Technical Report

Assessing heartwood in *E. bosistoana* cores from NIR hyperimages

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EXECUTIVE SUMMARY

Assessing heartwood quality with current technology in a research context is resource intensive and not feasible in a commercial setting. NIR imaging has the potential to remotely assess heartwood quality almost instantaneously, opening the door for developing quality control of heartwood (e.g. for natural durability) through breeding and grading.

This pilot study on 175 *E. bosistoana* cores indicated that NIR imaging can be used to a) identify heartwood and sapwood on a wood surface and b) assess heartwood quality. A descriptive model was able to reliably identify heartwood and sapwood in the *E. bosistoana* stem cores. The heartwood extractive content was predicted with a RMSE of less than 3%. Considering a heartwood extractive content range from 0 to over 25%, this is a usable outcome. However, the findings should be validated through direct measurements.

A by-product of NIR imaging is the information of the spatial variation of heartwood quality in a sample. Spatial variation in heartwood quality is a topic which has not attracted much attention in the past due to the lack of a suitable analytical technique, but a homogeneous spatial distribution of heartwood extractives is critical for a well performing naturally durable product.

In the first instance NIR imaging should be usable directly for NZDFI’s phenotyping efforts of heartwood. However, the technology appears to have great potential to be used for timber grading in respect to natural durability. Developing a grading method and standard for natural durability would greatly increase the consistency and consumer acceptance of the product.

There are clear but unexplored routes to improve the accuracy of this technology in future, which were outside the scope of this work.

INTRODUCTION

Wood as a natural material is characterised by large variation in its properties. Some of this variation can be controlled e.g. by choosing a suitable species. However, variability within a species is significant, affecting efficient engineering designs. Therefore timber is graded into more homogeneous assortments, which in the case of structural timber are accompanied by material characteristics and regulated by national standards (NZS3631:1988, 1988). A further strategy to homogenise (and improve) timber properties is to narrow the genetic diversity in the forest plantations through breeding programmes. Both strategies rely on efficient (and in the case of production grading fast and non-destructive) assessments. These are available for some timber properties like stiffness (bending or acoustics) or strength (knots) and routinely used on all solid structural timber.

Natural durability, the resistance of heartwood against biodegradation, is also highly variable. Standards have been developed to classify natural durability of timber species (AS5604, 2005; EN350-1, 1994; EN350-2, 1994; Scheffer and Morrell, 1998), but, in contrast to the above mentioned mechanical timber properties, no grading standards exist to reduce within species variation, reflecting the lack of a suitable quick and non-destructive assessment.

AS5604 recognises within species variability only in regards to tree age and states that

> *" … the inner heartwood (the first few growth rings around the pith), generally, has lower natural durability than the rest of the heartwood."*

and also notes

> *"The list … is subject to change, particularly when the resource varies, e.g., the production from a young fast growth plantation compared with a mature, higher density resource."*

However, inner heartwood or the wood of young trees can have good durability (Bush et al., 2011) while the outer heartwood from old stands can be underperforming depending on locality like anecdotal reports of good and bad performing red beech (*Fuscospora fusca*) posts from NZ's East and West Coast suggest.

Resistance against biodegradation is essential for use of wood as a construction material. Natural durability was a sought after timber characteristic before the advent of timber preservation (Blair, 1879). Current building standards specify the 'guaranteed service life' for building components. The NZ standard 3602 specifies three categories of 50-, 15- and 5-years depending on accessibility and relevance to structural integrity (Zealand, 2003). With the 50-year criteria the standard recommends preservative treated timber, however selected naturally durable species are listed. With consumers becoming more and more critical of preservative treated timber and the unsolved disposal/recycling of such products creates resurgence in the demand for natural durable timber. To ensure consumers are satisfied with the performance of naturally durable timber, it needs to match their current experience of the consistently and highly performing treated timber. To achieve this, the variability of naturally durable timber needs to be decreased or the performance level reduced to the least durable fraction of the resource.

Efforts to reduce the variability in natural durability, e.g. through breeding, silviculture or grading, require robust but affordable analytical tools (Harju et al., 2009). Field and laboratory tests used to assess durability are destructive and time consuming, ranging from weeks to decades, and therefore are not suitable (AWPC, 2007; EN350-1, 1994). A key cause for the decay resistance of heartwood are the secondary metabolites, known as extractives, deposited by some trees species in the heartwood (Hawley et al., 1924). As heartwood extractives are also often coloured, heartwood colour was tested as a predictor of natural durability. Relationships of limited strength between colour parameters and natural durability were reported for *Eucalyptus grandis* (Nelson

and Heather, 1972), redwood (*Sequoia sempervirens*) (Wilcox and Piirto, 1976) or larch (*Larix* spp.) (Gierlinger et al., 2004).
Near infrared (NIR) spectroscopy is a non-destructive and quick technique to obtain information on the chemical composition of materials (Osborne et al., 1993) and has been applied to wood (Tsuchikawa and Kobori, 2015). Quantifying the extractive content of wood has been shown to be one of the easier applications of NIR spectroscopy to wood (Gierlinger et al., 2003; Li and Altaner, 2019a; Taylor et al., 2008). Several NIR technologies have been developed, differing in the resolution, spectral range and placement of the sample in respect to the detector (Streamer, 2013). More laborious methods like transmission, integrating spheres or fibre optics, which give high quality spectra, have been used reliably to investigate wood properties in a research context (Tsuchikawa and Kobori, 2015). NIR cameras are more limited in their spectral range, but excel by providing spatial information (also known as hyperspectral images) as well as speed and ease of spectra acquisition. Hyperspectral imaging is now routinely used in remote sensing as well as product quality control and waste/raw material sorting. Hyperspectral imaging with NIR cameras has seen little use in respect to timber grading (Harris and Altaner, 2013; Tsuchikawa and Schwanninger, 2013), but have the potential for a quick contactless assessment of natural durability via extractive content. This would allow the development of a grading system for sawn timber in respect to natural durability. No technique to grade timber for naturally durability is currently available, but grading, i.e. quality control, would immensely benefit the acceptance of naturally durable timber.

Phenotyping breeding trials for heartwood quality is a significant cost (Harju and Venäläinen, 2006) and quick NIR imaging technology could make NZDFI's breeding programme more efficient.

Objectives

The objective of this study was to explore the feasibility of quantifying extractive content in *E. bosistoana* heartwood with a NIR camera. The study made use of existing *E. bosistoana* samples originating from the NZDFI tree breeding programme, which has previously been assessed for extractive content with a NIR fibre optics probe.

METHODS

Material

175 full stem diameter cores, previously obtained from 6.6 to 8.9-year old *E. bosistoana* trees at the base from 6 different trials, were selected for this study. These represented a stratified sample for NIR predicted extractive content from the New Zealand Dryland Forests Initiative (NZDFI) breeding population (Table 1).

Corelength (i.e. stem diameter under bark at ~0.5 m) and heartwood diameter were measured with a ruler in the green state after highlighting heartwood by the application of 0.1% (w/v) aqueous methyl orange solution. After drying the cores at 60°C, NIR spectra were collected from the radial-tangential surface with a fibre optics probe (Bruker) every 5 mm along the heartwood. The radial tangential-surface was sanded for samples from four of the six sites (Table 1). In case less than 15 mm heartwood were present spectra were taken at least 3 points close to the pith. The extractive content (pEC) was predicted for each spectra using a PLSR model (Li and Altaner, 2019a) and averaged for each core.

NIR

Data acquisition

Hyperspectral images were collected in a dark room with a Headwall Photonics system including a halogen light source, a movable stage and the Hyperspec III software. The detector array was 320 pixels wide and collected 235 spectral bands between 550 and 1700 nm. A 50 mm lens with an equivalent focal length of 25 mm was used and the distance between the lens and samples was 370 mm. The exposure time was set to 34 ms, the write speed was 25 frames per second and the camera stage moved with 10.8 mm/s, capturing 450 rows for each image. Before scanning, the camera was calibrated using a black (lens cap on) and white (standard white Teflon tile) reference. Each core was scanned once.

Image processing and assigning pixel categories

Spectra of all pixel were extracted as csv-files from the hyperimage with the Scyven software (Habili and Oorloff, 2015). Data was then further processed in R (Team, 2020). First pixel containing the black background were deleted by setting a minimum threshold for the sum of the intensity at all wavelengths, leaving only data representing the wood sample (Figure 1). Then the centre line (black) along the core was identified as the median x value of the remaining pixel for each row (y) in the image. The edges of the core were removed by selecting 5 pixels to the left and right of the centreline. Also the core ends were removed by deleting the top 4 (maximum y value) and bottom (minimum y value) rows.
Subsequently the available corelength and heartwood diameter measurements were used to assign the selected pixel to heartwood, sapwood or the transitions zone (Figure 1). The proportion of heartwood (heartwood diameter divided by corelength) of the core and the centre, i.e. the pith, (median of y values) were calculated for each hyperspectral image. The heartwood-sapwood border was defined as the y values half the heartwood proportional distance either side of the pith. 5 rows (y values) on either side of the heartwood-sapwood border were classed as transition zone (blue). Pixels were defined as heartwood (red) if they were between the transition zones and as sapwood (green) if they were outside the transition zone.
It is worth noting that these assignments of wood type were not necessarily correct as heartwood is not necessarily centred on the pith and the pith is not necessarily centred in the core, however the majority of the assigned heartwood and sapwood pixel truly represented these wood types and consequently dominated the NIR spectra.

