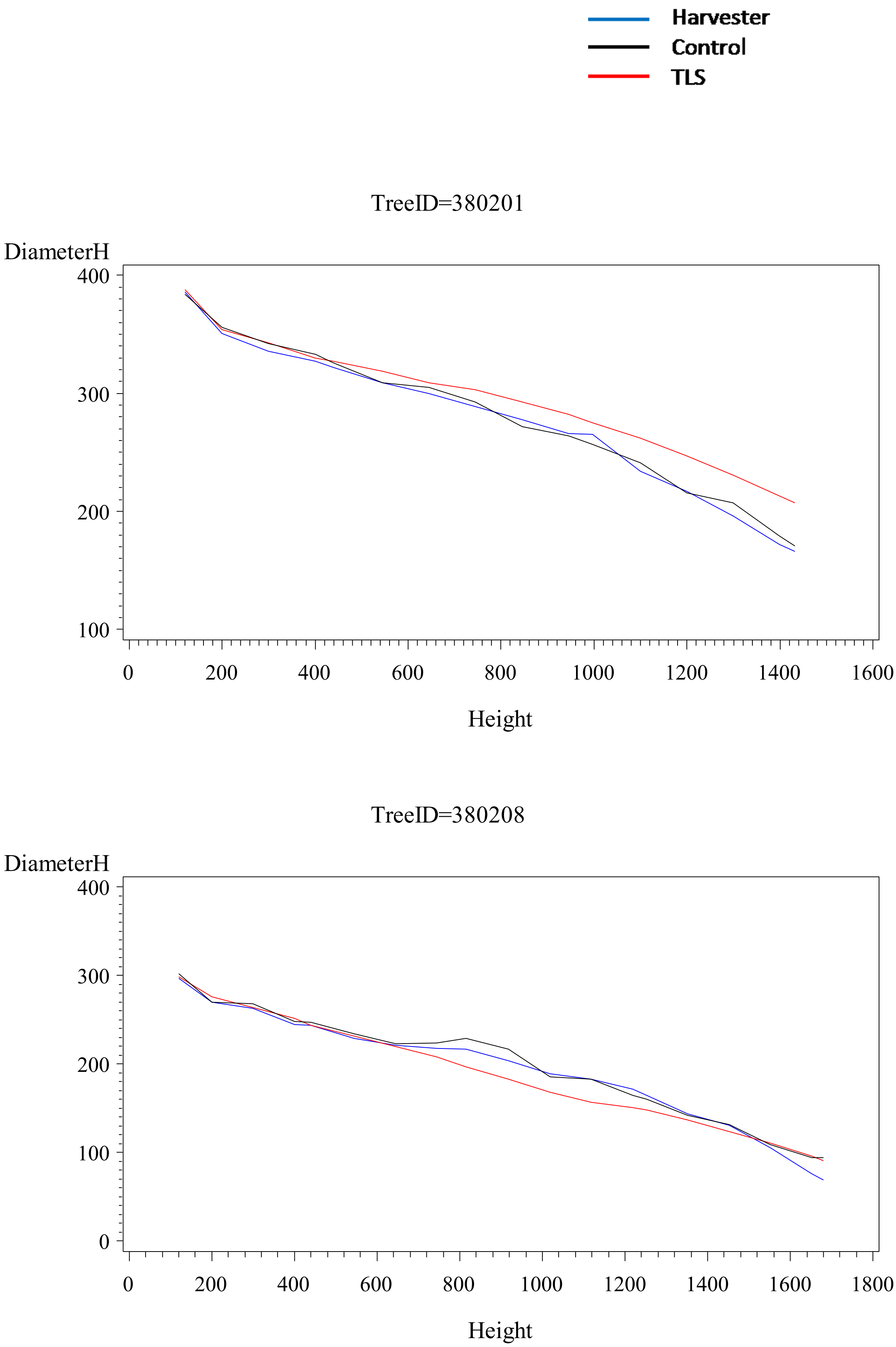
Harvester
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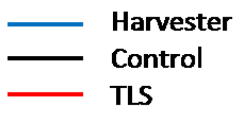
Appendix 1


