A transportable magnetic resonance imaging system for *in-situ*
measurements of living trees: The Tree Hugger

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Abstract

This paper presents the design of the ‘Tree Hugger’, an open access, transportable, 1.1 MHz ¹H nuclear magnetic resonance imaging system for the *in-situ* analysis of living trees in the forest. A unique construction employing NdFeB blocks embedded in a reinforced carbon fibre frame is used to achieve access up to 210 mm and to allow the magnet to be transported. The magnet weighs 55kg. The feasibility of imaging living trees *in-situ* using the ‘Tree Hugger’ is demonstrated. Correlations are drawn between NMR / MRI measurements and other indicators such as relative humidity, soil moisture and net solar radiation.

Keywords: nuclear magnetic resonance (NMR); magnetic resonance imaging (MRI); wood; tree; water;

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1 Introduction

Wood is a renewable resource with important and widespread uses including building construction, furniture manufacture, panel products, paper, and energy production. Wood may be used in a sawn solid-form such as in construction timber, reconstituted in panel products and paper pulp or re-engineered such as in glulam, plywood or a range of modern wood engineered products [1]. The pressure from society, global economics, climate change and the need for more sustainable raw materials are increasing interest in understanding the sustainability of plantation forestry and improving methods for processing wood [2]. Key issues for tree management revolve around water resources: the impact of trees on water tables, and the impact on trees of the drier summers that are forecast under climate change. Wood drying is a major factor in timber processing because of the high cost and the necessity to minimise distortion and fibre collapse. There still remain many fundamental questions concerning water movement in living trees [3] and water loss and uptake in wood [4]. Magnetic resonance imaging (MRI) offers the opportunity to non-destructively and non-invasively study moisture and moisture transport in wood and in particular living wood. In this paper we look to develop this opportunity through the design and demonstration of an NMR magnet suitable for measurements on living trees in the field.

In the green state, wood has a high water content that can be characterized by ^1H NMR. Parameters usually measured include the transverse, T_2 , and longitudinal, T_1 , nuclear spin relaxation times. These parameters depend on the local environment of the water molecule and are a reflection of its mobility. There have been numerous studies of relaxation time distributions in wood [5-8] revealing multi-modal patterns that represent water in different structural environments. The distributions typically include a slowly relaxing component (T_1 and $T_2 \sim 100\text{ms}$) and one or more intermediate relaxing components (T_1 and $T_2 \sim 1\text{-}10\text{ms}$), assigned to the cell lumen and water in cell walls, respectively. The slowly relaxing component is only seen above the fibre saturation point. The intermediate component(s) can be divided between water absorbed on internal surfaces, water in clusters and to hydrogen bonds in plasticised wood polymer. A faster relaxing T_2 component ($\sim 10\text{-}100 \mu\text{s}$) with longer T_1 , characteristic of hydrogen in the wood solid has also been observed. NMR has

56 been used to study diffusion associated with wood cells [9]. In recent work there have
57 been investigations into water exchange in wood using 2D NMR relaxation exchange
58 spectroscopy [10] and the bound water interactions and local wood densities [11].

59 MRI has been demonstrated as a non-destructive method to image the gross structural
60 features of wood [12,13]. It has also been used to monitor flow of moisture [14] in
61 wood. The majority of this prior work has been carried out on small samples of felled
62 timber. However, the use of MRI for investigating intact, small (and not-so-small)
63 living plants in pots in the laboratory has also been demonstrated. An early example is
64 the work by Van As and Schaafsma [15] who measured the water flow in an intact
65 cucumber plant. Later, Kockenberger *et al.* used the pulsed field gradient (PFG) NMR
66 method to measure water transport in an intact six-day-old seedling [16] while
67 Clearwater and Clark investigated the xylem vessel contents of woody lianas [17].
68 Windt, van As and co-workers have demonstrated the use of dedicated hardware for
69 MRI studies on living trees up to 40 mm in diameter and several metres high in a
70 climate controlled (laboratory) environment [18,19].

71 There is growing interest and technological advancement in portable, *in-situ* MRI.
72 Such systems include down-bore-hole NMR logging tools for oil wells proposed by
73 Jackson *et al.* [20] and the NMR MOBILE Universal Surface Explorer (NMR MOUSE)
74 developed by Eidmann *et al.* [21]. Van As *et al.* [22] demonstrated the use of a small
75 permanent magnet system to study water content and transport in cucumber plants in
76 greenhouse and climate controlled chamber environments. Portable NMR systems
77 have been used to investigate the moisture content of wood [23,24] and have been
78 used in cultural heritage for the *in-situ* investigation of degradation of wooden
79 artwork by moisture [25]. The NMR-CUFF, developed by Windt *et al.* [26] and a
80 portable 0.47T magnet developed by Rokitta *et al.* [27], have been demonstrated
81 outside of the laboratory (in greenhouses) on small living plants up to 20 mm in
82 diameter. In 2006 Okada *et al.* presented preliminary MRI measurements of a living
83 maple tree outdoors [28]. More recently Kimura *et al.* have reported the use of a 0.3T
84 permanent magnet to image and investigate disease in small branches of a pear tree
85 outdoors [29]. The system used comprised a magnet mounted on a turntable and
86 mechanical lift that could be manoeuvred into place around tree branches up to 30
87 mm in diameter and up to 1600 mm above the ground.