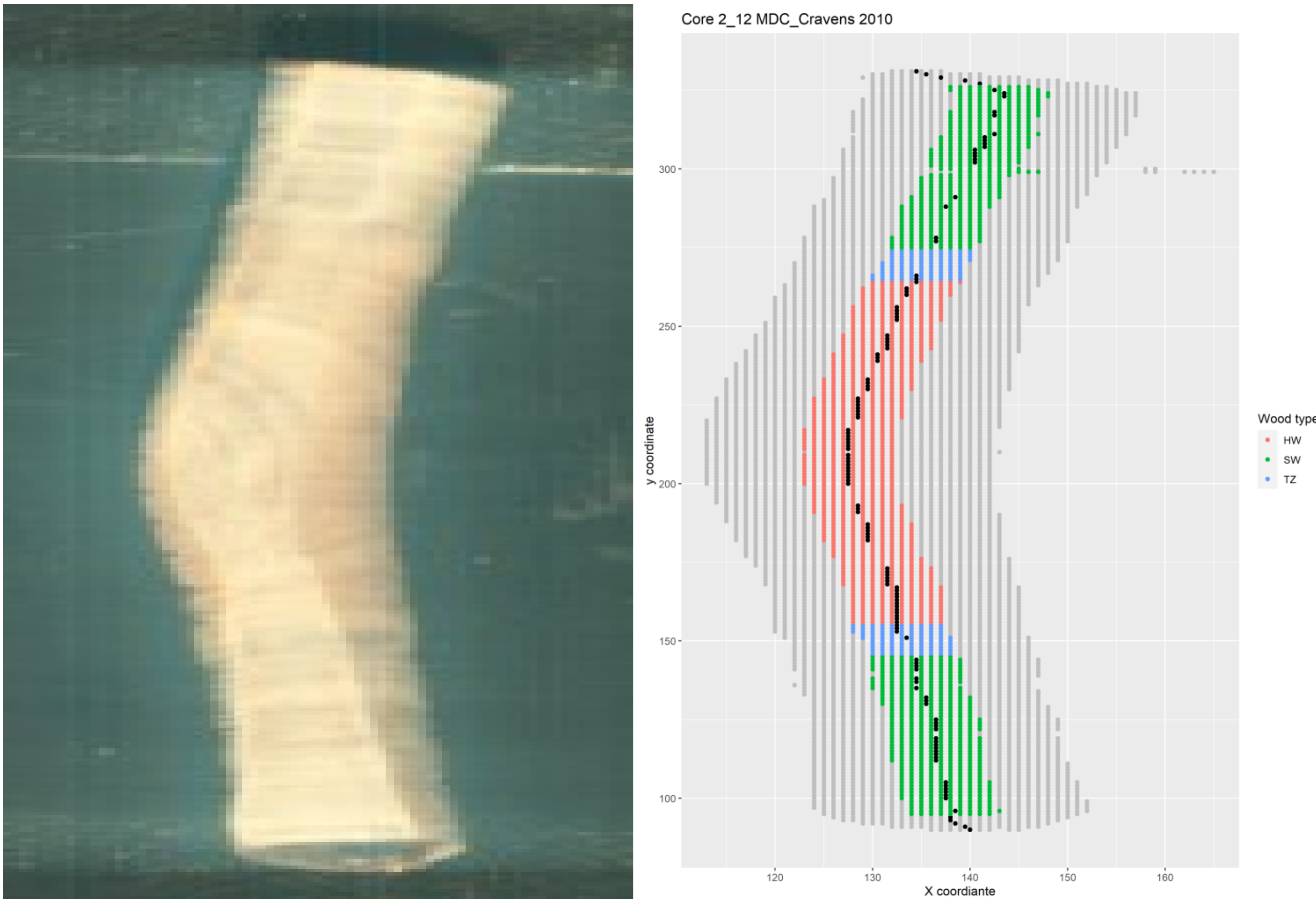

Figure 1: Example of an E. bosistoana core (left). Right: pixel with spectra classified as core (dots); grey – not selected, black – centreline, red – assigned as heartwood, green – assigned as sapwood and blue – assigned as transition zone. Note: x axis is stretched.

Classification of heartwood and sapwood

The NIR spectra were first normalised with the standard normal variate algorithm before being converted into the 2nd derivate using the prospectr package (Stevens and Ramirez-Lopez, 2020). The BGLR package was used to fit Bayesian Generalized Linear Regressions for sapwood and heartwood individually, using all spectra identified above. An explanatory model was constructed using all data, as the purpose was to identify the pixel representing heartwood in the dataset.

Predicting heartwood quality

Subsequently, the normalised spectra from pixel which was classified as heartwood by the BGLR heartwood model were averaged for each core. A predicted heartwood extractive content (pEC) was available for each core from previous fibreoptics probe NIR measurements. These were used for building a descriptive Partial Least Squares Regression for extractive content with the PLS package (Mevik and Wehrens, 2007). The data was not split into a calibration and validation set, but all cores were used with leave one out (LOO) cross-validation.

RESULTS

Descriptive statistics of the samples are found in Table 1. It should be noted that the predicated extractive content for some cores was negative (Figure 2), what is impossible and an artefact of the unrestricted response in the PLSR model.

Table 1: Summary statistics of E. bosistoana stem cores – means with standard deviation in parentheses.

Site	Age at coring (year)	Number of cores	Corelength (mm)	Heartwood diameter (mm)	predicted Extractive content (%)
Martin 2009	8.9	30	104 (17)	39.5 (19)	10.5 (5.1)
Martin 2010	6.6	30	89.5 (23)	29 (19)	11.5 (3.7)
MDC Craven 2009*	6.7	29	119 (24)	39 (19)	1.8 (2.2)
MDC Craven 2010	6.8	28	101 (29)	35 (20)	9.5 (4.1)
Lawson 2009*	6.7	28	96 (9)	25 (10)	4.7 (2.5)
Avery 2010	8.1	30	88 (16)	24 (15)	13.3 (7.0)
All		175	99.4 (23)	30.1 (18)	8.6 (5.9)

* Spectra were taken from the cross-sections of the cores. Cross-sections of cores were sanded (Figure 1) except those from the MDC Craven 2009 and Lawson 2009 site.

Classification of heartwood and sapwood

Two Descriptive Bayesian Generalized Linear Regression (BGLR) models for being heartwood (yes or no) and for being sapwood (yes or now) were built from the 329,703 available NIR spectra using the above described assignment of wood type from core length and heartwood measurements. The two analogous models agreed for 93.9% of all pixel, ranging from 78.7% to 99.4% for the individual cores. This was an encouraging result, as it was possible to identify heartwood and sapwood in *E. bosistoana* with an NIR camera. A quick and non-destructive assessment of heartwood could enable machine grading of such timber.

The proportion of identically classified pixel with the two models was only weakly correlated (r = 0.33) to the heartwood extractive content predicted from fibre optics probe NIR spectra (Figure 2).

The predicted wood type with the BGLR heartwood model for each pixel in the hyperspectral image of all cores are shown in Appendix 1. It can be seen that the model yielded sensible results, with the majority of HW pixel in the centre of the stem. The proportion of pixel classified as heartwood by the BGLR model allowed the calculation of a predicted heartwood quantity. The correlation coefficient to the measured heartwood quantity on the core with a ruler after staining was r = 0.78 (Figure 3).

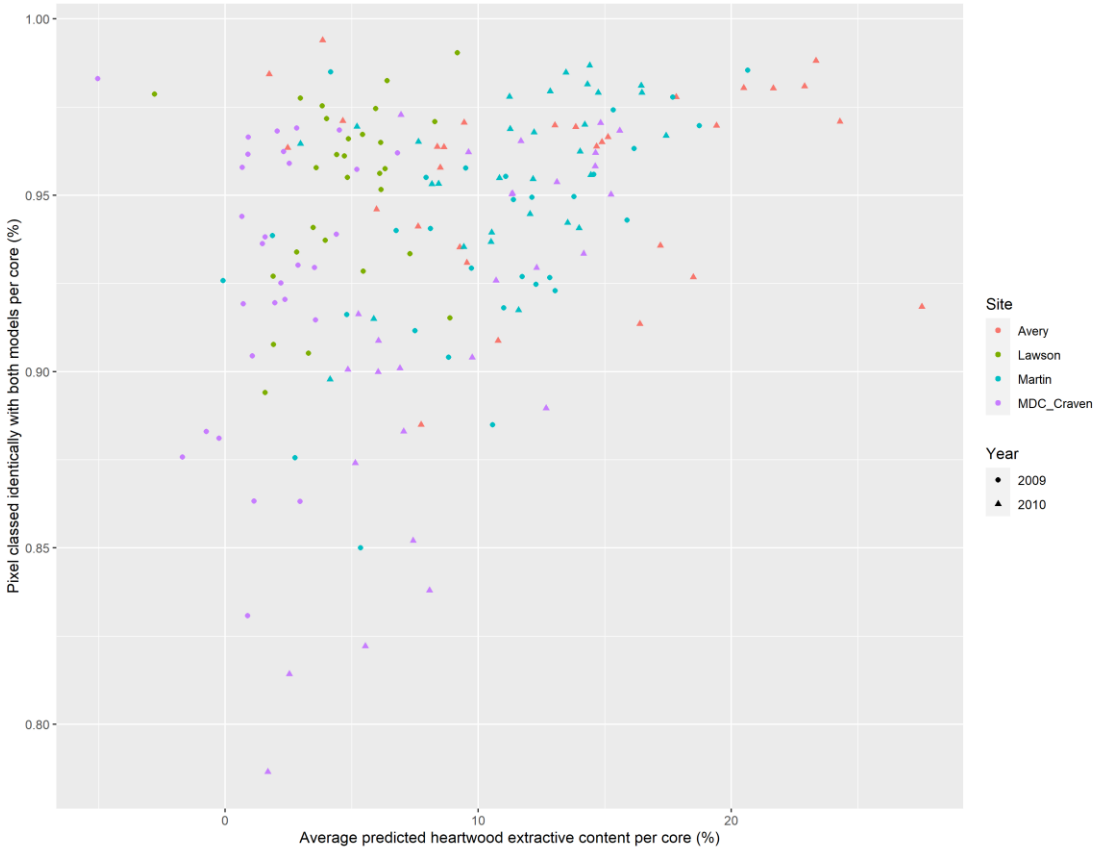

Figure 2: Percentage of pixel classified as the same wood type by the BGLR Heartwood and Softwood models for each core depending on the average predicted heartwood extractive content.

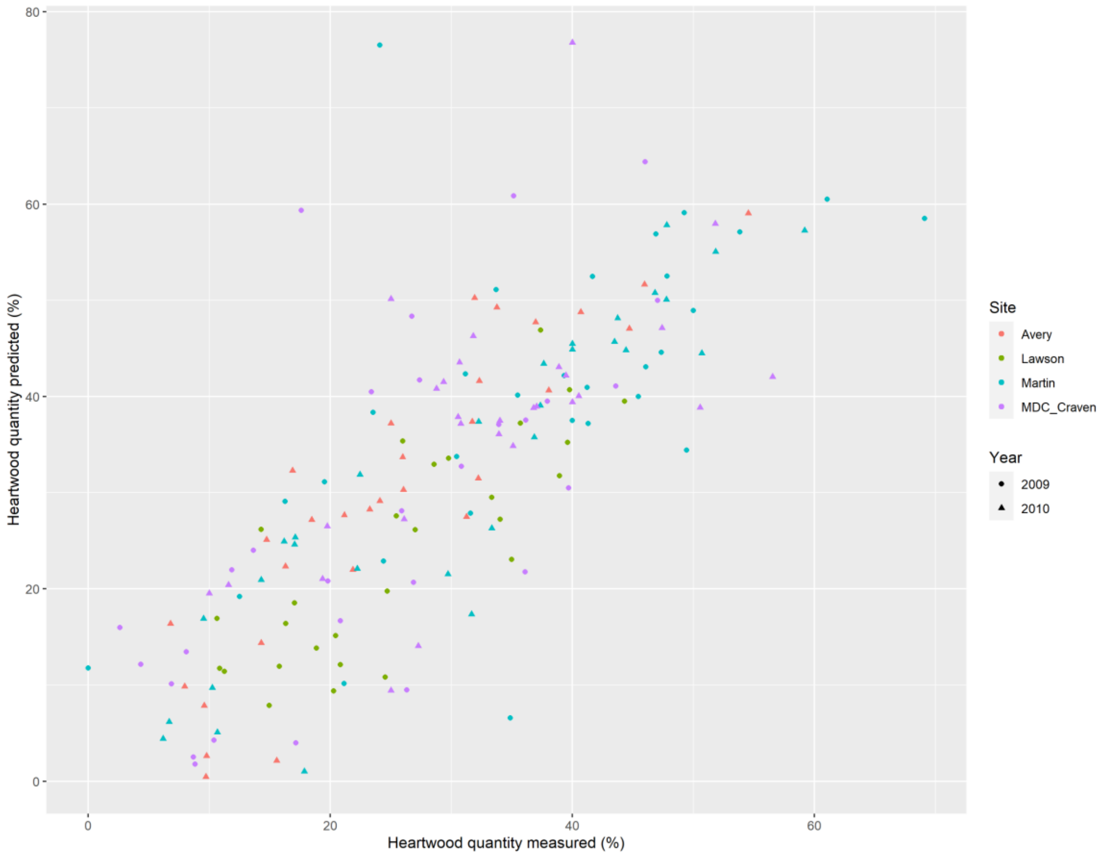

Figure 3: Relationship between measured heartwood quantity on the cores after staining and the proportion of predicted heartwood pixel in the hyperimages with the BLGR model (r = 0.78).

