University
of Tsukuba

Outdoor plant measurements using compact/mobile MRI systems

K. Kose[1], Y. Terada[1] and T. Haishi[2]

1. Institute of Applied Physics, University of Tsukuba,
2. MRTechnology Inc.

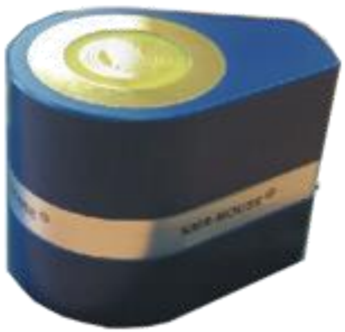
Outline

1. Introduction : **outdoor MRI for plants**
2. In situ & ex vivo NMR/MRI of **pear fruit**
   in situ MRI, in situ NMR, ex vivo NMR
3. In situ MRI of **tree** branches and trunks
   branches of pear tree (~20 mm dia.)
   Challenge for larger trees (>60mm dia.)
4. Conclusion

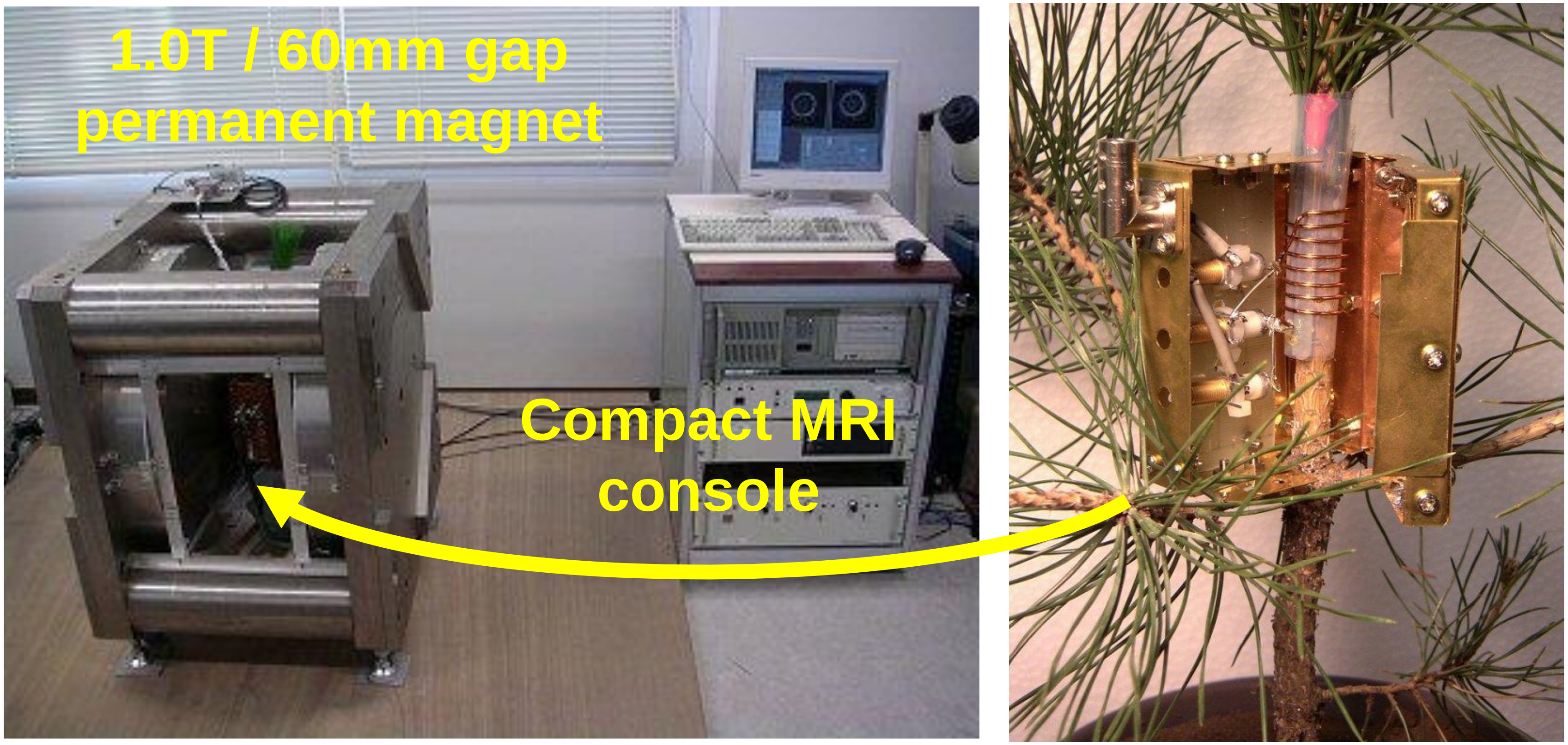
Indoor/outdoor NMR/MRI

Indoor (immobile?) NMR/MRI systems

Outdoor (mobile) NMR/MRI systems

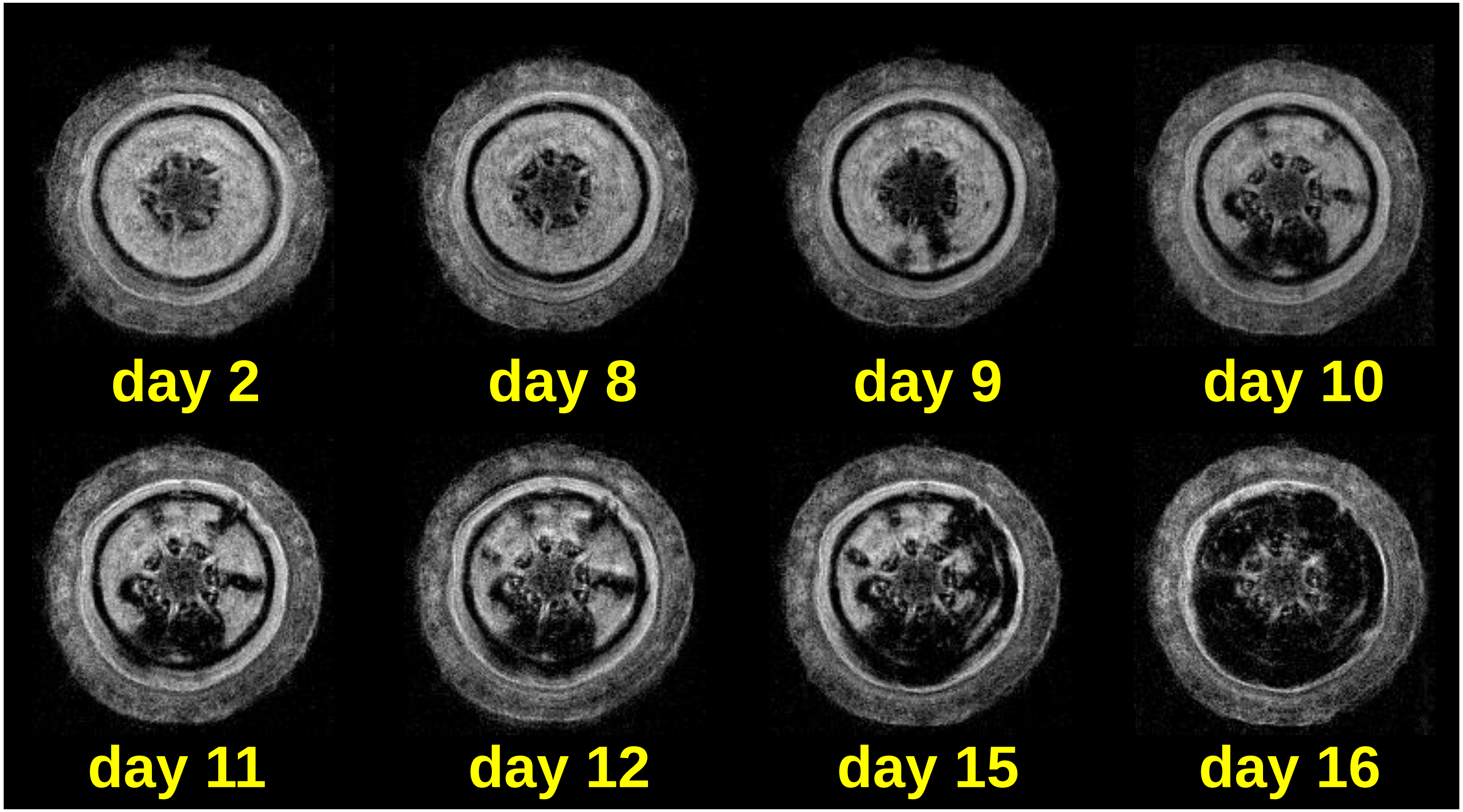


2005: *in-situ* observation of pine wilt disease



S. Utsuzawa, K. Fukuda, D. Sakaue. Use of magnetic resonance microscopy for the nondestructive observation of Xylem cavitation caused by pine wilt disease. Phytopathology, 95:737-743 (2005).