Harvester
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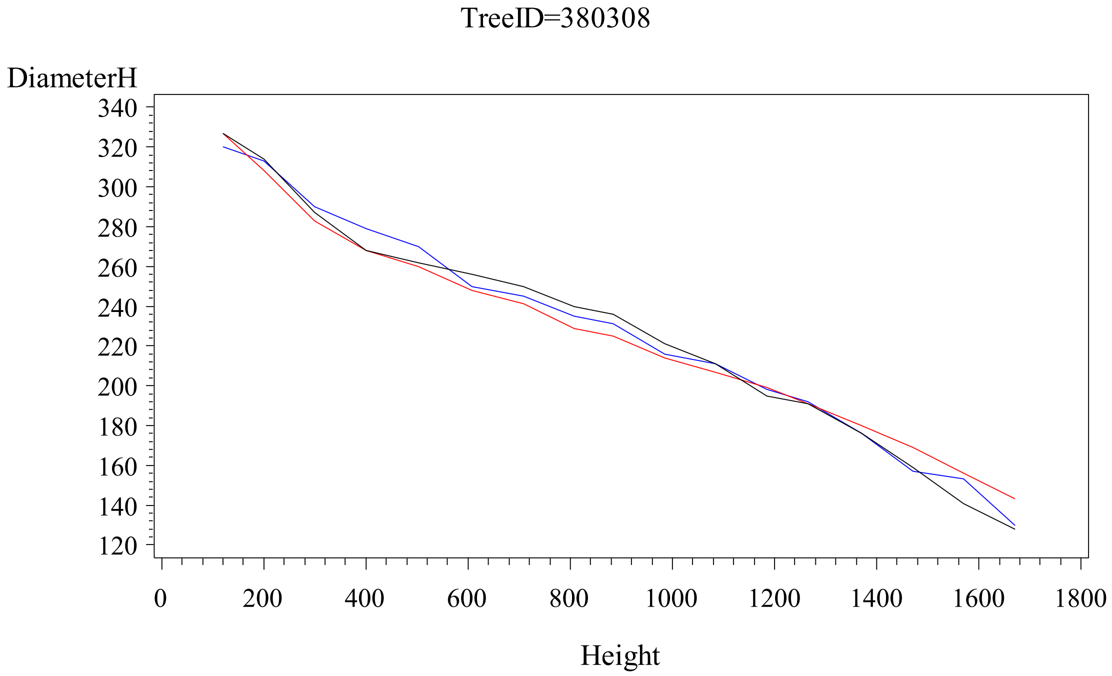
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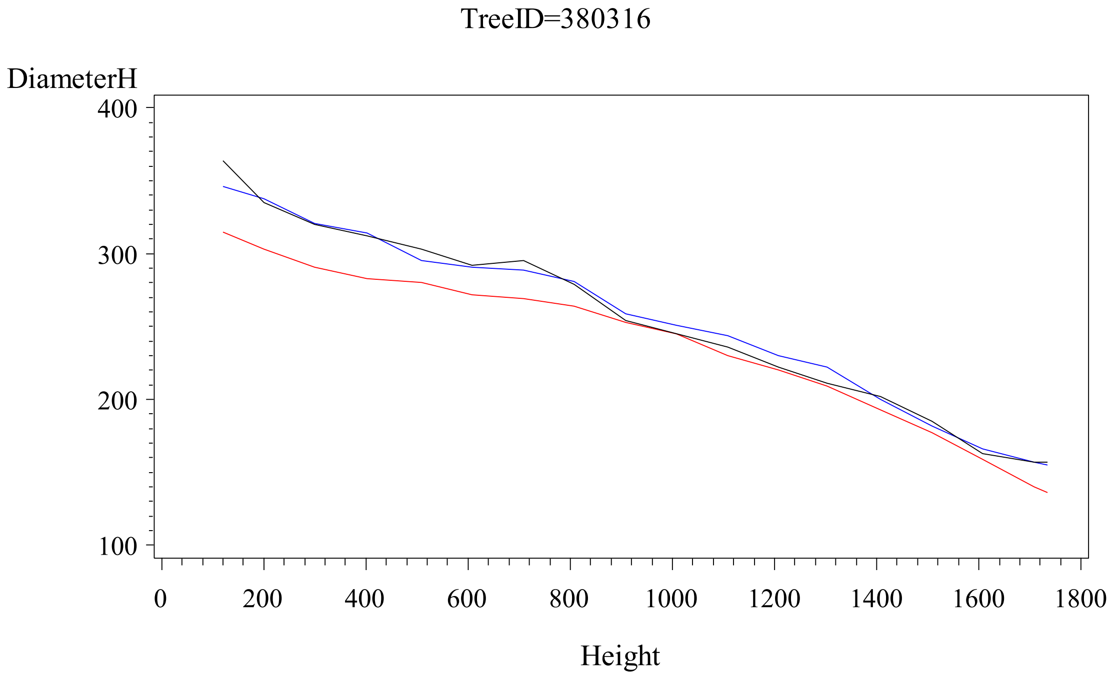
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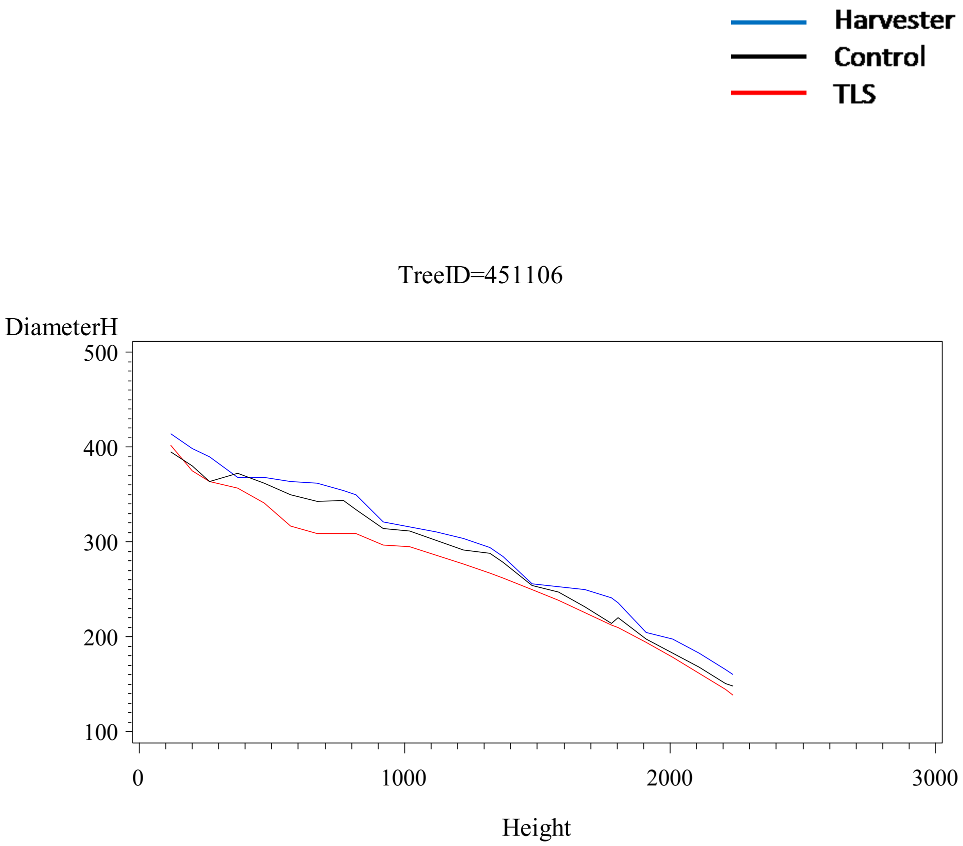
Appendix 1