In the context of this work, the classification of wood type with the BGLR model for heartwood and sapwood allowed to generate a more accurate calibration dataset for quantifying extractive content. This is because the assignment of wood type (i.e. heartwood, sapwood or transition zone) to the pixel in the hyperspectral images from the heartwood diameter percentage was not necessarily correct (for example due to pith eccentricity). An example of the assigned and predicted wood types for a core is shown in Figure 4.

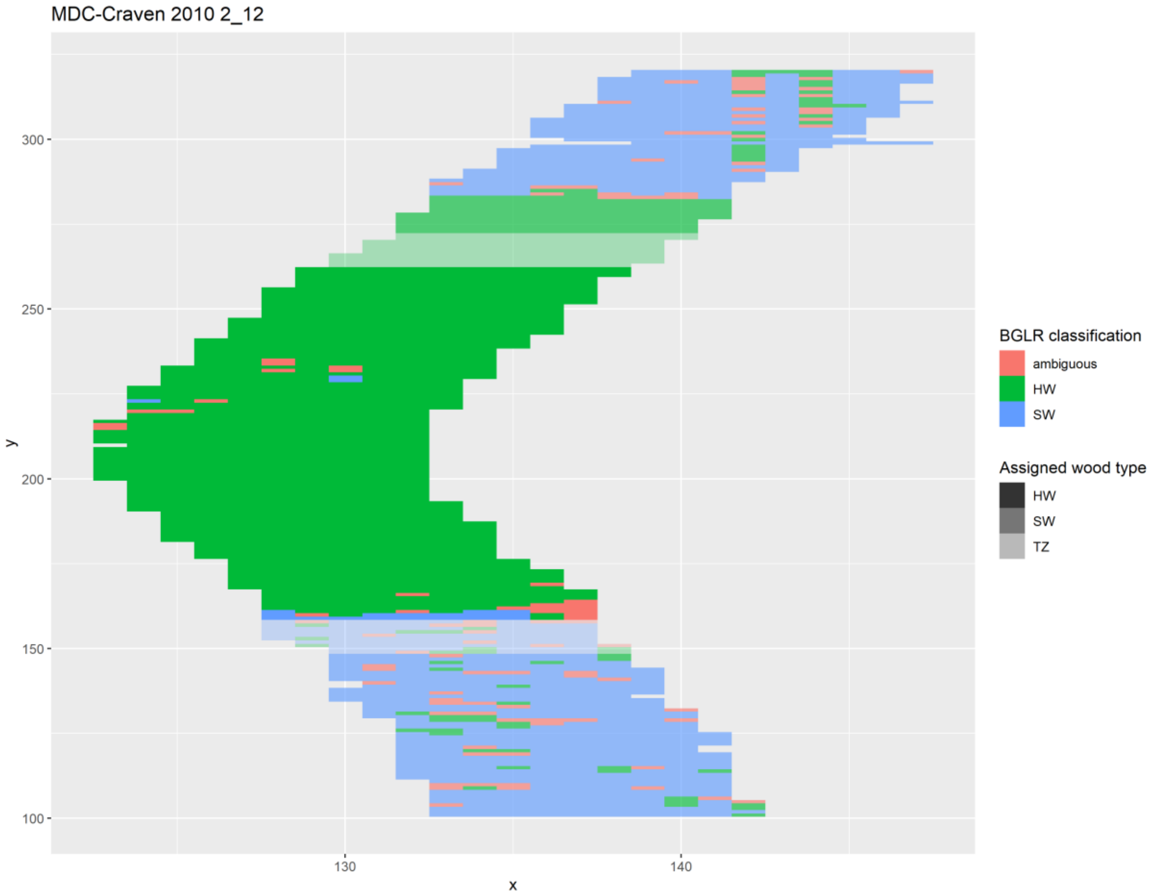

Figure 4: Pixel classified by both, the BGLR heartwood and sapwood models – green (heartwood by both models), blue (sapwood by both models), red (ambiguous). Overlaid as colour saturation the assigned wood types from corelength and heartwood percentage measurements (heartwood most intense, transition zone least intense colour saturation).

Quantification of extractive content

The averaged heartwood spectra, as classified by the BGLR heartwood model described above, of each of the 175 *E. bosistoana* cores were used to model EC with a partial least square regression (PLSR) algorithm. Averaging before or after normalisation did not significantly change the outcome. Results for averaging after normalisation are reported here.

A descriptive model for predicted extractive content achieved a residual mean square error of prediction (RMSEP) of 2.87% using 6 principal components (Figure 5). This compared to a RMSE of <1% for the more elaborate PLSR models using the higher quality fibreoptics probe spectra (Li and Altaner, 2018; Li and Altaner, 2019a; Li and Altaner, 2019b). Considering the heartwood extractive content in the samples ranged from -5.0 to 27.5 %, a RMSEP of 2.87% assessing heartwood quality quick and contactless with a NIR camera from hyperimages seems practically feasible. In particular when considering that the this PLSR model was basic and, based on previous experience, improvements are likely possible by optimising spectra pre-processing (EPO normalisation), variable selection and utilising other multivariate statistical methods like Bayesian statistics (to account for a restricted response), random forests or machine learning. This was however, outside the scope of this work.

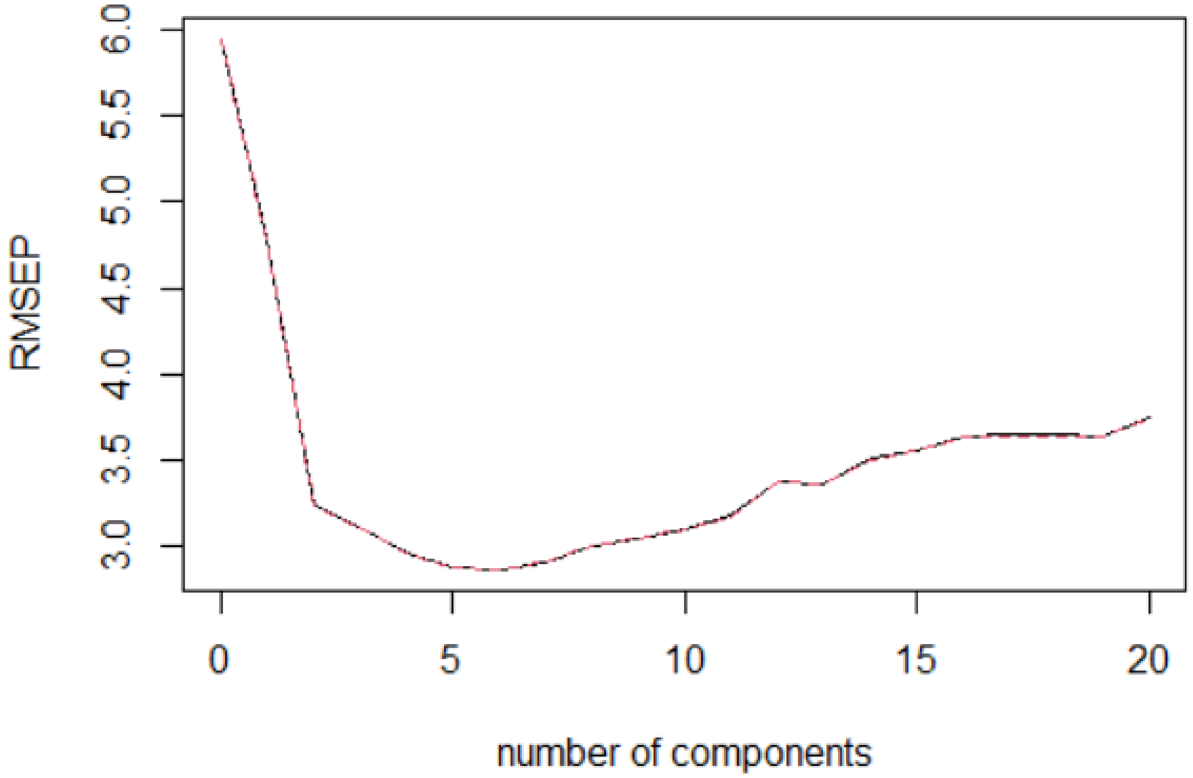

Figure 5: Residual mean square error of prediction (RMSEP) of a PLSR model predicting average extractive content in heartwood of E. bosistoana cores from hyperimages depending on the number of principal components.

The above described PLSR model for extractive content developed from average heartwood spectra of the hyperimages of the 175 *E. bosistoana* cores was applied to all 329,703 spectra/pixel in these images. The mean predicted extractive content was 9.4% (std 7.2%) and 1.1% (std 4.7%) for the pixel identified as heartwood and sapwood with the BGLR model, respectively. This compared to an average predicted heartwood extractive contend from the fibreoptics probe spectra of 8.6% (std 5.9%) (Table 1). The correlation between the two predictions of average core heartwood extractive content was strong (r = 0.91) (Figure 6). This was to be expected if the spectra contain similar information as the fiberoptics probe data was used to calibrate the hyperimage based model.

To note is the large range (-63.6% to 56.3%) of predicted extractive contents from the hyperimages. The extremes could be regarded as outliers (Figure 7). A possibility to reduce the extremes (and possibly improve the accuracy of the model) is to restrict the model to the physically possible range of 0 to 100% extractive content, for example with a Bayesian approach.