Time series of a cross section of a pine tree:
rapid increase of cavitation by pinewood "nematodes"



Transverse images of Japanese black pine obtained with 1.0 T MRM
2D Spin Echo (TR = 500 ms, TE = 22 ms, NEX = 4), 8.5 minutes acq.
Matrix: 256 x 256, Resolution: 75 μm x 75 μm x 4 mm

Outdoor plant MRI systems : **2006~**

2006: Maple tree

2009: Pear fruit

2010: Pear branch

2010: Pear fruit

2011: Solar cell MRI

2012: Larger tree

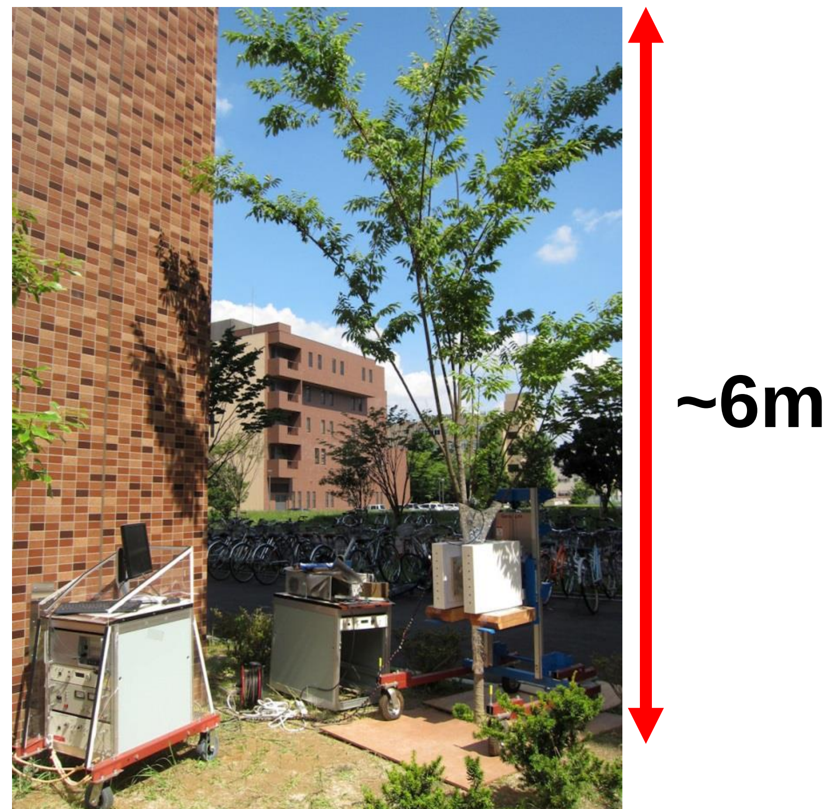
Outdoor plant MRI measurements

Advantages:

(1) Plants in **natural environments** can be measured

(2) No need for **plant preparation** for laboratories

(3) No **limitation in sample size**



Outdoor plant MRI measurements

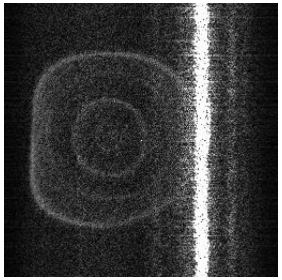
Problems to be overcome:

(1) MRI systems for outdoor environments are **subject to** climate change, extreme environment, intense external noise

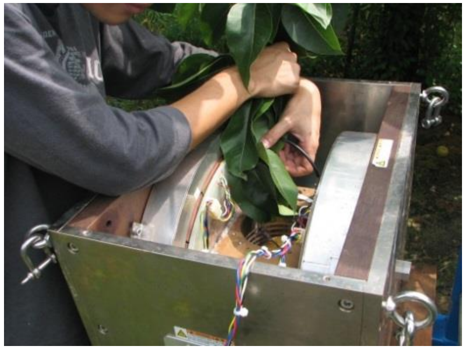
(2) Access to the **sweet spot** of the MRI systems is not easy (homogeneous static magnetic field, field gradients, RF field)

Sudden climate change

Strong wind



Intense external noise



Access to sweet spot

Outline

1. Introduction : **outdoor MRI for plants**

2. In situ & ex vivo NMR/MRI of **pear fruit**

   in situ MRI, in situ NMR, ex vivo NMR

3. In situ MRI of **tree** branches and trunks

   branches of pear tree (~20 mm dia.)

   Challenge for larger trees (>60mm dia.)

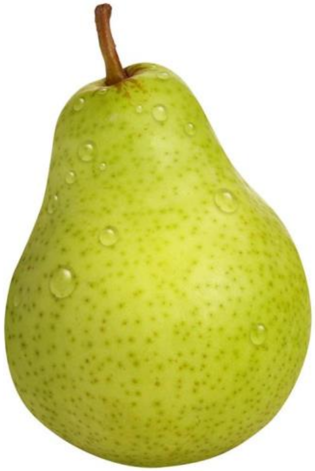
4. Conclusion

In situ & *ex vivo* NMR/MRI of pear fruit

2009: **In situ MRI** using a 0.12 T MRI system for **five** Japanese pears

2010: **In situ NMR** using a 0.2 T system for **six** Japanese pears

2011: **Ex vivo outdoor NMR** using a 0.2 T MRI system for **84** Japanese pears



Western pear

Unsuitable for MRI

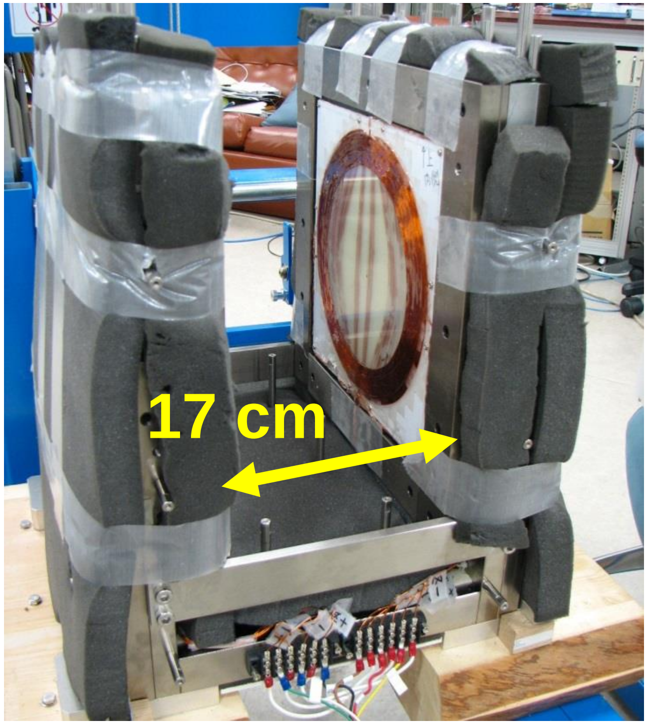
Sweet spot!