In this paper we describe an MRI magnet and spectrometer system that has been specifically designed for the imaging of living trees. It is transportable and offers an open access space of 210 mm diameter. We present NMR measurement results from a study of a bird cherry (*Prunus padus*) tree over a summer growing period and show how these correlate well with environmental indicators such as relative humidity, soil moisture content, solar radiation and conventional thermal dissipation sap flow measurements.

2 The “Tree Hugger” magnet and spectrometer

The “Tree Hugger”[†] magnet is purpose designed to fit around a living tree. To this end, key design criteria included a requirement for “open access” and minimal weight in order that it is transportable. Several designs were explored including traditional “C-core”, Halbach arrays and specifically “NMR cuffs”. The final design may look like a “C-core” in external appearance, but in fact does not feature a magnetic material return flux path. It is shown schematically in Figure 1a. The two poles comprise 5 concentric rings of magnetic material made from 174 small and carefully matched single blocks of NdFeB. The block sizes range from $25 \times 20 \times 9 \text{ mm}^3$ (inner ring) to $28 \times 57 \times 18 \text{ mm}^3$ (outer ring). The radial profile of the rings was optimised using proprietary optimisation software so as to yield a homogenous magnetic field over a central sphere between the poles. The rings are at radii ranging from 15.2 to 196 mm. The rings are set in two fibre-reinforced-resin substrate plates that are held apart by a polymer block at one end. This construction is strong enough to yield a rigid construction able to withstand the considerable attractive magnetic force between the poles. The magnet has a central field strength of 0.025 T. The plate separation is 210 mm with design homogeneity of 1000 ppm over a 200 mm diameter-sample-volume (dsv). However, the actual build homogeneity is closer to 2000 ppm over 140 mm dsv, due partly to inevitable imperfections and also the fact that one magnetic block slipped by about 1 mm during bonding. Such homogeneity is normally considered poor. However, it should be noted that 2000 ppm at 1 MHz is equivalent to 100 ppm

[†] The name “tree hugger magnet” was first coined by Professor John Strange and Dr Peter Blümner at the University of Kent in the late 1990’s.

at 20 MHz or 20 ppm at 100 MHz. The actual field gradient created by an assumed linear 2000 ppm over a 70 mm distance (radius-sample-volume) is just 285 Hz/cm or circa 0.67 mT/m. While passive shimming of the magnet is potentially possible, as has been shown elsewhere [31,32] this has not yet been attempted with the “Tree Hugger”. The magnet weighs 55 kg (22kg magnetic material, 33kg frame). The temperature drift of the magnetic material is 1.1 kHz / °C. *In situ* temperature drift due to solar radiation was minimized by insulating the magnet poles with 50 mm thick sheets of Celotex (Celotex Insulation Ltd, Ipswich, UK). Measurements of drift in the field were typically 3 kHz/hour without insulation but were reduced to 140 Hz/hour with insulation. This is less than 15% of an image pixel width in units of frequency per acquisition.

MRI requires magnetic field gradients. To this end a standard set of NMR gradient coils have been constructed using conventional current windings again set in resin plates along with water-cooling pipes. The two gradient plates each weigh 15 kg and can produce a field gradient of 1.06 mT/m/A for the z-gradient (defined as between the poles) and 0.64 mT/m/A and 0.68 mT/m/A for the x and y gradients respectively. The gradient plates slide into slots alongside, and are secured to, the magnet pole plates as required. The access space is not reduced by attaching the gradients. Figure 1b shows the magnet as built with the gradient plates pulled half way out.

The NMR coil is based on a standard solenoidal winding except that it can be opened along its length so that it can be wrapped around the tree. The coil used in this work is 14 cm in length and diameter and comprises 20 turns. This is achieved by etching the windings as copper stripes on a large flexible printed circuit board with a long purpose designed edge connector made of PTFE and standard electrical fittings. The coil is manufactured with an integrated copper Faraday shield made from multiple layers of woven-copper cloth spaced from the coil by PTFE spacers mounted on, and running the length of the printed circuit board. The coil is series tuned to 1.1 MHz with a capacitor. A resistor is used to bring the resistance up to 12.5 Ohms and a transformer to convert this to 50 Ohms as we have previously described for other systems [30]. We find this coil tuning arrangement well suited to low frequency, large volume NMR coils.

Figure 1c shows the magnet with gradient and radio frequency coils fitted wrapped around a living tree.

The radio-frequency electronics comprises a Maran DRX spectrometer (Oxford Instruments, Oxon, UK) and a 1 kW Tomco RF power amplifier (Tomco Technologies, Australia) with a combined weight of 46 kg. We use three in-house design and build gradient amplifiers capable of generating 25 A gradient pulses per channel at 30% duty cycle. These amplifiers are also used to provide continuous first order x , y and z gradient shim currents through the gradient coils. Each amplifier comprises three stages of amplification: a pre-amplifier stage based on NE5532AP (Texas Instrument) low-noise Op-Amps; a driver stage based on MJE15032 NPN and MJE15033 PNP (ON Semiconductor) devices; and a power stage. The power stage is based on 4 pairs of MJL4281AG NPN and MJL4302AG PNP (ON Semiconductor) transistors in class B push-pull configuration connected in parallel. The amplifiers are stabilised by negative feedback and are dc coupled throughout. The voltage gain is set to 38 dB and is linear to better than 1.5%. With a 1.5 Ω resistive load, the pulse rise time is 10 μ s (10%-90%) and there is no measureable droop between two 1 ms pulses spaced 3 ms apart. The three amplifiers together weigh 26.5 kg

3 Method

NMR images were obtained using a 2D spin-warp sequence [33]. The read gradient was applied along the x -axis (Fig. 1a) before the 180 degree sequence refocusing pulse and after during data acquisition. The phase encode gradient was applied along the z -axis. When used, slice selection was achieved with a soft 90 degree Gaussian excitation pulse and the slice selection gradient was applied along the y -axis, parallel to the (vertical) tree trunk. Typical experimental parameters are given in Table 1.