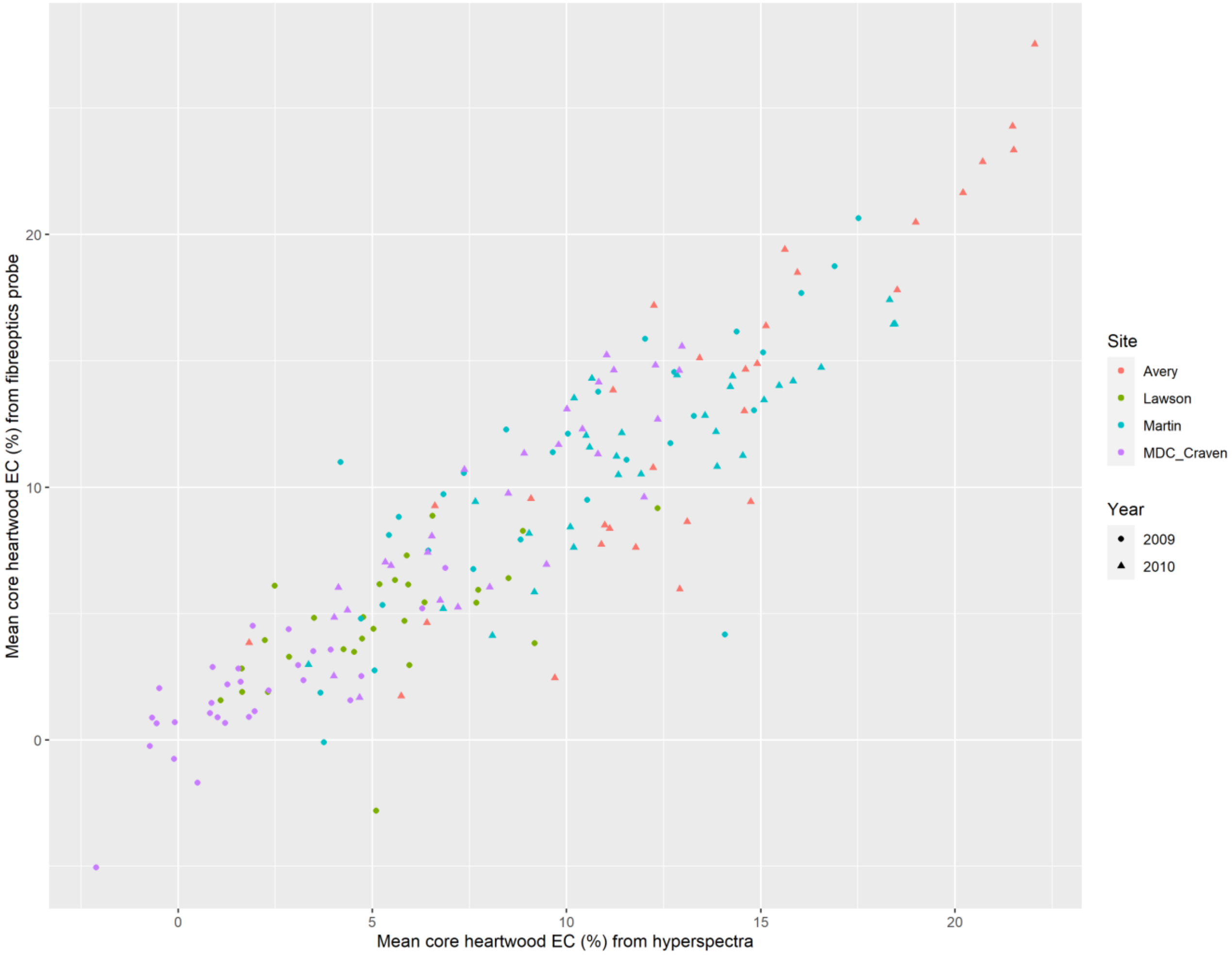

Figure 6: Correlation (r = 0.91) between mean heartwood extractive content for 175 E. bosistoana cores assessed from spectra obtained with a NIR fibreoptics probe and a NIR camera, respectively.

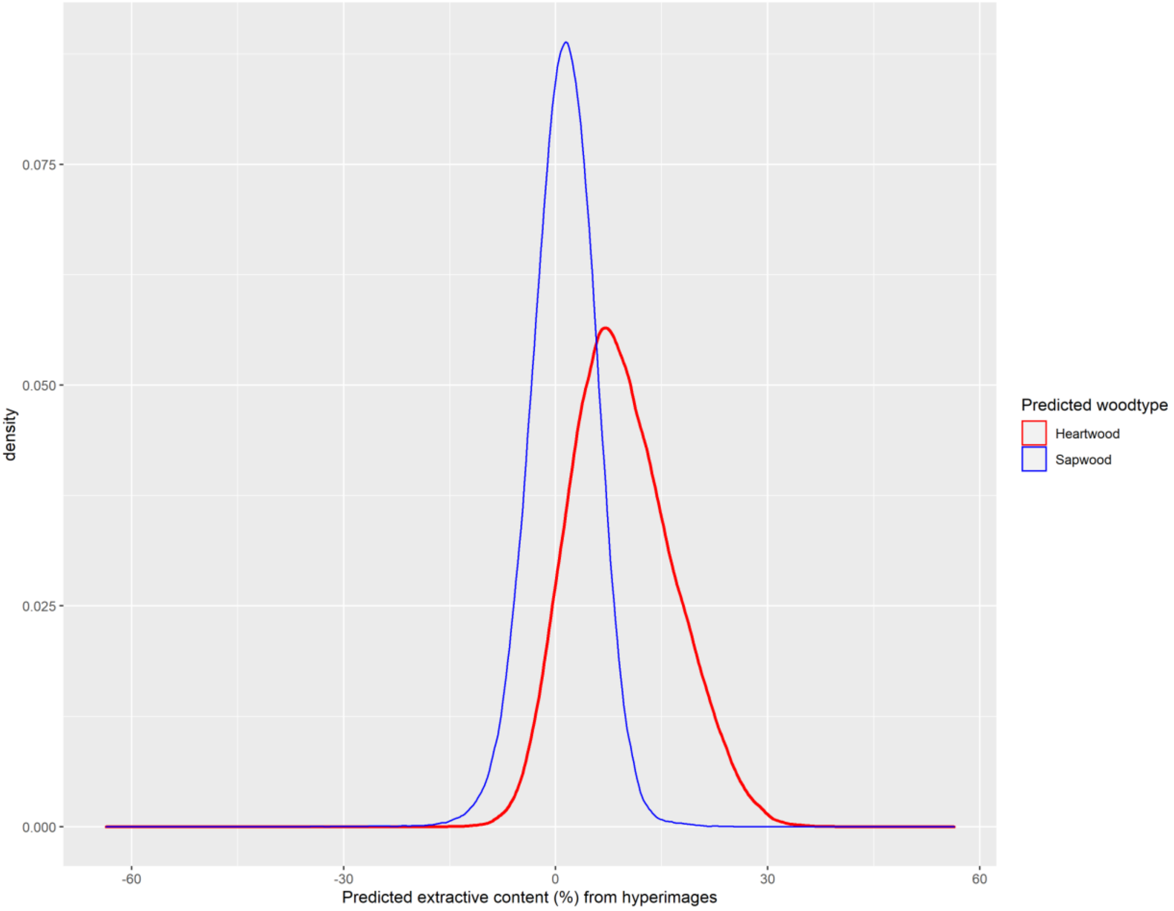

Figure 7: Density distribution of predicted extractive content in the 329,703 pixels/spectra from the 175 E. bosistoana cores which were identified as heartwood and sapwood by the BGLR model, respectively.

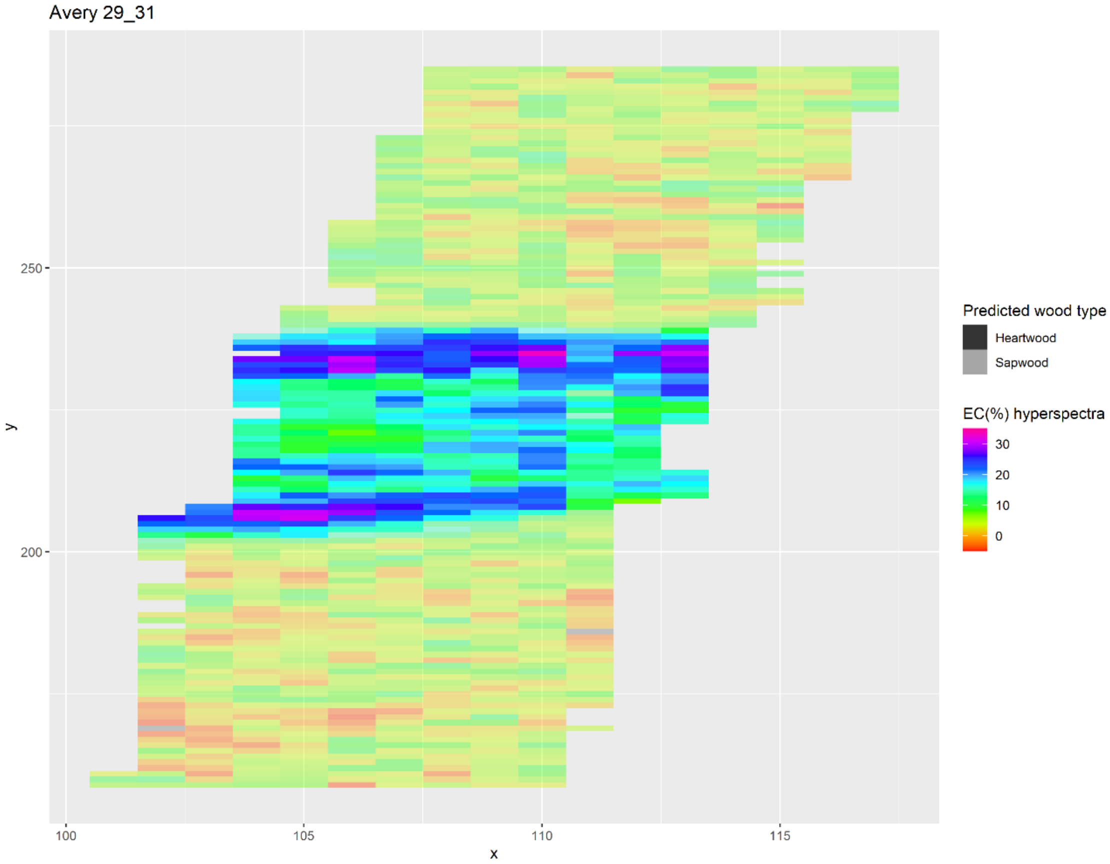

Figure 8: Spatial variation in predicted extractive content in heartwood (saturated colours) and sapwood (les saturated colours) in a E. bosistoana stem core.

Applying the PLSR model to the hyperimages allowed mapping the spatial variation in extractive content of the cores (Figure 8). Visualisation of extractive content distribution in all cores can be found in Appendix 2. To note is the apparent spatial variation in extractive content within the heartwood of the cores. Trees with even and uneven spatial extractive distributions were observed. While these results should be confirmed by solvent extraction of heartwood regions with high and low extractive content, it is conceivable that the extractive content is indeed variable within the heartwood of a tree. Such variation was reported in stem and root discs from *E. bosistoana* and *E. globoidea* by fibreoptics probe measurements (Li, 2018). It is also consistent with within tree variation of decay test results from mass loss assessments and the clearly visible variation in heartwood extractives in species such as *Microberlinia brazzavillensis* also known as zebrano (Kohl, 2012).

It appeared that the surface quality (sanded or not - Table 1) had an effect on the predicted extractive content. In particular for the sapwood the EC values were lower for the not sanded cores from the MDC Craven 2009 and Lawson 2009 sites (Appendix 2). This surface effect should be investigated further and could be mitigated by spectra corrections (Giordanengo et al., 2008; Li and Altaner, 2018).

CONCLUSION

This pilot study showed that NIR imaging can be used as a quick and contactless method to assess heartwood in durable eucalypts.

In the first instance this could facilitate the phenotyping of durably eucalyptus trees for heartwood quality by average extractive content, as hyperimaging can be automated as demonstrated by Scion's DiscBot. Streamlined phenotyping for heartwood traits would be directly beneficial to the NZDFI programme, but should also be possible for other species such as cypresses or redwoods.

Further, the NIR imaging technique additionally includes spatial information of heartwood quality within the sample. While typical coarser radial patterns in extractive content are known (Anderson, 1961; AS5604, 2005; Sherrard and Kurth, 1933), the more irregular and more local variation seen here has not attracted much research in the past. Nevertheless, a homogeneous distribution of extractives throughout the heartwood is desirable for highly durable timber and NIR imaging opens the door to explore genetic and environmental effects of this phenomenon.

Lastly, the successful assessment of heartwood quality by NIR imaging will allow to grade timber for durability to ensure a consistent product. No grading standard for natural durability has been developed yet, but a quality standard would greatly increase the confidence of the customer in the product.

Recommended next steps

It should be noted that this procedure was indirect, i.e. predicting a predicted extractive content, which in turn was used as proxy of natural durability. The precision of the hyperimage model should be validated by solvent extraction of previously imaged samples. This would also confirm the observed spatial variation within samples.

While the here developed basic PLSR model is usable (RMSE 2.87%), it should be verified if improvements in accuracy are possible by applying more elaborate spectra processing, variable selection and statistical methods.