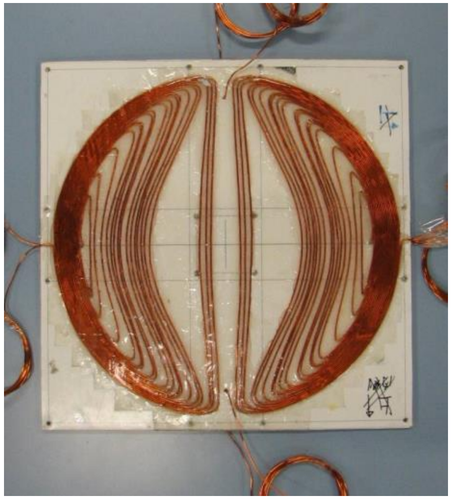
Japanese pear

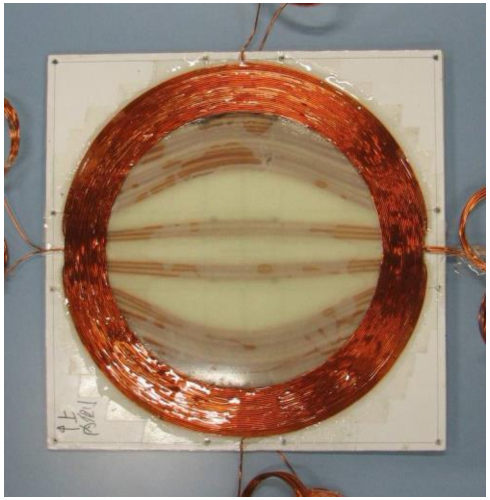
Suitable for MRI

Sweet spot!

In situ MRI using a 0.12T MRI system (2009)



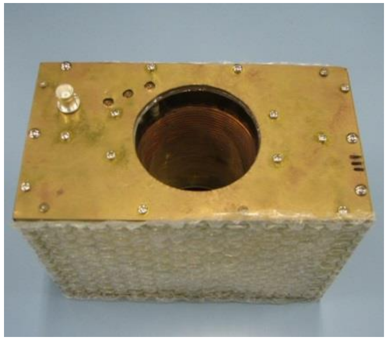


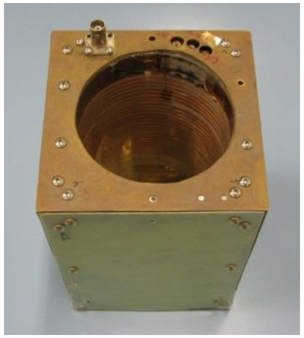


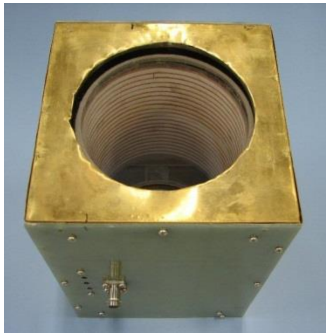
GA optimized coil **Maxwell pair**

Gx: 1.17, Gy: 1.15, Gz: 3.13 [mT/m/A]