The magnet was left continuously *in-situ* around a bird cherry tree for a period of 3 months during the summer 2011 and taken to site periodically at other times. The tree was planted in the late 1980s and had a trunk diameter of 90 ($\pm$ 2) mm at the centre of the RF coil 550 ($\pm$ 5) mm above the ground. The crown of the tree was around 2.5 – 3 m and the height of the tree was 6.1 m. The soil is sandy and well drained. The tree was one of a small plantation of around 20 trees spaced in a square array with spacing

4-5 m. The tree chosen was growing unusually straight which facilitated the study. The spectrometer was wheeled to site and cross-section images of the tree acquired periodically throughout the summer. Electrical power could have been provided by a portable generator but was, in fact, sourced via a cable from a nearby (25 m) storage shed.

The tree and its immediate environs were serviced by a weather station close to the tree and this was backed up by a second nearby weather station. These weather stations are described in Table 2. Soil moisture sensors (ML2x ThetaProbe, Delta-T Devices, Cambridge) were installed either side of the tree (1.5 m from the base), in a line parallel to the tree (east / west in subsequent text). Sap velocity thermal dissipation probes (Dynamax Inc., Houston) were placed 750 (± 5) mm above the centre of the RF coil again east / west on either side of the tree trunk and recorded on the same data logger as used to record data from the weather station.

4 Results

4.1 Resolution test

Figure 2 shows a test image recorded from a phantom sample comprising a square array of water filled 8 mm internal diameter NMR tubes with a basic lattice spacing of 11.8 mm. Therefore, there is a mark space ratio of 8:3.8 (equals approximately 2) across the phantom. The image was acquired using slice selection with a slice of around 55 mm. One tube was left unfilled to orient the array. The image clearly shows the unfilled tube and most of the tubes individually resolved. The image shows significant shear distortion due to the residual magnet inhomogeneity resultant from the misplaced NdFeB block. Fortunately, much of the inhomogeneity is relatively well defined and the resultant shear could likely be largely corrected by image processing. However this has not been done to this, or any other image reported here. The calculated pixel size is 1.1 mm (the data is zero filled to 128 points). The actual image resolution is about 2.5 mm, based on the observation that all the tubes are clearly resolved.

In much of the following work, integrated intensities across critical regions of images are reported. In order to assess the noise in such images, the phantom sample was measured 3 times during the course of a week. Post-late August, when electrical earthing of the lap-top computer and water cooling pump were improved, the variation in total intensity across the three measurements was better than 1%. Pre-late August, the noise was somewhat worse, with reproducibility closer to $\pm 3\%$. Intensity variation of tree images to be discussed is harder to gauge as the tree water content is continuously changing. However, by calculation from the phantom variability, and by inspection of successive tree images in “quiet” periods, we judge that the reproducibility of the tree image daily-maximum integrated-intensity is circa $\pm 6\%$ in mid August, and better than this in September.

4.2 *Tree physiology and water distribution*

Figure 3 shows an exemplar image of the cross section of the tree. The image was recorded with the standard set of parameters (no slice selection) (Table 1) and took 34 minutes to acquire. In particular the echo time was $2\tau = 4$ ms. A 13 mm internal diameter test tube filled with doped (CuSO_4) water was attached to the tree as a reference signal and can be seen in the image. The different areas of the tree structure are clearly seen. The sapwood (or xylem) shows most brightly in the image (higher magnitude). This is where the majority of water is found in the tree and where the water transport up the trunk takes place. The heartwood is seen as a darker region in the centre. The heartwood is completely dead with a higher accumulation of extractives and a lower water content (typically 50% in cherry) than the sapwood resulting in the lower magnitude of signal. The low intensity outer ring is due to the bark where again there is less water than the sapwood and where T_2 is lower. We note that several authors report that the brightest region of a tree cross-section MR image is the cambial zone between the bark and sapwood [18, 19, 34]. The cambial zone is typically only a few cells wide, with a thickness of perhaps 20 - 60 μm [35]. Hence, while this ring is seen by others in high resolution images acquired at higher field strength, we simply do not have the resolution or slice selectivity to see it separately: it is incorporated into the sapwood.

A set of comparable images were acquired to measure the echo time dependence of the image intensity and hence to obtain a spatially resolved estimate of the spin-spin

relaxation time. Images were acquired, on a warm, dry day in mid September, using τ = 2, 4, 8, 16, 32, 64 and 128 ms. Example images are shown in Figure 4. As τ is increased, water hydrogen with a T_2 shorter than 2τ progressively attenuate in the image. This allows water in different structural environments to be selectively visualised. Regions of interest representing the sapwood and heartwood were selected in the images as illustrated by the circles on the image in Figure 4a. The average signal per pixel of these regions is plotted in Figure 5. One and two component exponential decay fits were used to fit the data. The T_2 of the test water sample is estimated to be 25.0 ± 1.4 ms compared to a laboratory measurement at 20 MHz of 40 ms. Mitchell *et al.* [36] have published the T_2 of CuSO₄ doped water as a function of concentration at frequencies of 5 and 60 MHz. Our results are in line with their data.