It has been shown that fungal mass loss of *E. bosistoana* heartwood can be predicted from fibreoptics NIR spectra and that these predictions were correlated to those for extractive content (Li et al., 2020). Therefore, direct mass loss models for the NIR camera should be explored.

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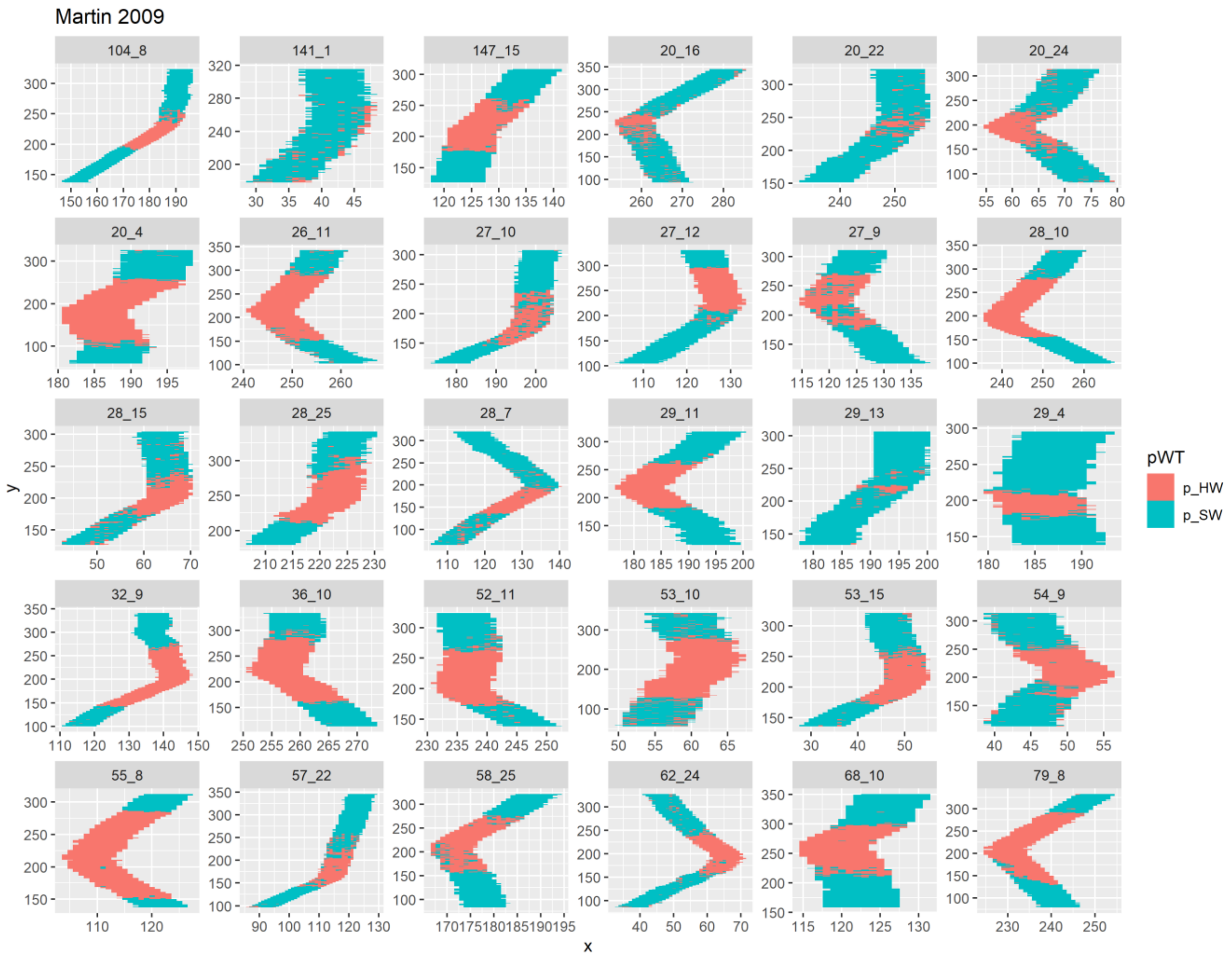
APPENDICES

Appendix 1: Classification of wood type for all cores using the BGLR heartwood model