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Height

Arbetsrapporter från Skogforsk fr.o.m. 2013

2013

Nr 786 Grönlund, Ö. & Eliasson. L. 2013. Knivslitage vid flisning av grot. Effects of knife wear on performance and fuel consumption for a small drum chipper. 12 s.

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Nr 804 Iwarsson-Wide, M., Olofsson, K., Wallerman, J., Sjödin, M., Torstensson, P. O., Aasland, T., Barth, A. & Larsson, M. 2013. Effektiv volymuppskattning av biomassa i vägkanter och ungskogar med laserdata. – Effective estimate of biomass volume on roadsides and in young forests using laser data 40 s.

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2014

Nr 817 John Arlinger, Torbjörn Brunberg, Hagos Lundström och Johan Möller. Jämförelse av JD1170E och JD1470E i slutavverkning hos SCA Skog AB hösten 2013. Comparison of JD1170E and JD1470E in final felling at SCA Skog AB, autumn 2013. 29 s.

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SKOGSBRUKETS FORSKNINGSINSTITUT · THE FORESTRY RESEARCH INSTITUTE OF SWEDEN
Uppsala Science Park, SE-751 83 UPPSALA, Sweden Ph. +46 18 18 85 00 skogforsk@skogforsk.se http//www.skogforsk.se