0.12 T, 17 cm gap
Homogeneity: 100 ppm at 85 mm dsv, 170 kg

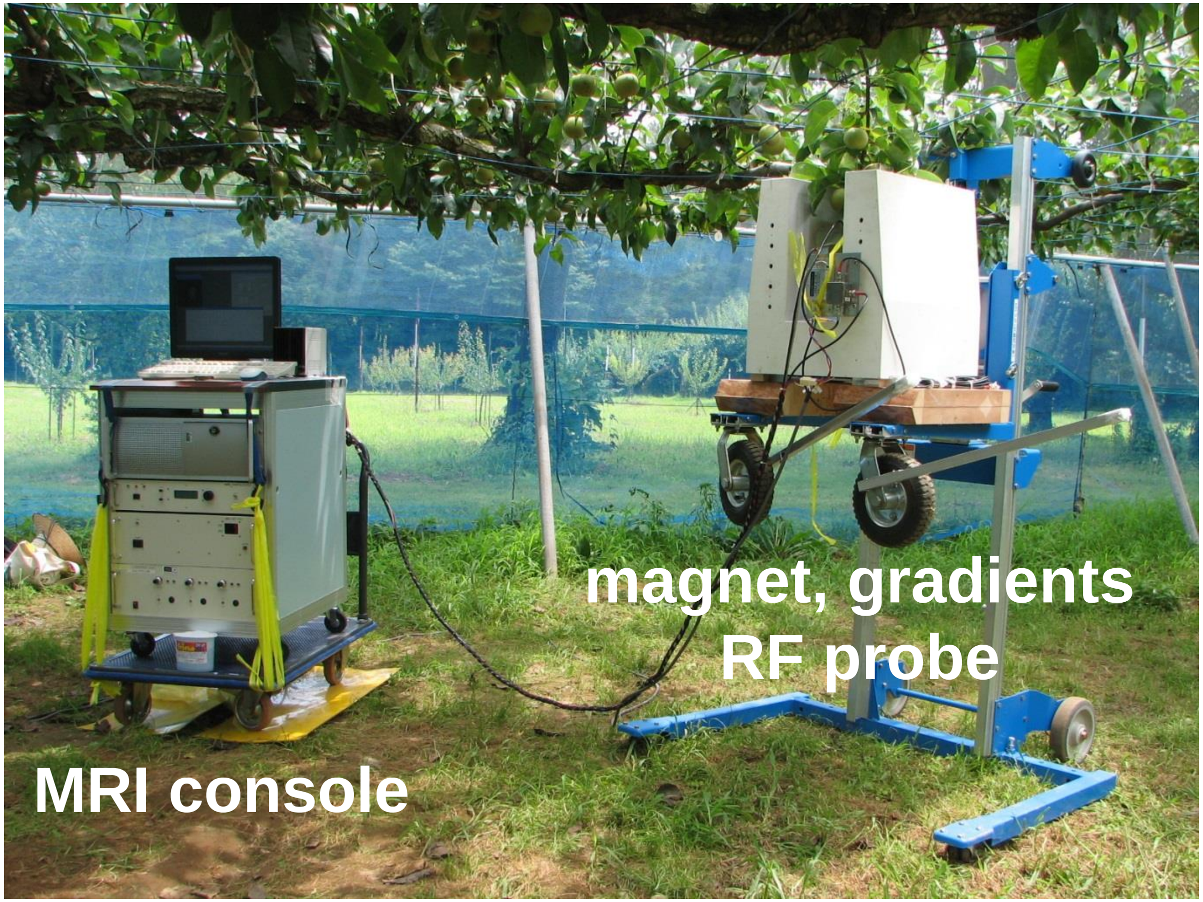






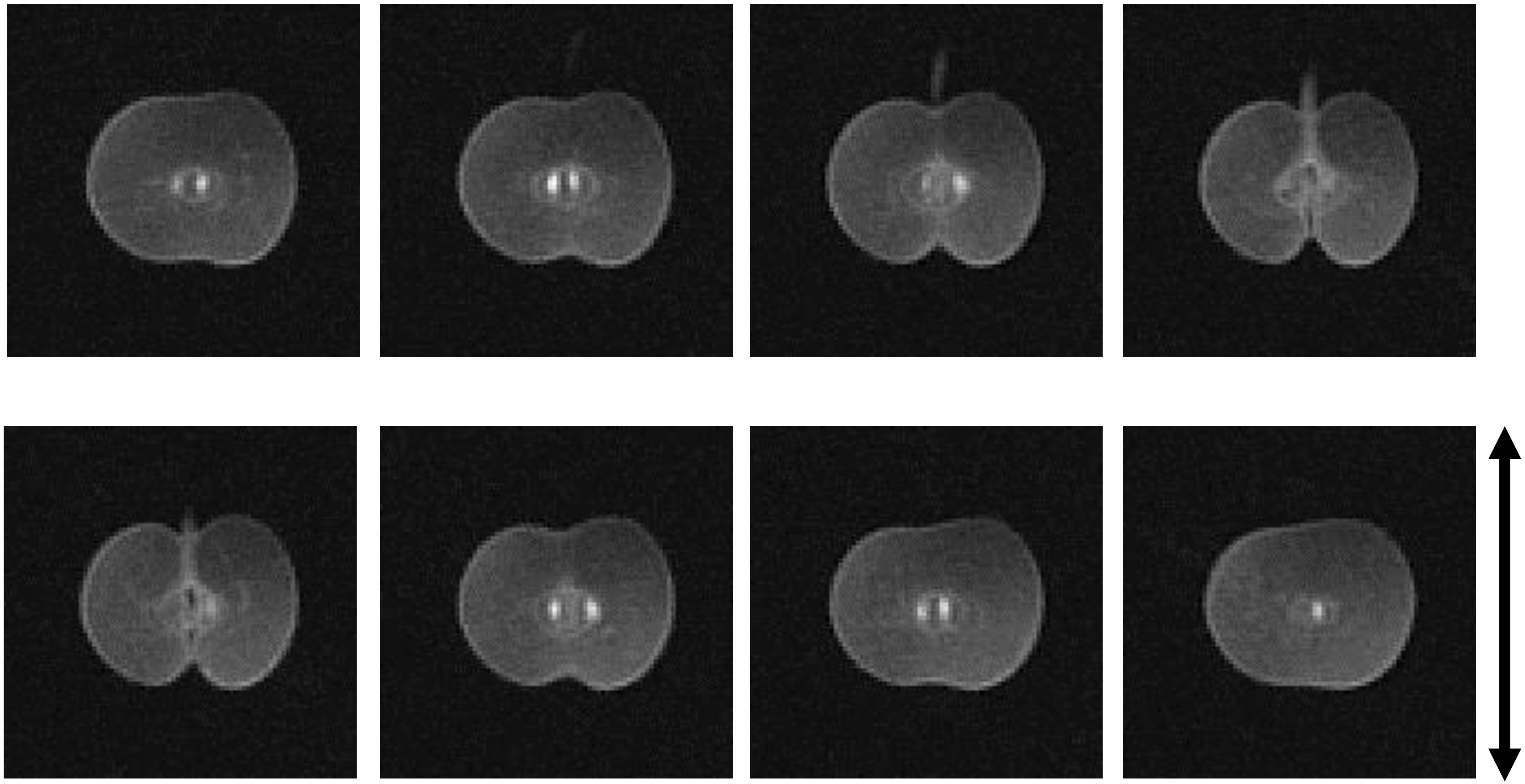
RF coils were optimized for growing pears.

In situ MRI using a 0.12T MRI system (2009)



3D images (128 x 128 x 128 matrix) of five pears were acquired *in situ* from July 10th to August 12th.