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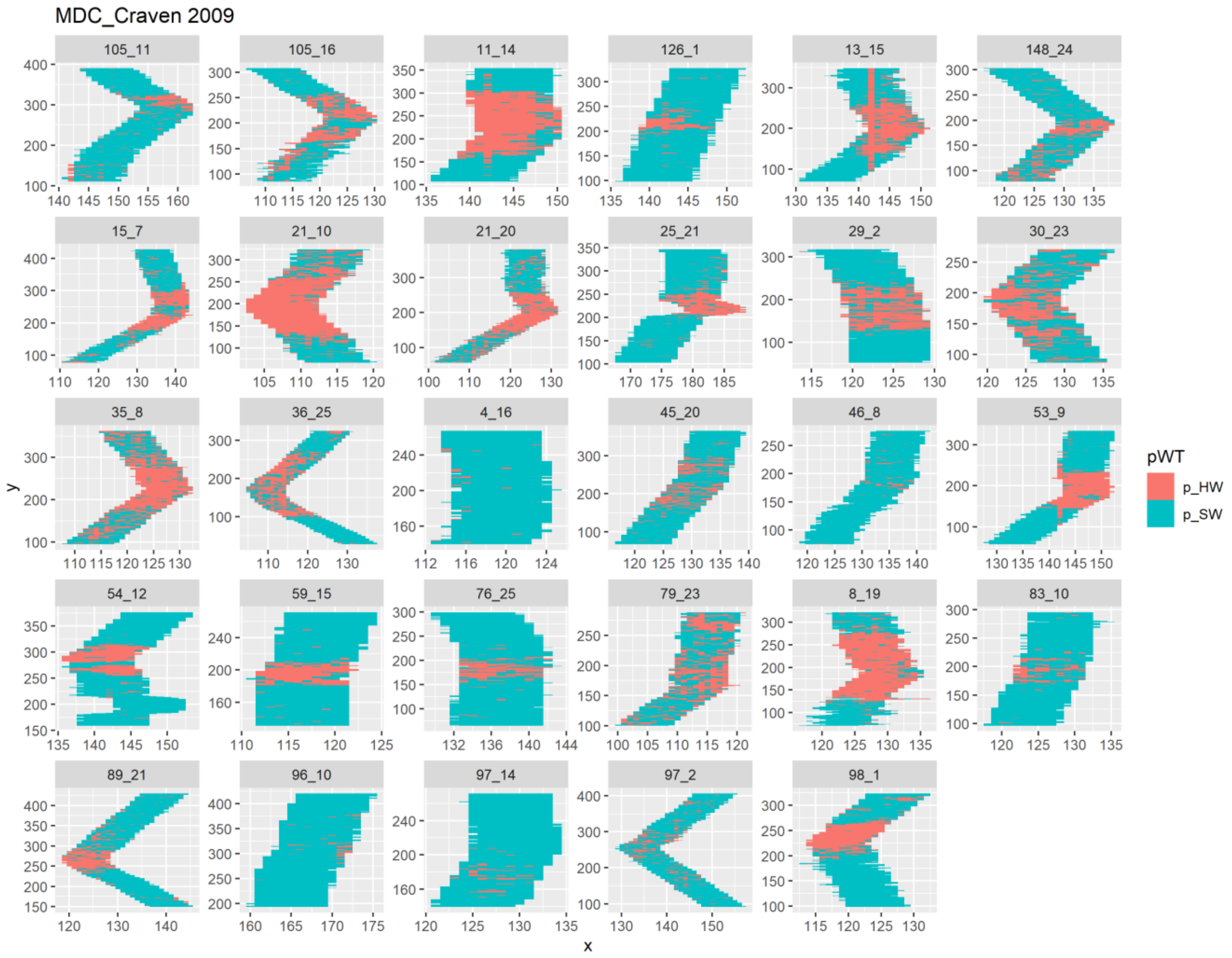
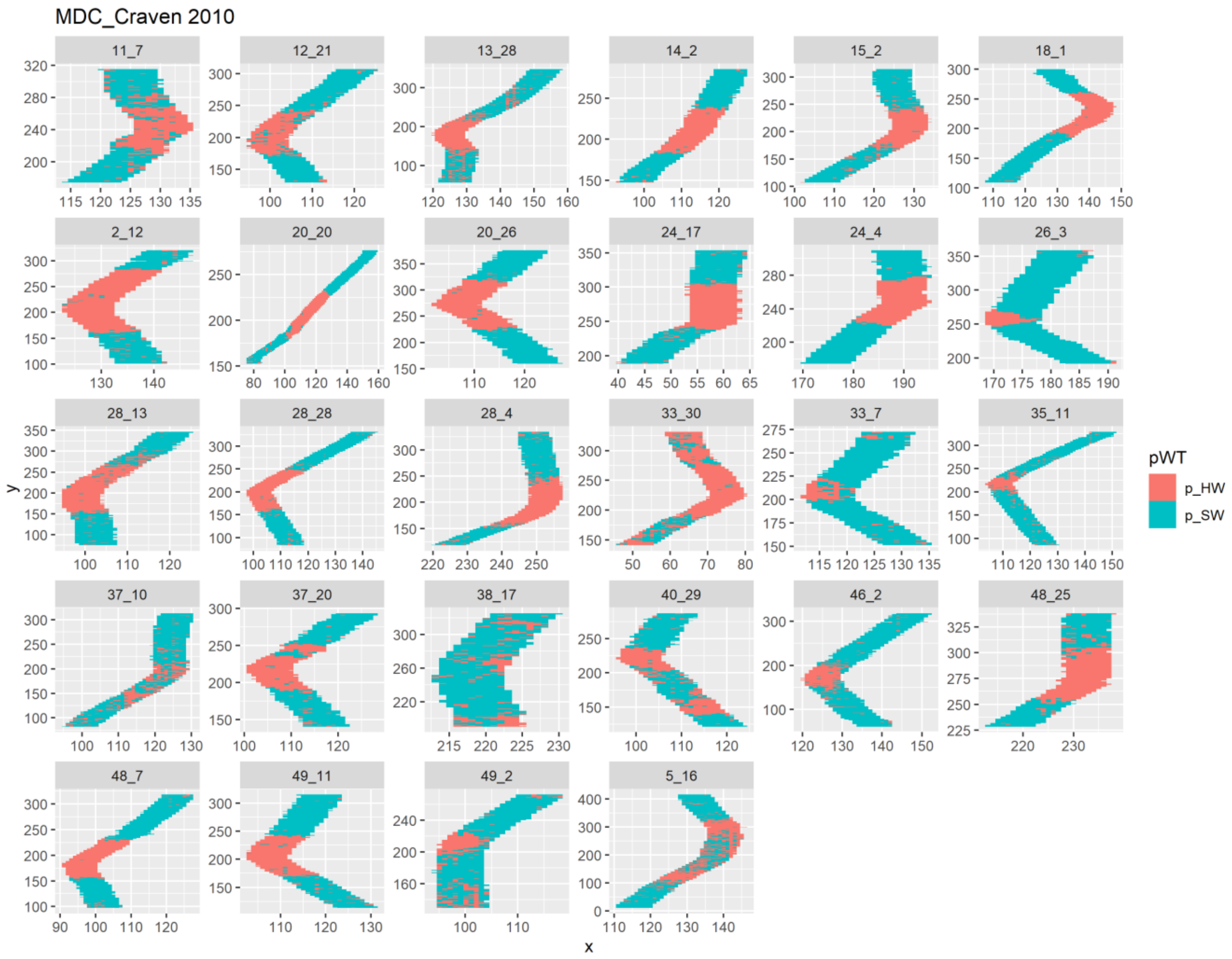
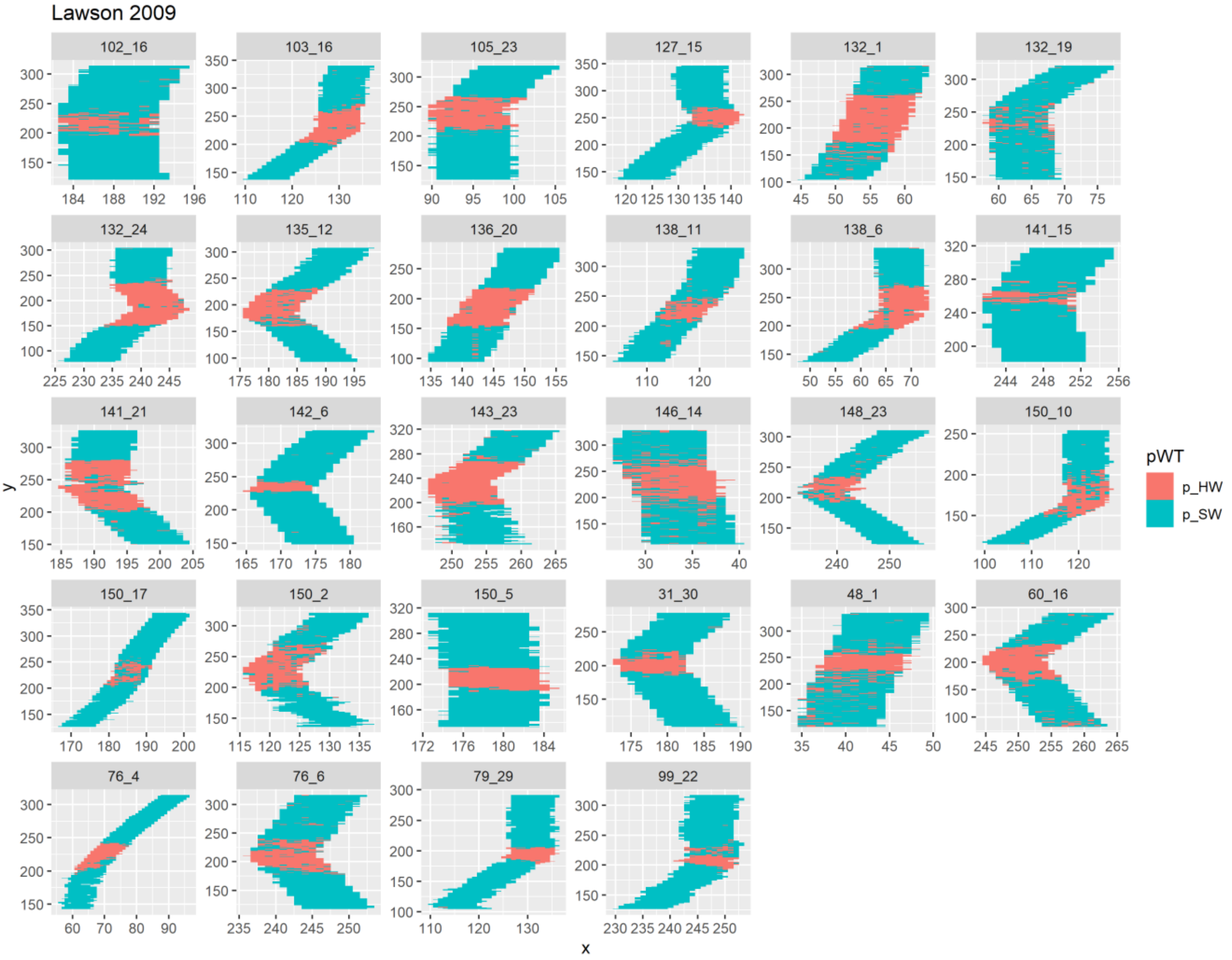
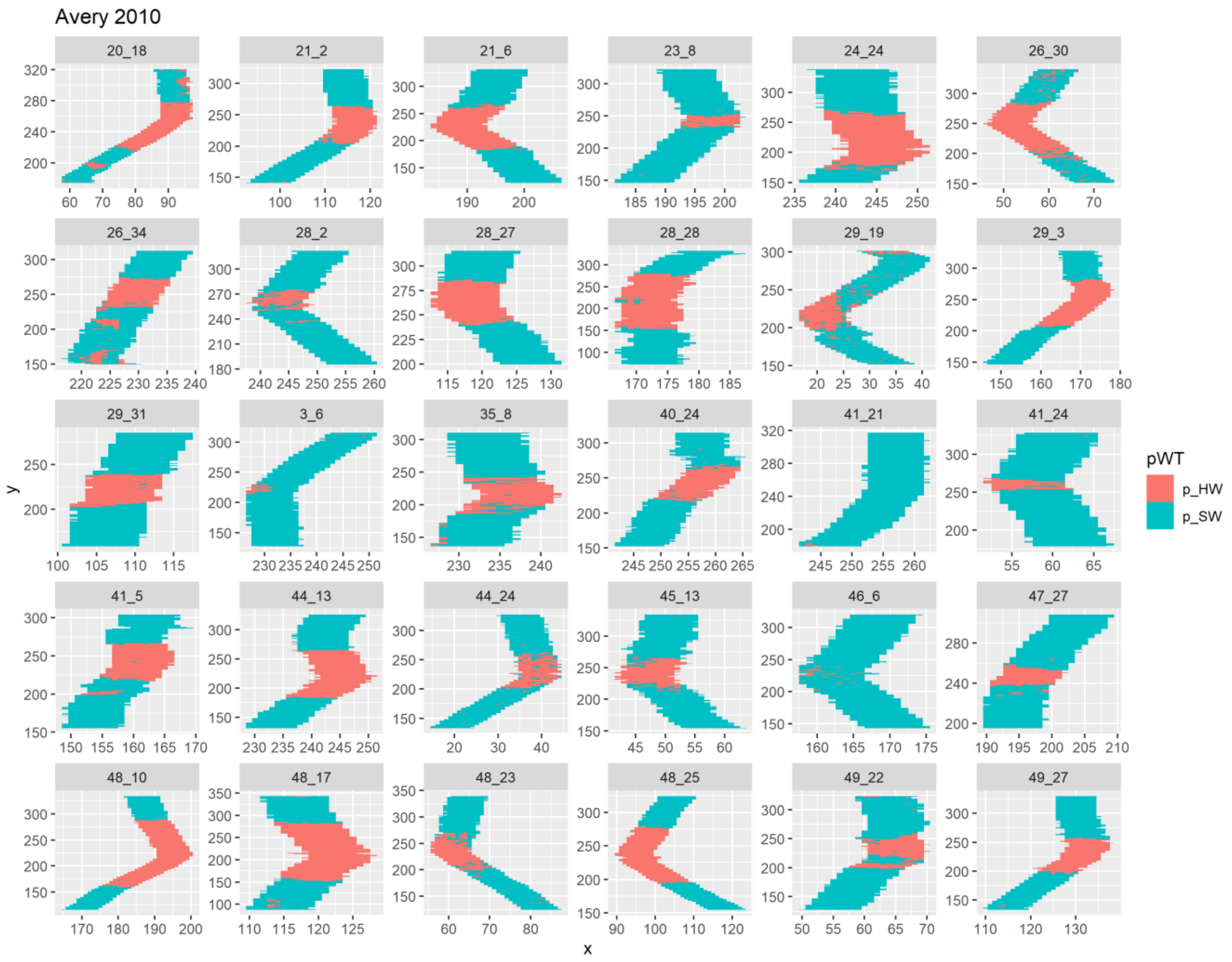
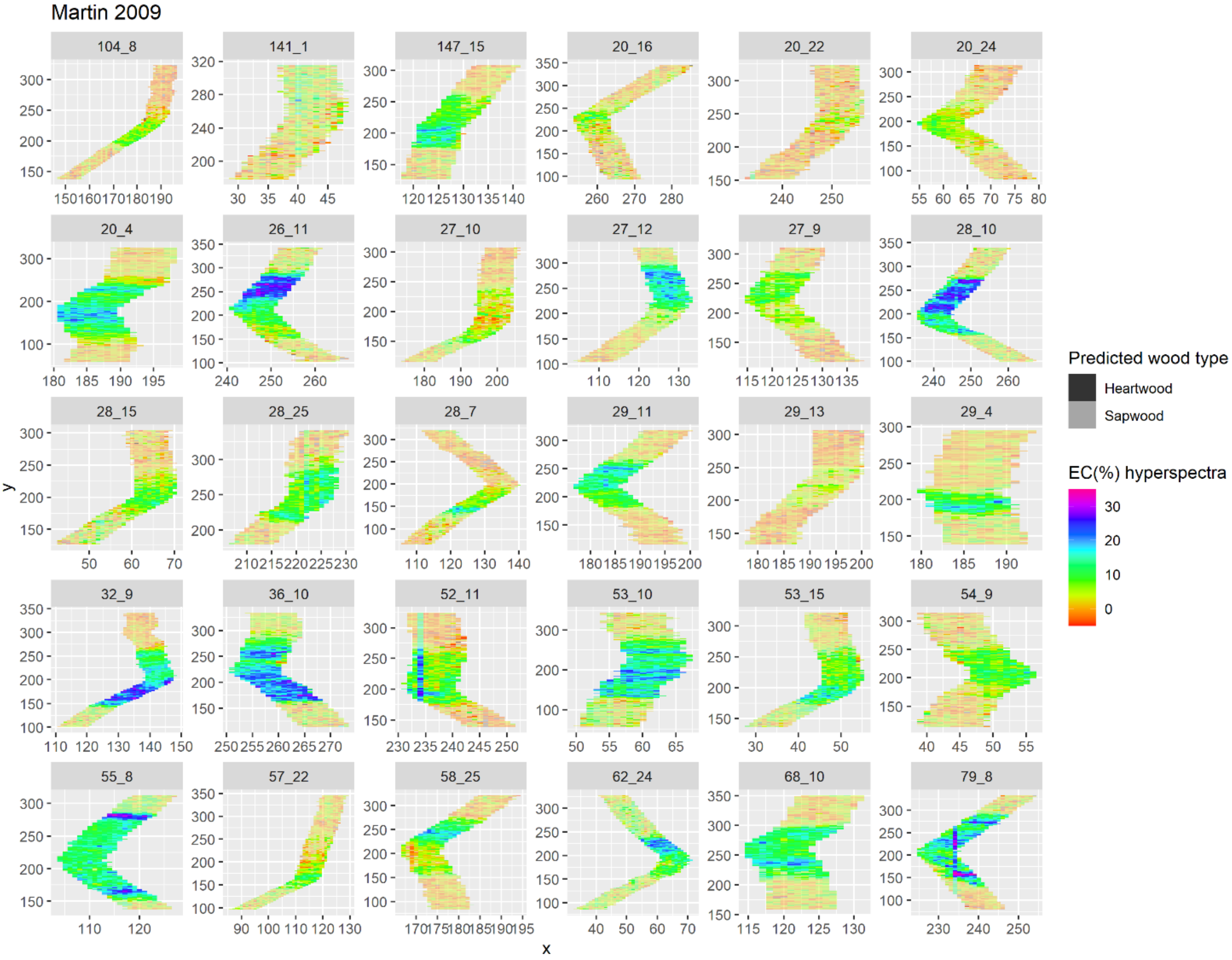