In the wood, the two component T_2 fits were demonstrably better than the one component fits. The data quality does not warrant an attempted fit with even more components. Using the two component fits, the T_2 values in the heartwood and sapwood regions were estimated and are shown, along with the component amplitudes in Table 3. Errors were determined from a combination of slightly varying the region of interest (so as to include / exclude marginal pixels) and by repeatedly adding white noise of the same standard deviation as the image background to the data sets. The majority of previous work measuring T_2 in wood has involved softwoods due to their simpler structure. Bird cherry is a hardwood. The T_2 values found using two component exponential fits in this work, show a T_2 of around 2.8 ± 0.2 ms in the heartwood and 2.1 ± 1.1 ms in the sapwood. This T_2 can be assigned to bound water, as in Elder *et al.* [37] where values of T_2 between 0.75 ms and 3 ms were found. Elder *et al.* also report a medium component of T_2 between 10 ms and 100 ms for the four hardwood species they investigated. This medium T_2 value was seen in the living tree heartwood with T_2 around 40 ms. This component had lower amplitude than the fast T_2 component in the heartwood and is assigned to the liquid water in the cells of the heartwood. A slow, greater than 100 ms, T_2 component value usually assigned to water in the vessel elements is reported in previous work [18, 37, 38]. This was seen in the sapwood region with a T_2 of around 111 ms. These T_2 values and amplitudes suggest, as expected, that there is more mobile water in the sapwood than the heartwood. It would be expected that the amplitude of the slower relaxing components would be higher than the faster components: however, the opposite was found.

Differences in relaxation behaviour compared to expectation are not explained by molecular diffusion in the magnet inhomogeneity gradient. Taking the diffusion coefficient of free water, $D = 2.2 \cdot 10^{-9} \text{ m}^2/\text{s}$, the additional attenuation at the maximum echo time, 256 ms, is 9.4%, at 128 ms it is 1.2% while at all other echo times it is less than 0.2%. Analysis of simulated data, using the actual data acquisition echo times, shows that the resultant error in the longest measured T_2 (111 ms) is less than 4%. Therefore we infer that the inhomogeneity gradient, while affecting the T_2 measurement, is not a major source of error. Diffusive attenuation due to the imaging gradients is negligible.

4.3 Daily water cycle

The southern UK summer 2011 was characterised by a long, hot and dry spring followed by a warm but wet summer compared to UK averages.

Figure 6 (upper part) shows a plot of image magnitudes from the daily cycle of the tree on three days in mid August: the 15th, 17th and 19th. Images of the tree were acquired from early morning until late evening. Figure 6 (lower part) show associated indicators: net solar radiation and relative humidity. On the 17th and 19th the image intensity starts moderately high in the early morning and falls back before the expected daily cycle begins. In contrast, the high start is not there on the 15th, or otherwise occurred earlier. This is thought to be due to the effects of relative humidity (RH) during the preceding night. There is low RH overnight on the 14/15th whereas overnight on the 16/17th and the 18/19th the RH is high. Due to the high RH, less water is lost overnight through the leaves on the 16/17th and the 18/19th compared to the 14/15th so that the amount of water stored in the tree trunk builds up. Then, as the tree becomes active in the morning, with increased radiation and falling RH, leaf transpiration increases and the stored water is removed from the tree trunk: the image magnitude decreases. The effect of RH can also be seen in the time of the maximum image magnitude on the 15th and 19th. On the 15th the RH starts low and drops early so that the image maximum is before noon. In contrast, on the 19th the RH starts high and drops late so that the image maximum does not occur until mid-afternoon. The effect of the net radiation can also be seen in the image magnitude plots. The higher net

radiation on the 19th (along with higher soil moisture content on this day, not shown) leads to a higher peak in image magnitude than on other days. A combination of low soil moisture content, low net solar radiation, and RH pattern (late morning fall and early evening rise in RH) on the 17th means that the tree is much less active on this day than the others and hence that there is less variation in image magnitude.

4.4 *Soil moisture and droughting study*

The plots in Figure 7 show integrated NMR image magnitudes and soil moisture content plotted over 8 days in late May and early June and 12 days in mid August 2011. Images were not acquired on all days due to rain. The magnitudes plotted are the maxima recorded each of these days for the integrated sapwood. Soil moisture was recorded pseudo-continuously 1-1.5 m from the base of the tree. The plots show the image magnitude falling and rising in strong correlation with the soil moisture content. It can be seen in the plots that magnitude in May/June decreases further and faster than in August (to 55% and 80% of maximum respectively) even though the soil moisture contents are similar. This increased fall in magnitude can be explained by the lower relative humidity in May/June. The relative humidities for two days at the start of each period were compared. The lower relative humidity on 31st May and 1st June (minimum of 37% and 36%, respectively) mean that more water can be lost via the leaves and the dry soil means there is limited water to replace the water lost via transpiration. The higher relative humidity on August 10th / 11th (minimum 55% and 75% respectively) means that less water is lost through transpiration so the tree retains more water and the magnitude drops at a slower rate.