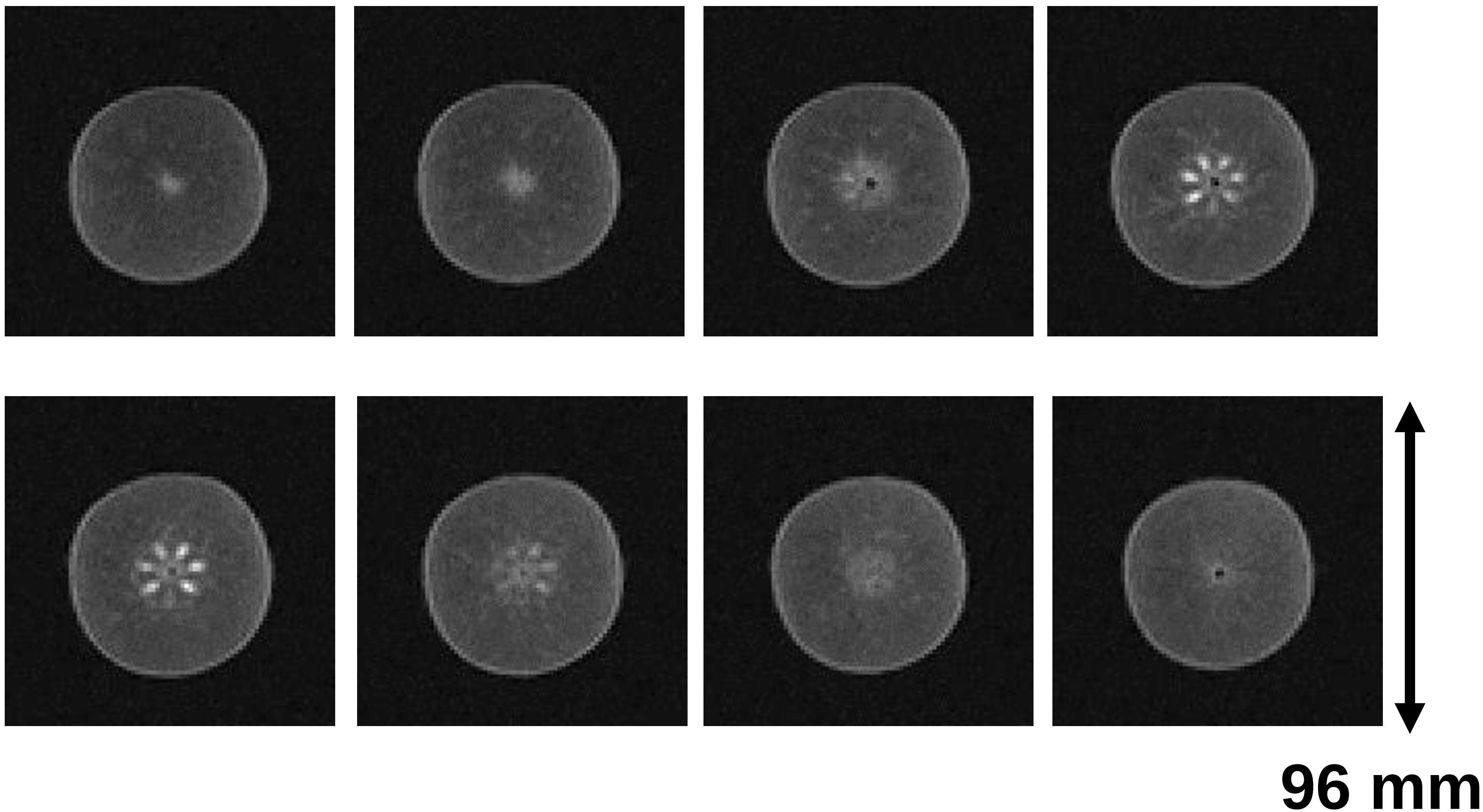
Vertical sections of the sample 1



TR/TE = 200 ms/12 ms, image matrix = 128^3

voxel size : $(1.2\ mm)^3$, scan time = 55 minutes

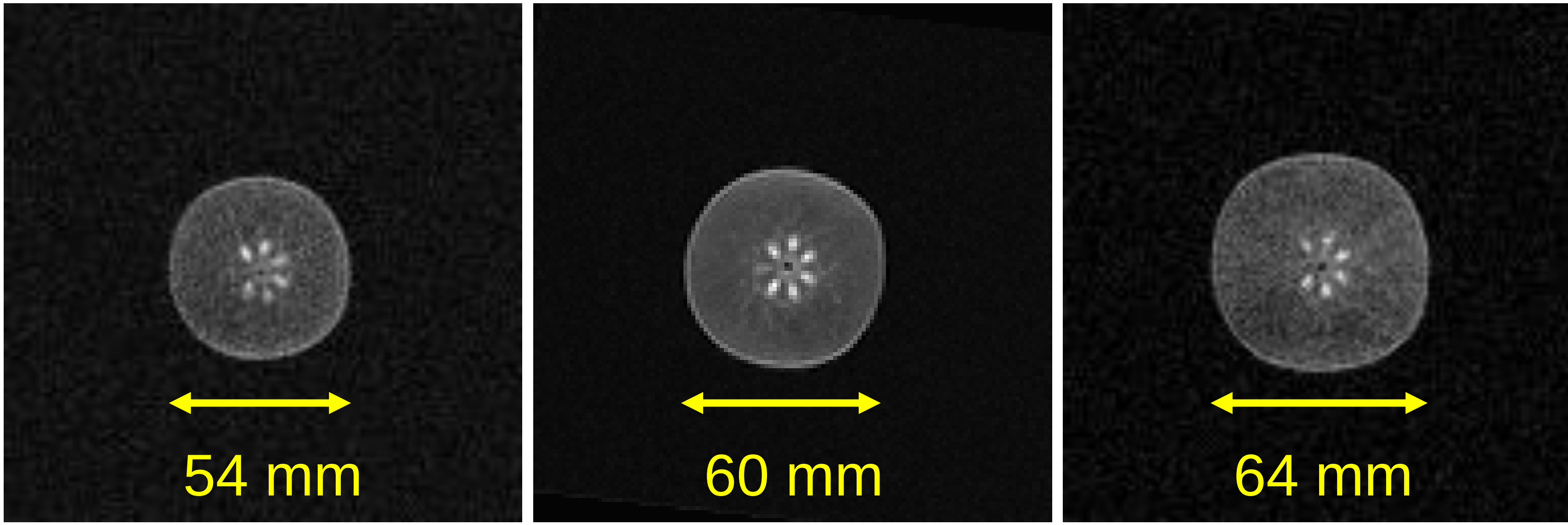
Horizontal sections of the sample 1



TR/TE = 200 ms/12 ms, image matrix = 128^3

voxel size : $(1.2\ \mathrm{mm})^3$, scan time = 55 minutes

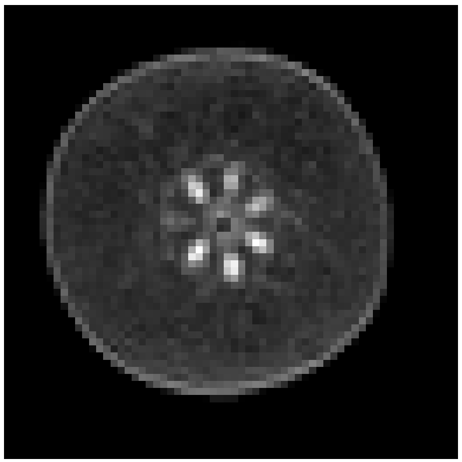
Growing process : sample 1（1）



July, 10th **July, 16th** **July, 22nd**

The growing process is clearly visualized.

Growing process: sample 1（2）



76.8 mm

July, 16th

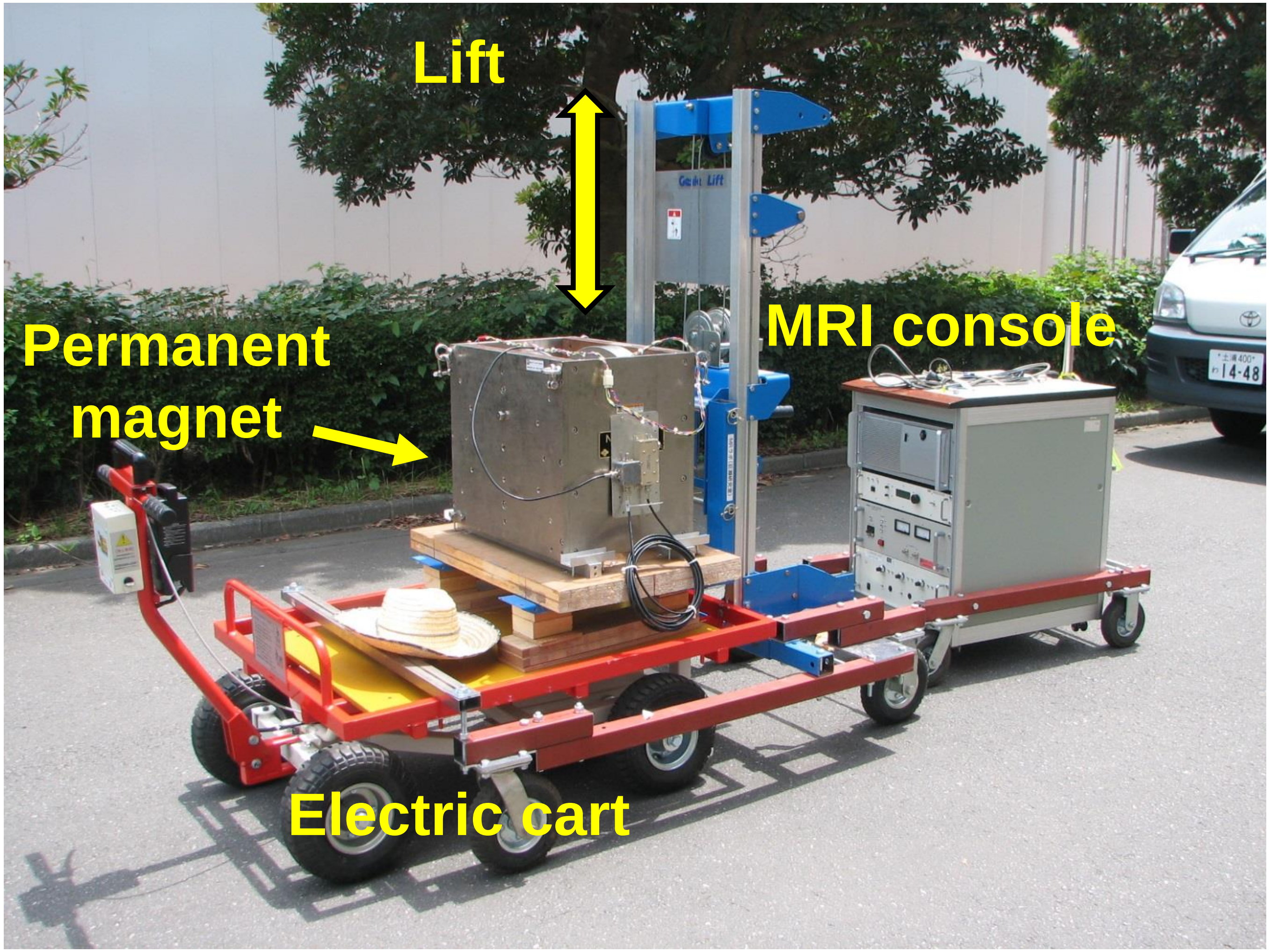
4 weeks

128 mm

August, 12th

Because the image contrast changed substantially, **relaxation time measurements** are indispensable!

In situ NMR using a 0.2T MRI system (2010)



Y. Geya, T. Kimura, H. Fujisaki, Y. Terada, K. Kose, T. Haishi, H. Gemma, Y. Sekozawa, **J Magn Reson 226, 45-51 (2013)**.