MDC_Craven 2009
105_11
105_16
11_14
126_1
13_15
148_24
15_7
21_10
21_20
25_21
29_2
30_23
35_8
36_25
4_16
45_20
46_8
53_9
54_12
59_15
76_25
79_23
8_19
83_10
89_21
96_10
97_14
97_2
98_1
y
x
pWT
p_HW
p_SW

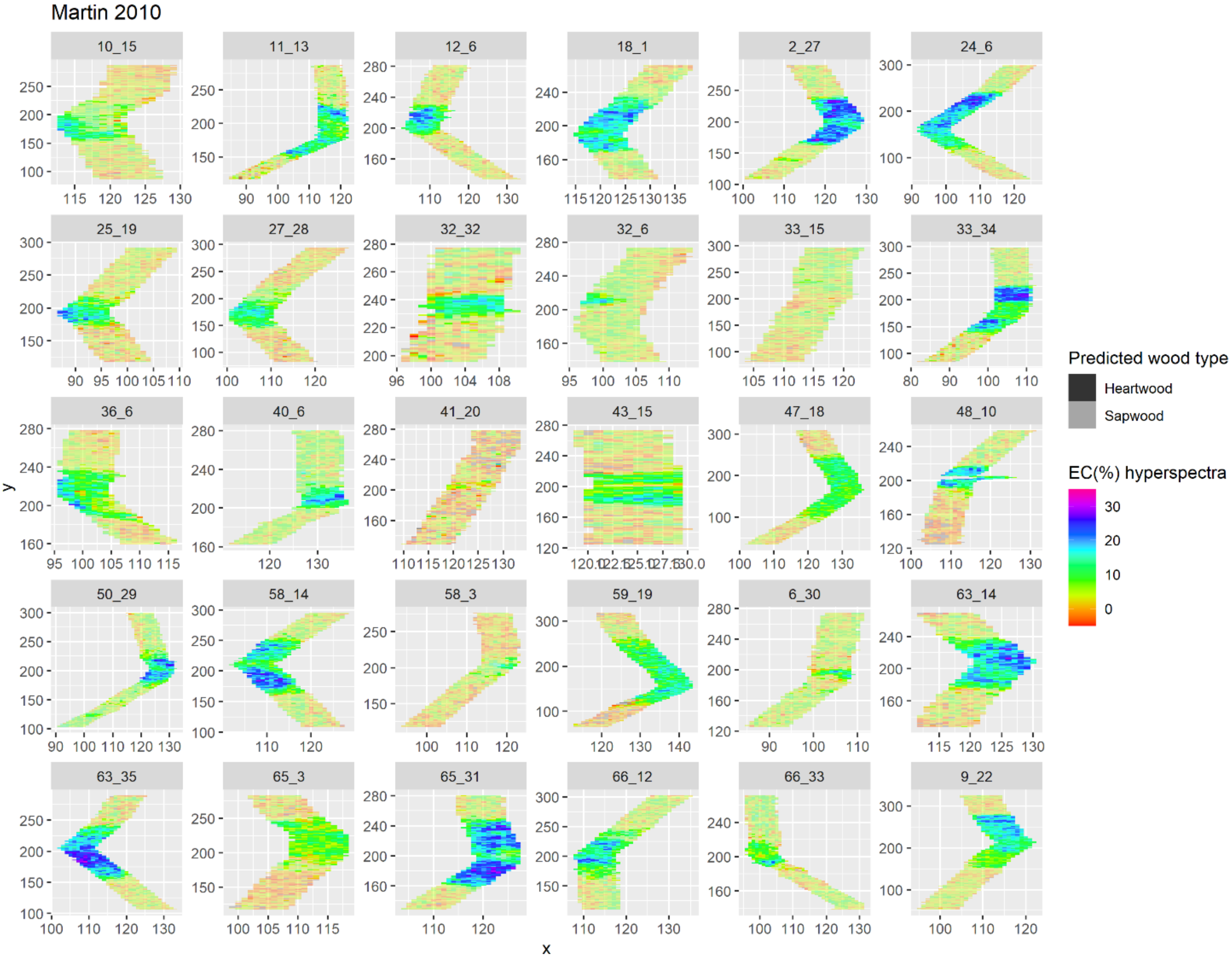

MDC_Craven 2010
11_7
12_21
13_28
14_2
15_2
18_1
2_12
20_20
20_26
24_17
24_4
26_3
28_13
28_28
28_4
33_30
33_7
35_11
37_10
37_20
38_17
40_29
46_2
48_25
48_7
49_11
49_2
5_16
y
x
pWT
p_HW
p_SW

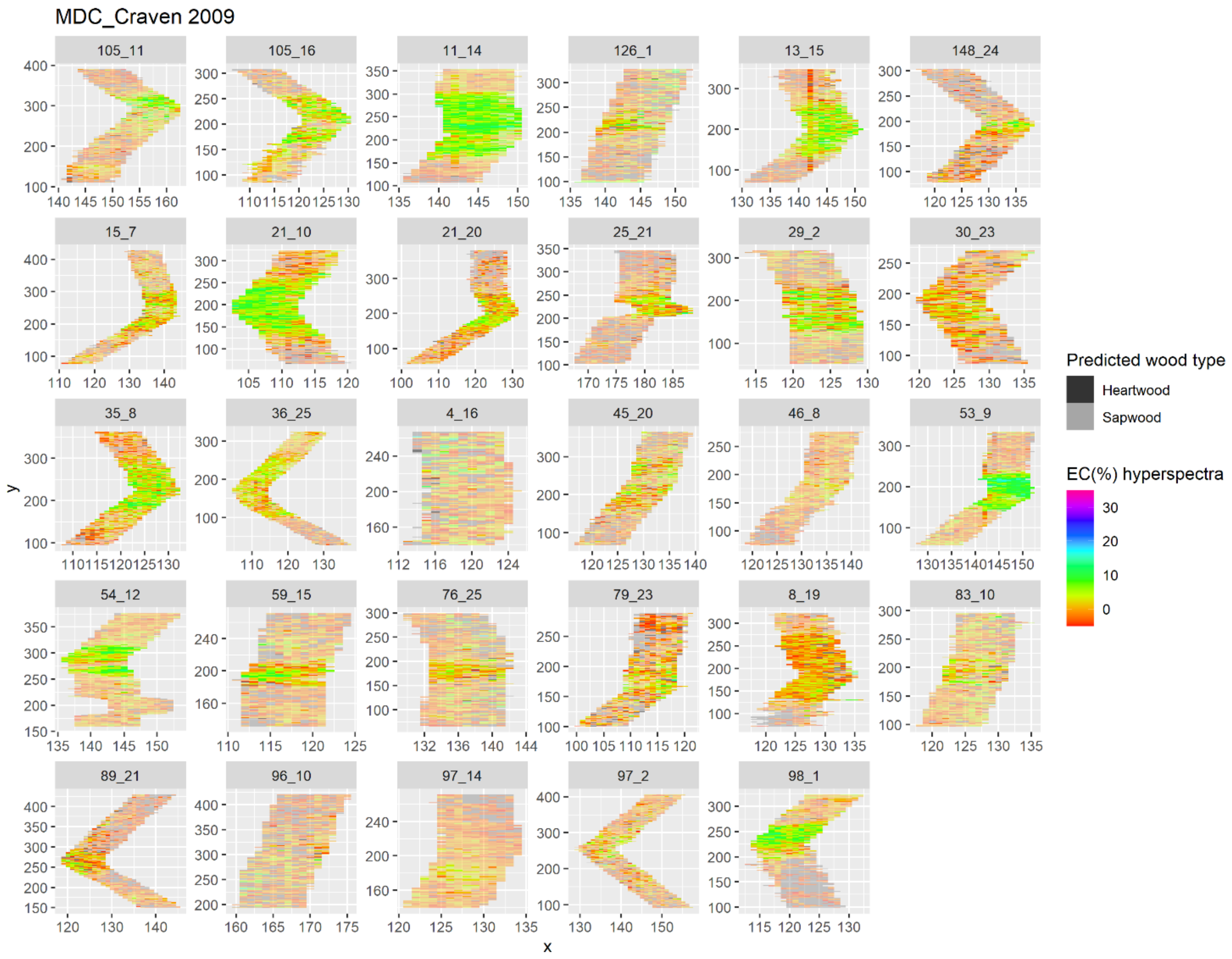

Lawson 2009
102_16
103_16
105_23
127_15
132_1
132_19
132_24
135_12
136_20
138_11
138_6
141_15
141_21
142_6
143_23
146_14
148_23
150_10
150_17
150_2
150_5
31_30
48_1
60_16
76_4
76_6
79_29
99_22
x
y
pWT
p_HW
p_SW

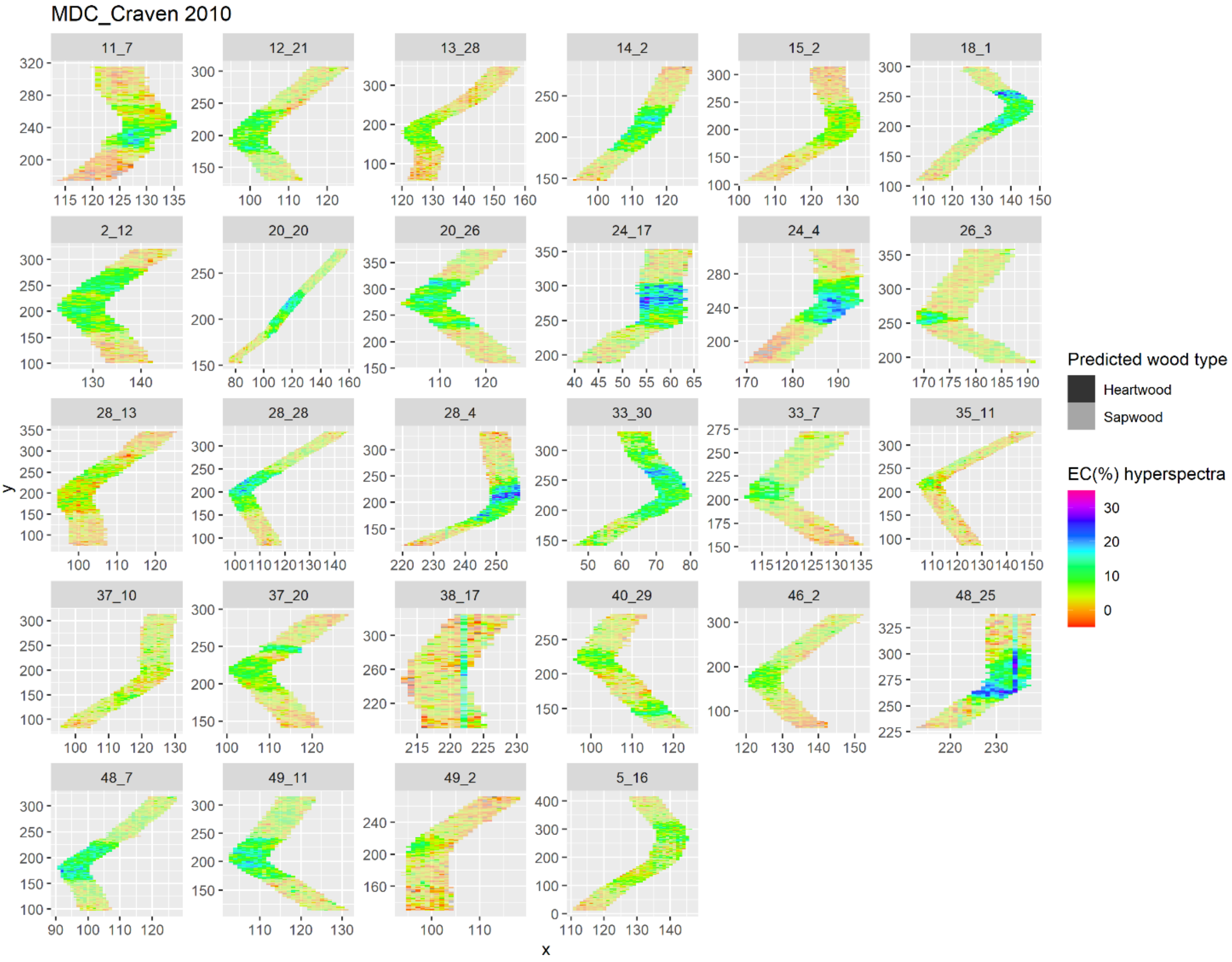

Avery 2010
20_18
21_2
21_6
23_8
24_24
26_30
26_34
28_2
28_27
28_28
29_19
29_3
29_31
3_6
35_8
40_24
41_21
41_24
41_5
44_13
44_24
45_13
46_6
47_27
48_10
48_17
48_23
48_25
49_22
49_27
y
x
pWT
p_HW
p_SW