Figure 8 (upper) shows the soil moisture content for the 30th July to the 1st August. For these three days the ground on the east of the tree was covered with plastic sheeting to keep the roots dry and the ground on the west was watered with 1000 litres of water on the 30th July and 300 litres on the 31st July using a sprinkler system in a 2x2.6 m² area. The plot in Figure 8 (lower) shows the image magnitudes over a twelve hour period on 1st August. The graph shows greater magnitude in the east side of the tree. This is the opposite side to the wet ground. This increased magnitude in the east side of the tree is also shown in the sap flow plot in Figure 8. Data for the 1st

September is also shown. On this day the soil moisture content was comparable either side of the tree and the image magnitude is also equally comparable on either side.

The difference in image magnitude between the west and east sides of the tree on the 1st August is confirmed by simple inspection of Figure 9, from which the data is extracted, compared to Figure 3. The image shows increased magnitude in the east side of the tree. This increased amount of water in the opposite side of the tree to the watered ground suggests that the flow in the tree is moving in a spiral pattern – so called “grain rotation” that is thought to aid uniform distribution of water resources within the tree [39]. To check this observation we removed a bark strip close to the NMR measurement height and measured the grain angle: $14 (\pm 1.5)^\circ$. This translates to a grain rotation of $195 (\pm 25)^\circ$ at the outside of the sapwood (40 mm from the centre of the tree) between soil level and the centre of the NMR coil in good agreement with the observation.

4.5 Seasonal changes

The changes in the moisture content and activity of the tree as the season changed from summer to autumn were monitored. Figure 10 shows plots of the image magnitude and net radiation for daily cycles of the tree on one day in mid summer and one day in early autumn, 15th August and 13th September respectively. These days are chosen due to their similar relative humidity and net solar radiation. On both days the image magnitude changes in correlation with the net radiation and the maximum image magnitudes are similar. However, there is much less variation on the 13th September. The ratio of minimum to maximum magnitude on 15th August is 60% whereas on 13th September it is 90%. This is due to the reduced number of leaves and change in colour of the leaves on the tree, shown in Figure 10, in September leading to a lower transpiration rate (sap flow is an average of 340 g/hr compared to 1120 g/hr on 15th August) and less water being lost via the leaves. In September the tree appears to be just a reservoir of water, it is as wet as in the summer but with much less flow.

5 Overall discussion, outlook and conclusion

We have successfully demonstrated an open access, transportable, 1.1 MHz ^1H nuclear magnetic resonance magnet for the *in-situ* analysis of living trees. The system has been used to make images across the stem of a small bird cherry tree over a 3 month period during the 2011 summer. The system showed clearly the water distribution across the stem with large contrasts in image intensity between the higher moisture content sapwood and the lower moisture content heartwood and bark. The system is able to identify the distribution of water in different wood structural environments by changing the echo time (2τ) so that water in the cell lumen and water in the cell wall can be separately identified.

The system was able to run continuously and record images approximately every 34 minutes. This allowed diurnal and seasonal changes in the water profile across the tree to be visualised. The image intensity was shown to be strongly correlated to meteorological conditions and in particular RH, soil moisture and solar radiation. However, the tree response varied with the season. Similar meteorological conditions in June and September led to quite different responses in the sap flow because the leaves had already begun to change in September and there was much less transpiration. A further study demonstrated the tree response to differential soil moisture by irrigating the soil on one side of the tree and keeping the other side dry. The image from the “Tree Hugger” had clear differences around the sapwood area and illustrates that the water has followed the spiral grain of the tree so that the water had rotated about 180 degrees by the time it was measured at 550 mm above the ground.

Notwithstanding the forgoing previous interpretation, the data in Figures 6 and 10 pose an interesting question. The tree moisture content as measured by MRI tends to have an overall daily maximum in the middle of the day, just when transpiration might be expected to be greatest and hence when water reserves are being most rapidly consumed. The only full 24 hour cycle data we have suggests that there is a corresponding overall minimum in the early, pre-dawn hours. While we may speculate that there is a complex interplay between the rates of charging and discharging of water within the trunk from the roots and leaves respectively we have as yet been unable to fully interpret the result. We seek to explore it further in a future growing-season, perhaps by measurements at different heights along the trunk.

The “Tree Hugger” provides new opportunities for detailed measurements of water movement in living trees, in logs and in sawn timber. It has the potential to help provide an improved understanding of tree physiology and in particular the movement of water through changes in image magnitude on perhaps an hourly basis in living trees. Some particular areas of use could be as follows:

- It can provide a much more accurate integration of water across the whole tree stem than the use of individual sap flow sensors. In addition it avoids the problems of wound response associated with sap flow sensors that have to be inserted into the tree [40]

- The system can be left *in situ* for long periods allowing detailed monitoring of diurnal and seasonal changes in water content that would augment current assessments of total water usage of trees.

- Differential water content across the stem can be monitored and therefore the impacts of rooting restrictions such as ditches, pavements, roads, etc. could be evaluated.