In situ NMR using a 0.2T MRI system (2010)

0.2 T, 16 cm gap
Homogeneity: 41 ppm for 100 mm dsv, 200 kg

3DSE, 256 x 256 x 16
TR = 400 ms, TE = 20 ms
4NEX, 1.8 hours

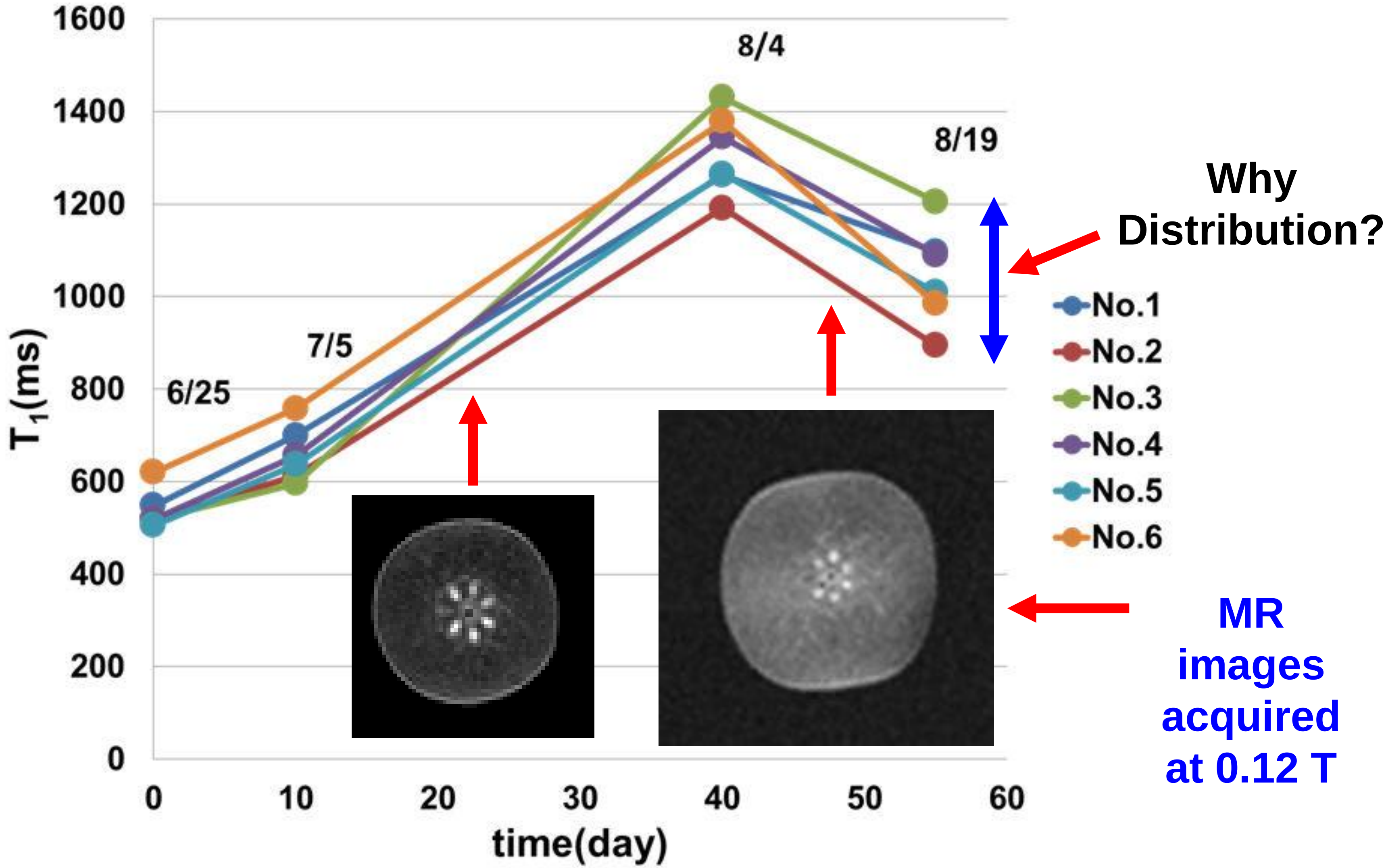
We used a very **light-weight permanent magnet**, which was originally developed for the **International Space Station**.

In situ NMR using a 0.2T MRI system (2010)

Sample setting to the sweet spot of the system

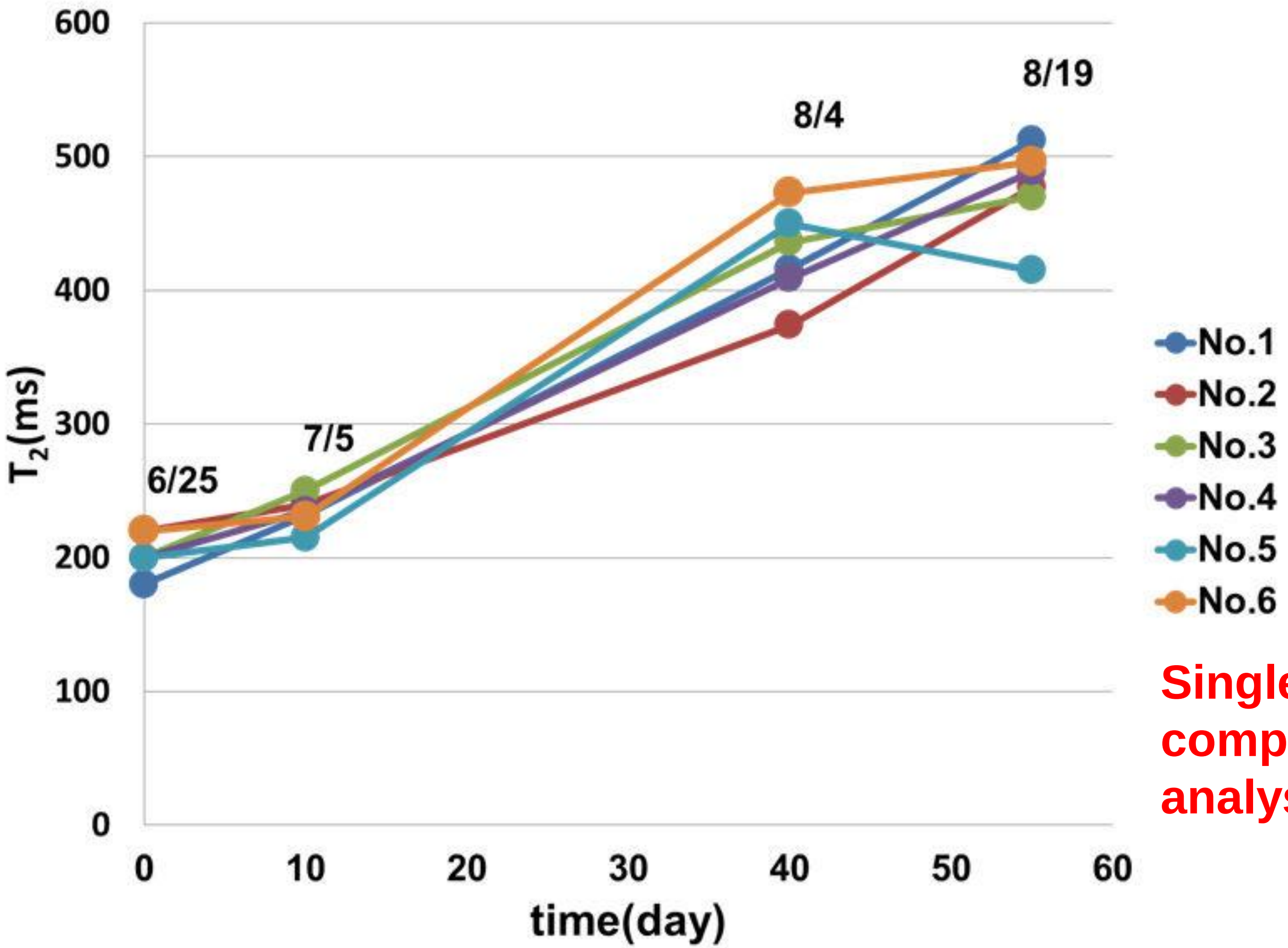
Because the stalk of the pear fruit is **fragile**, setting the pears in the **sweet spot** of the magnet is difficult.

In situ T_1 measurements for six pears



T_1 monotonously increased with time but **finally decreased**.