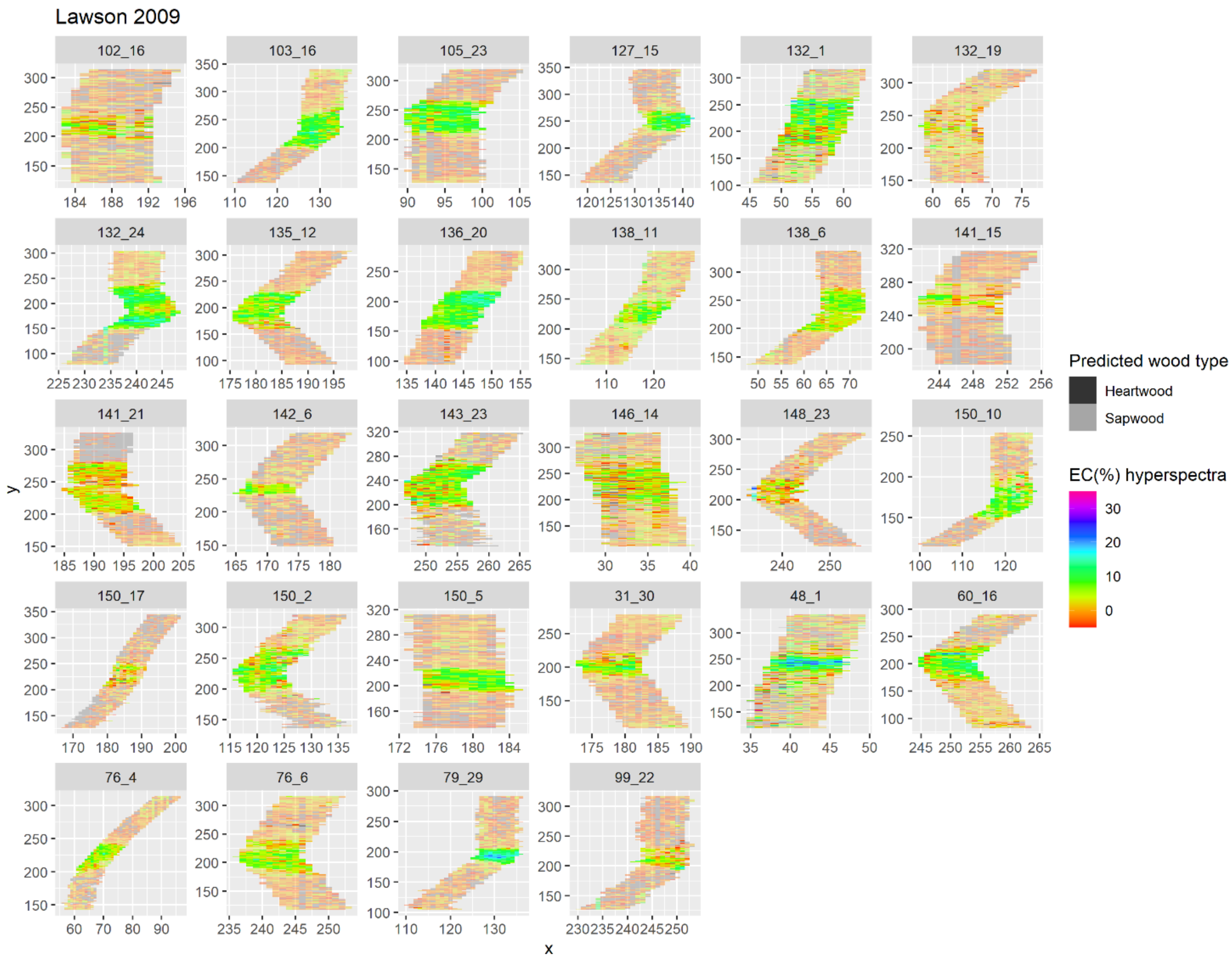
Appendix 2: Extractive content predicted with a PLSR model from NIR hyperimages

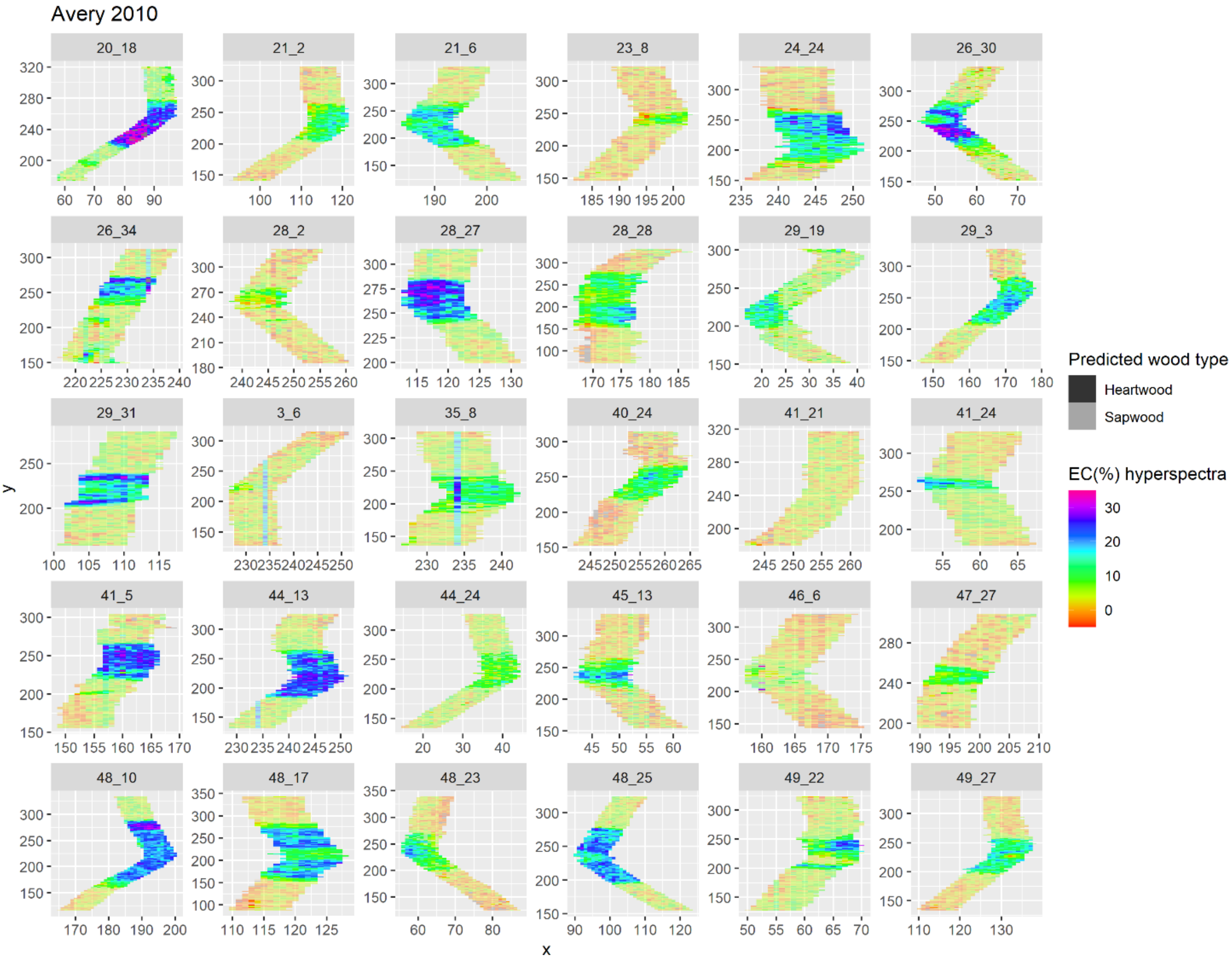



Martin 2010
10_15
11_13
12_6
18_1
2_27
24_6
25_19
27_28
32_32
32_6
33_15
33_34
36_6
40_6
41_20
43_15
47_18
48_10
50_29
58_14
58_3
59_19
6_30
63_14
63_35
65_3
65_31
66_12
66_33
9_22
y
x
Predicted wood type
Heartwood
Sapwood
EC(%) hyperspectra
30
20
10
0


MDC_Craven 2009
105_11
105_16
11_14
126_1
13_15
148_24
15_7
21_10
21_20
25_21
29_2
30_23
35_8
36_25
4_16
45_20
46_8
53_9
54_12
59_15
76_25
79_23
8_19
83_10
89_21
96_10
97_14
97_2
98_1
x
y
Predicted wood type
Heartwood
Sapwood
EC(%) hyperspectra
30
20
10
0


MDC_Craven 2010
11_7
12_21
13_28
14_2
15_2
18_1
2_12
20_20
20_26
24_17
24_4
26_3
28_13
28_28
28_4
33_30
33_7
35_11
37_10
37_20
38_17
40_29
46_2
48_25
48_7
49_11
49_2
5_16
y
x
Predicted wood type
Heartwood
Sapwood
EC(%) hyperspectra
30
20
10
0


Lawson 2009
102_16
103_16
105_23
127_15
132_1
132_19
132_24
135_12
136_20
138_11
138_6
141_15
141_21
142_6
143_23
146_14
148_23
150_10
150_17
150_2
150_5
31_30
48_1
60_16
76_4
76_6
79_29
99_22
x
y
Predicted wood type
Heartwood
Sapwood
EC(%) hyperspectra
30
20
10
0


Avery 2010
20_18
21_2
21_6
23_8
24_24
26_30
26_34
28_2
28_27
28_28
29_19
29_3
29_31
3_6
35_8
40_24
41_21
41_24
41_5
44_13
44_24
45_13
46_6
47_27
48_10
48_17
48_23
48_25
49_22
49_27
y
x
Predicted wood type
Heartwood
Sapwood
EC(%) hyperspectra
30
20
10
0