- The “Tree Hugger” should be ideal for monitoring rewetting in mature trees following a severe drought. MRI has previously been used to study refilling of cells after cavitation. However, these studies have been confined to e.g. saplings and roots using small magnets and coils [41,34]. The “Tree Hugger” offers the opportunity to make these measurements non-invasively on more mature trees, which has been a criticism of previous measurements and other methods and has led to a great deal of debate within the tree physiology community [42]

- The system is potentially able to monitor heartwood development as the boundary between the heartwood and sapwood moves outwards in the autumn and the transition zone dries out. It may also be able to identify fungal ingress into trees as the fungus modifies the cell wall structure. At present such fungal movement can only be determined by destructive sampling of the tree.

The “Tree Hugger” is a new non-invasive system for investigating structure and water content in mature trees and wood. The key advantage of the current system with

426 regard to previous MR systems used for this purpose is size: the “Tree Hugger” can
427 image trunks of the order of 100 mm in diameter.

428

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References

- 1 J.L. Bowyer, R. Shmulsky, J.G. Haygreen, *Forest Products and Wood Science*, 5th Edition. Blackwell Publishing Professional, Ames, Iowa. ISBN-13: 978 0 8138 2036 1 (2007).
- 2 M. Lindner, W. Werhahn-Mees, T. Suominen, D. Vötter, S. Zudin, M. Pekkanen, R. Päivinen, M. Roubalova, P. Kneblík, F. Brüchert, E. Valinger, L. Guinard, S. Pizzirani *Conducting sustainability impact assessments of forestry-wood chains: examples of ToSIA applications*. *European Journal of Forest Research*, (2011) DOI: 10.1007/s10342-011-0499-z
- 3 M.T. Tyree, M.H. Zimmermann, *Xylem structure and the ascent of sap*. Berlin, Germany: Springer Verlag (2002).
- 4 C.A.S Hill, A.J. Norton, G. Newman, *The water vapour sorption properties of Sitka spruce determined using a dynamic vapour sorption apparatus*, *Wood Science and Technology*, 44 (2010) 497-514.
- 5 A.J. Nanassy, *Water sorption in green and remoistened wood studied by the broad-line component of the wide line NMR spectrum*, *Wood Science*, 7 (1974) 61-68.
- 6 G.F. Byrne, M.D. Fenn, M.I. Burgar, *Nuclear-magnetic-resonance studies of water in tree sections*, *Agricultural and Forest Meteorology*, 38 (1986) 307-317.
- 7 P. Fantazzini, A. Maccotta, M. Gombia, C. Garavaglia, R.J.S. Brown, M. Brai, *Solid-liquid nuclear magnetic resonance relaxation and signal amplitude relationships with ranking of seasoned softwoods and hardwoods*, *Journal of Applied Physics*, 100 (2006) 0749071-7.
- 8 L.G. Thygesen, T. Elder, *Moisture in untreated, acetylated, and furfurylated Norway spruce studied during drying using time domain NMR*, *Wood and Fiber Science*, 40 (2008) 309-320.

- 9 C.D. Araujo, A.L. Mackay, K.P. Whittall, J.R.T. Hailey, A diffusion-model for spin-spin relaxation of compartmentalized water in wood, *Journal of Magnetic Resonance Series B*, 101 (1993) 248-261.
- 10 J. Cox, P.J. McDonald, B.A. Gardiner, A study of water exchange in wood by means of 2D NMR relaxation correlation and exchange, *Holzforschung*, 64 (2010) 259-266.
- 11 S.V. Dvinskikh, M. Henriksson, L.A. Berglund, I. Furo, A multinuclear magnetic resonance imaging (MRI) study of wood with adsorbed water: Estimating bound water concentration and local wood density, *Holzforschung*, 65 (2011) 103-107.
- 12 P.C. Wang, S.J. Chang, Nuclear magnetic resonance imaging of wood, *Wood and Fiber Science*, 18 (1986) 308-314.
- 13 A. Merela, P. Sepe, I. Oven, Serša, I. Three-dimensional in vivo magnetic resonance microscopy of beech (*Fagus sylvatica L.*) wood, *Magnetic Resonance Materials in Physics Biology and Medicine*, 18 (2005) 171-174.
- 14 K. Ilvonen, L. Palva, M. Peramaki, R. Joensuu, R. Sepponen, MRI-based D₂O/H₂O-contrast method to study water flow and distribution in heterogeneous systems: Demonstration in wood xylem, *Journal of Magnetic Resonance*, 149 (2001) 36-44.
- 15 H. Van As, T.J. Schaafsma, Non-invasive measurement of plant water flow by NMR, *Biophysical Journal*, 45 (1984) 469-472.
- 16 W. Kockenberger, J.M. Pope, Y. Xia, K.R. Jeffrey, E. Komor, P.T. Callaghan, A non-invasive measurement of phloem and xylem water flow in castor bean seedlings by nuclear magnetic resonance microimaging, *Planta*, 201 (1997) 53-63.
- 17 M.J. Clearwater, C.J. Clark, In vivo magnetic resonance imaging of xylem vessel contents in woody lianas, *Plant Cell and Environment*, 26 (2003) 1205-1214.