In situ T_2 measurements for six pears



Single component analysis

T_2 monotonously increases with time.

In situ NMR using a 0.2T MRI system

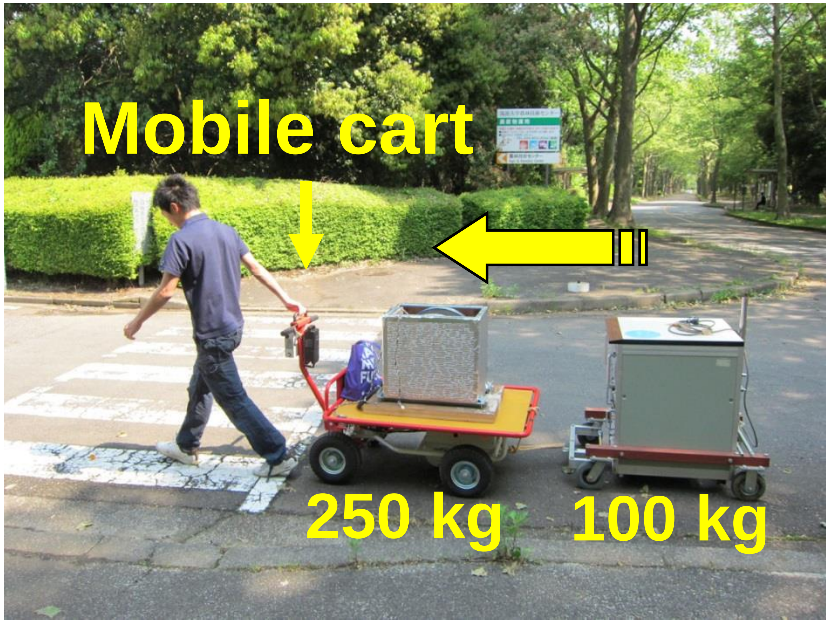
Problems:

1. It is difficult to place the pears in the **sweet spot** of the MRI system (magnetic field) because the stalk is **fragile** and is not sufficiently long.

2. The origin of the **distributions** of the relaxation times over the samples are unknown.

→ **Ex vivo** relaxation time measurements for many pears.

Ex vivo NMR using a 0.2T MRI system (2011)



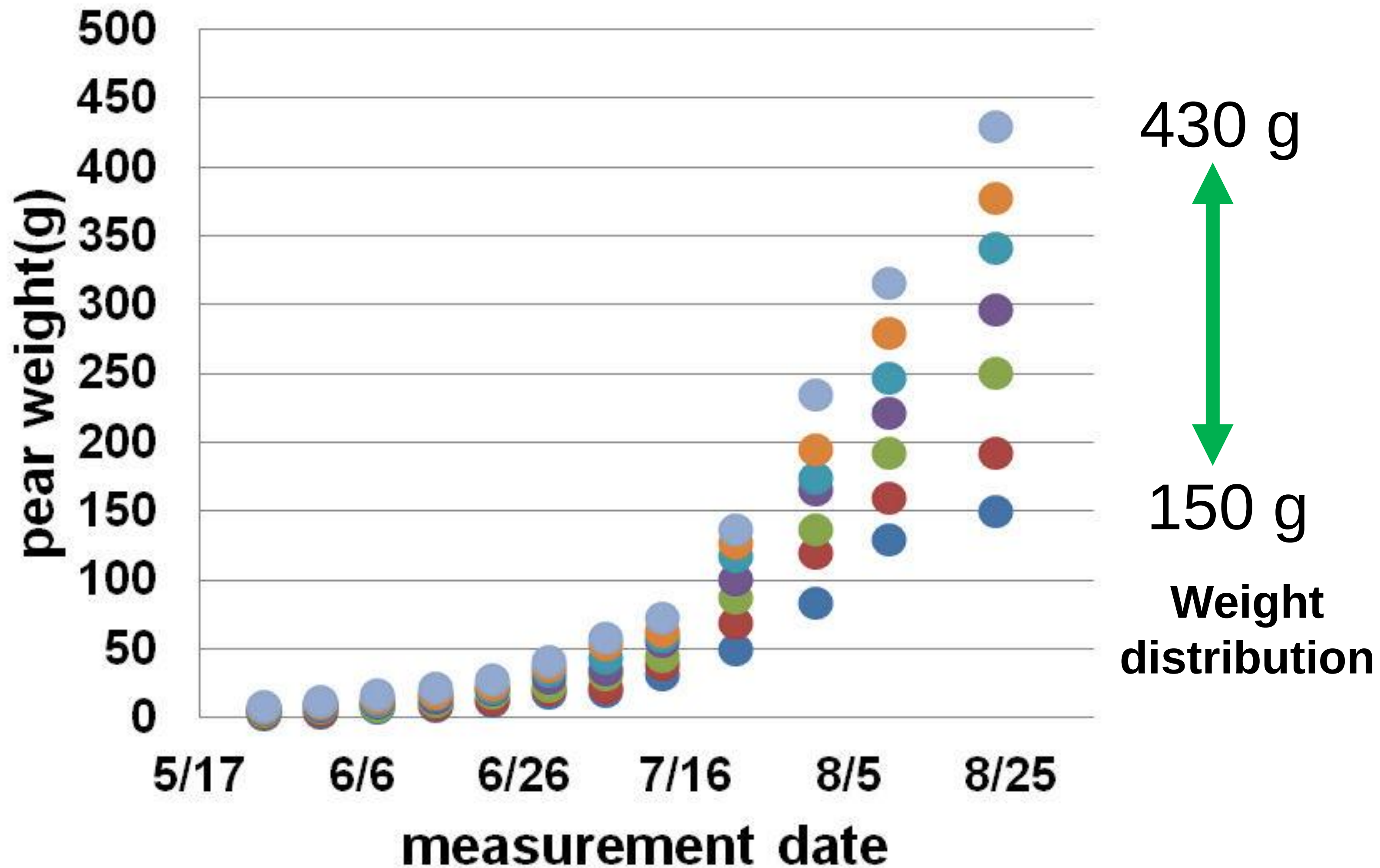
Lightest on the day

Heaviest on the day

The weight is evenly distributed.