- 18 C.W. Windt, F.J. Vergeldt, P.A. De Jager, H. Van As, MRI of long-distance water transport: a comparison of the phloem and xylem flow characteristics and dynamics in poplar, castor bean, tomato and tobacco, *Plant Cell and Environment*, 29 (2006) 1715-1729.
- 19 N.M. Homan, C.W. Windt, F.J. Vergeldt, E. Gerkema, H. Van As, 0.7 and 3 T MRI and sap flow in intact trees: Xylem and phloem in action, *Applied Magnetic Resonance*, 32 (2007) 157-170.
- 20 J.A. Jackson, R.K. Cooper, L.J. Burnett, J.F. Harmon, Remote NMR well logging, *Geophysics*, 46 (1981) 415-415.
- 21 G. Eidmann, R. Savelsberg, P. Blumler, B. Blumich, The NMR MOUSE, a mobile universal surface explorer, *Journal of Magnetic Resonance Series A*, 122 (1996) 104-109.
- 22 H. van As, J.E.A. Reinders, P.A. de Jager, P.A.C.M. van de Sanden and T.J. Schaafsma *In situ* plant water balance studies using a portable NMR spectrometer, *Journal of Experimental Biology*, 45 (1994) 61-67.
- 23 C. Casieri, L. Senni, M. Romagnoli, U. Santamaria, F. De Luca, Determination of moisture fraction in wood by mobile NMR device, *Journal of Magnetic Resonance*, 171 (2004) 364-372.
- 24 P. Pourmand, L. Wang, S.V. Dvinskikh, Assessment of moisture protective properties of wood coatings by a portable NMR sensor, *Journal of Coatings Technology and Research*, 8 (2011) 649-654.
- 25 L. Senni, C. Casieri, A. Bovino, M.C. Gaetani, F. De Luca, A portable NMR sensor for moisture monitoring of wooden works of art, particularly of paintings on wood, *Wood Science and Technology*, 43 (2009) 167-180.
- 26 C.W. Windt, H. Soltner, D. van Dusschoten, P. Bluemler, A portable Halbach magnet that can be opened and closed without force: The NMR-CUFF, *Journal of Magnetic Resonance*, 208 (2011) 27-33.

- 27 M. Rokitta, E. Rommel, U. Zimmermann, A. Haase, Portable nuclear magnetic resonance imaging system, *Review of Scientific Instruments*, 71 (2000) 4257-4262.
- 28 F. Okada, S. Handa, S. Tomiha, K. Ohya, K. Kose, T. Haishi, S. Utsuzawa, and K. Togashi, K. Development of a portable MRI for outdoor measurements of plants. 6th Colloquium on Mobile Magnetic Resonance, Aachen, Germany 6–8 September (2006).
- 29 T. Kimura, Y. Geya, Y. Terada, K. Kose, T. Haishi, H. Gemma, Y. Sekozawa, Development of a mobile magnetic resonance imaging system for outdoor tree measurements, *Review of Scientific Instruments*, 82 (2011) 053704.
- 30 P.J. McDonald, P.S. Aptaker, J. Mitchell, M. Mulheron, A unilateral NMR magnet for sub-structure analysis in the built environment: The Surface GARField, *Journal of Magnetic Resonance*, 185 (2007) 1-11.
- 31 D.I. Hoult, D. Lee, Shimming a superconducting nuclear magnetic resonance imaging magnet with steel, *Review Scientific Instruments*, 56, (1985) 131-135.
- 32 J. Perlo, F. Casanova, B. Blümich, Ex situ NMR in Highly Homogeneous Fields: ¹H Spectroscopy, *Science* 315 (2007) 1110-1112.
- 33 W.A. Edelstein, J.M.S. Hutchison, G. Johnson, T. Redpath, Spin warp NMR imaging and applications to human whole-body imaging, *Physics in Medicine and Biology*, 25 (1980) 751-756.
- 34 T. Umebayashi, K. Fukuda, T. Haishi, R. Sotooka, S. Zuhair, K. Otsuki, The development process of xylem embolisms in pine wilt disease monitored by multipoint imaging using compact magnetic resonance imaging. *Plant Physiology*, 156 (2011) 943-951.
- 35 W.F. Derr, R.F. Evert, The cambial and seasonal development of the phloem in *Robina pseudoacacia*. *American Journal of Botany*, 54 (1967) 147-153.

- 36 M.D. Mitchell, H.L. Kundel, L. Axel, P.M. Joseph, Agarose as a tissue equivalent phantom material for NMR imaging, *Magnetic Resonance Imaging*, (4) 1986 263-266.
- 37 T. Elder, N. Labbe, D. Harper, T.G. Rials, Time domain-nuclear magnetic resonance study of chars from southern hardwoods, *Biomass & Bioenergy*, 30 (2006) 855-862.
- 38 G. Almeida, S. Gagne, R.E. Hernandez, A NMR study of water distribution in hardwoods at several equilibrium moisture contents, *Wood Science and Technology*, 41 (2007) 293-307.
- 39 T.T. Kozlowski, C.H. Winget, Patterns of water movement in forest trees. *Botanical Gazette*, 124 (1963) 301-311.
- 40 G.W. Moore, B.J. Bond, J.A. Jones, F.C. Meinzer, Thermal-dissipation sap flow sensors may not yield consistent sap-flux estimates over multiple years. *Trees-Structure and Function* 24 (2010) 165-174.
- 41 I. Kaufmann, T. Schulze-Till, H.U. Schneider, U. Zimmermann, P. Jakob, L.H. Wegner, Functional repair of embolized vessels in maize roots after temporal drought stress, as demonstrated by magnetic resonance imaging. *New Phytologist* 184 (2009) 245-256.
- 42 Angeles, G, B. Bond, J.S. Boyer, T. Brodribb, J.R. Brooks, M.J. Burns, J. Cavender-Bares, M. Clearwater, H. Cochard, J. Comstock, S.D. Davis, J.-C. Domec, L. Donovan, F. Ewers, B. Gartner, U. Hacke, T. Hinckley, N.M. Holbrook, H.G. Jones, K. Kavanagh, B. Law, J. Lopez-Portillo, C. Lovisolo, T. Martin, J. Martinez-Vilalta, S. Mayr, F.C. Meinzer, P. Melcher, M. Mencuccini, S. Mulkey, A. Nardini, H.W. Neufeld, J. Passioura, W.T. Pockman, R.B. Pratt, S. Rambal, H. Richter, L. Sack, S. Salleo, A. Schubert, P. Schulte, J.P. Sparks, J. Sperry, R. Teskey, M. Tyree, The Cohesion-Tension Theory. *New Phytologist* 163 (2004) 451-452.

Table 1 Image acquisition parameters for 2D spin warp sequence

Parameter	Value
P ₉₀ hard / soft	0.022 ms / 0.1 ms
P ₁₈₀ hard	0.042 ms
τ (P ₉₀ -P ₁₈₀ pulse separation)	2 ms (min) – 128 ms (max)
Sampling rate	50 kHz
Relaxation delay	1000 ms
Gradient pulse length (G _x / G _z)	1 ms
G _x (read) / G _z (phase) / G _y (slice)	8.2 / $\pm$ 8.6 / 2.4 mT/m
Number of read points/ phase steps	64
Number of averages	32 (typical)

Table 2 Parameters measured and distance from the tree for the weather stations

	Weather station 1	Weather station 2
Distance from tree	2.5 m	150 m
Temperature	Yes	Yes
Relative humidity	Yes	Yes
Net radiation	No	Yes
Soil moisture	Yes	No
Rainfall	No	Yes

Table 3 T_2 parameters for two component exponential fits averaged over the sapwood and heartwood regions.

Region	Amplitude per pixel (arb. units)	T_2 (ms)
Sapwood	3.5 ($\pm$ 0.3)	111 ($\pm$ 18)
	11.2 ($\pm$ 2.5)	2.1 ($\pm$ 1.1)
Heartwood	1.6 ($\pm$ 0.1)	39 ($\pm$ 3)
	8.9 ($\pm$ 0.7)	2.8 ($\pm$ 0.2)

Figure captions.

Figure 1 a: Schematic of magnet design showing open access frame and concentric ring design (4 of 5 rings shown) of magnet with a mock tree between the poles; b: magnet as built with the gradient plates pulled half way out and c: magnet around a tree at Forest Research, Farnham, UK.

Figure 2 A 2D image of an array of water filled test tubes used as a resolution test phantom. One test tube is left absent for image orientation.

Figure 3 Cross section image of the bird cherry tree, recorded September 2011. The white dot towards the top of the image is the reference tube of water.

Figure 4 Cross section images of the tree using an echo time of $2\tau = 8, 16, 32$ and 64 ms (a to d). White circles in (a) show estimated areas of heartwood (inner) and sapwood (outer) used in image analysis.

Figure 5 Average image intensity per pixel in sapwood (circles) and heartwood (squares) as a function of echo time, τ . Two component exponential fits to the data are shown.

Figure 6 Top: Plots showing average image intensity for the tree for three non-consecutive summer days (squares 15th August, triangles 17th August, circles 19th August). Bottom: Net solar radiation (symbols, left axis) and relative humidity (lines,

right axis) for the same days. The times of sunrise (sr = 04:52 hrs, 17/8) and sunset (ss = 19:21 hours, 17/8) are additionally shown on the upper axis for reference.

Figure 7 Soil moisture content (lines, right axis) and maximum tree-image average-intensity (circles, left axis) over 8 consecutive days in May and June (top) and 12 days in August (bottom). The date tick labels are centred on midday.

Figure 8 Top: Plot showing soil moisture content for 30th, 31st July, 1st August and 1st September on either side of the tree (solid line: west; dotted line east) as well as sap flow for the 1st August and 1st September (heavy solid line: west; heavy dotted line: east). Bottom: Average image intensities for 1st August and 1st September (open squares: east; filled circles: west). Notice that on the 1st August the early morning image intensity is almost identical east and west (overlying data points) and that the sap flow and image intensity are both “reversed” compared to naïve expectation from the soil moisture content and is due to rotation of water around the tree by the spiral grain (see text). The soil moisture is comparable east and west on the 1st September, as are the image intensities: this day is used as a “control”. Note the break of axis between 1/8 and 1/9.

Figure 9 Image of tree acquired at 18:00 1st August 2011 showing reduced magnitude in the west side. The white line shows east / west split used in image analysis. This image was acquired with a lower gradient strength than given in the typical parameters in Table 1.

Figure 10 Image magnitude (black squares, left axis) and net solar radiation (open circles, right axis) on 15th August (top) and 13 September (bottom). (The fall in radiation at 13:00 on 13th September is due to increased cloud cover). Photographs show same area of tree on the 15th August and 13th September illustrating the changing leaf cover.

FIGURE 1

FIGURE 2

FIGURE 3

FIGURE 4

FIGURE 5

FIGURE 6

FIGURE 7

FIGURE 8

FIGURE 9

FIGURE 10 (including colour photos – these may be printed black and white)