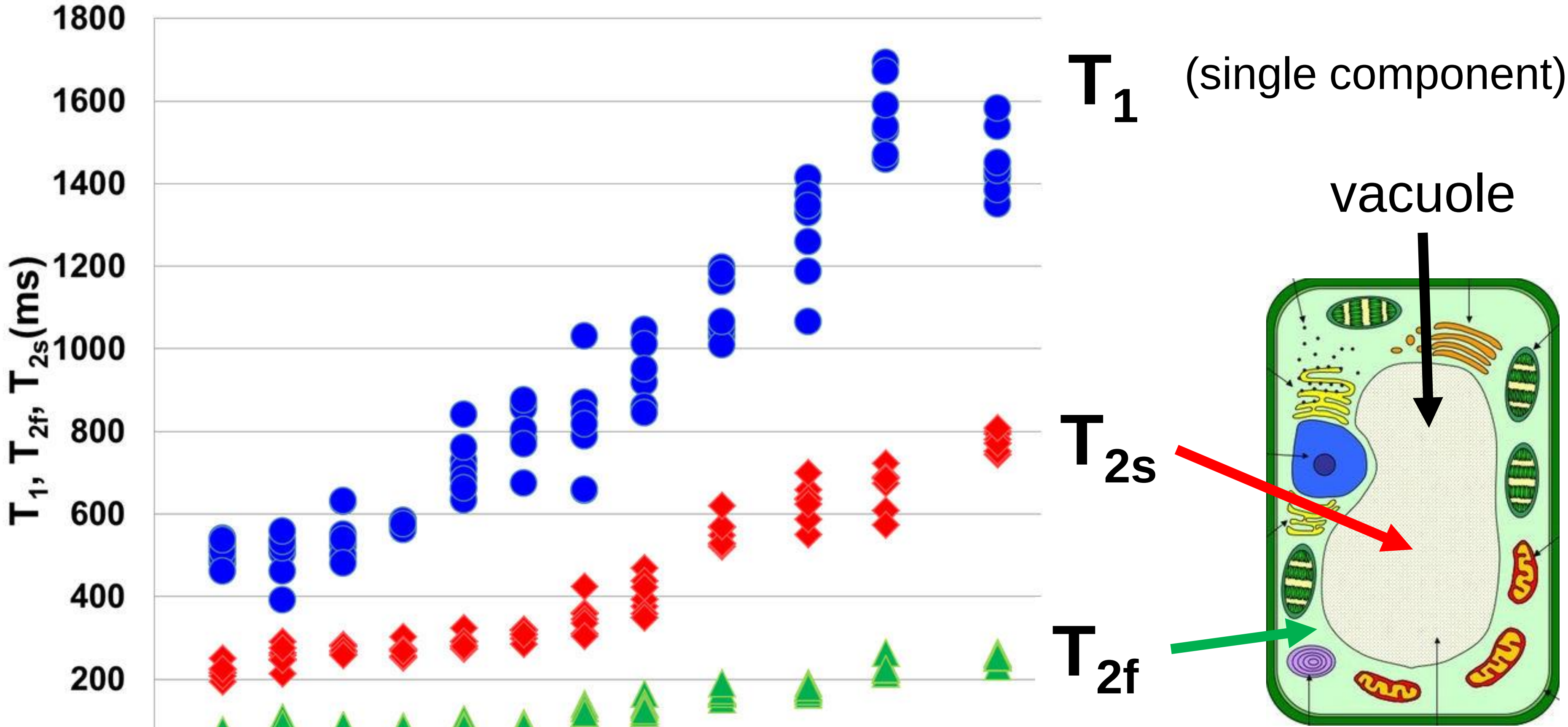
Relaxation times of seven pears were measured almost every week from **May 25th** to **August 23rd (cell enlargement period)**.

Weight distribution of the harvested pears



84 pears were harvested from a **single Japanese pear tree**, which bears more than **several hundreds pears** every year.

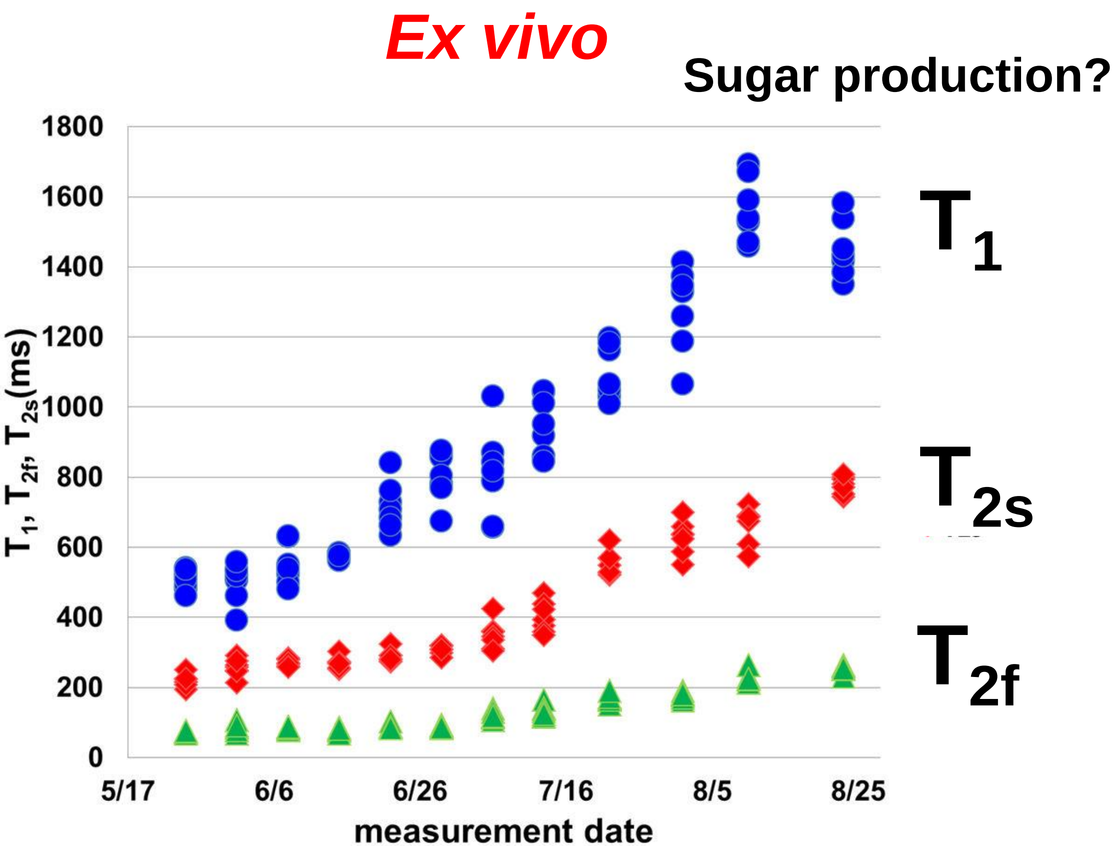
T_1, T_2 vs. measured date

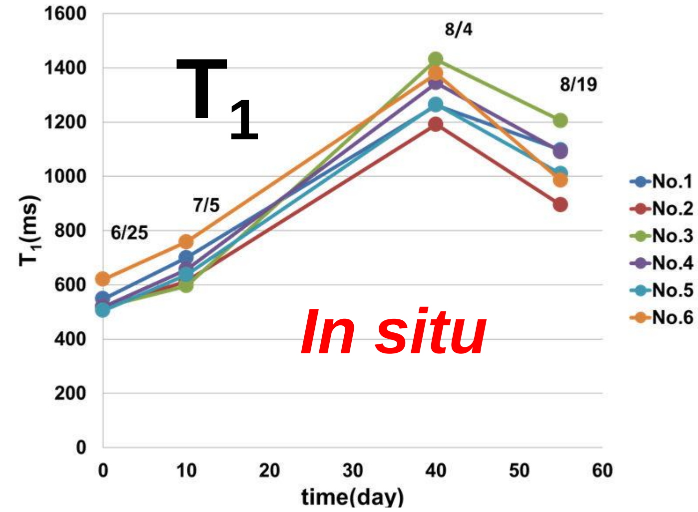


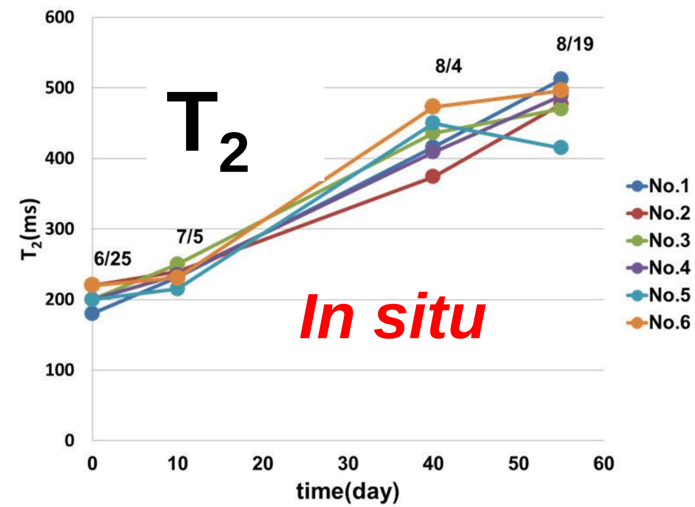
Schematic plant cell

Relaxation times increase with time but T_1 finally decreases.

Comparison between *ex vivo* and *in situ* results

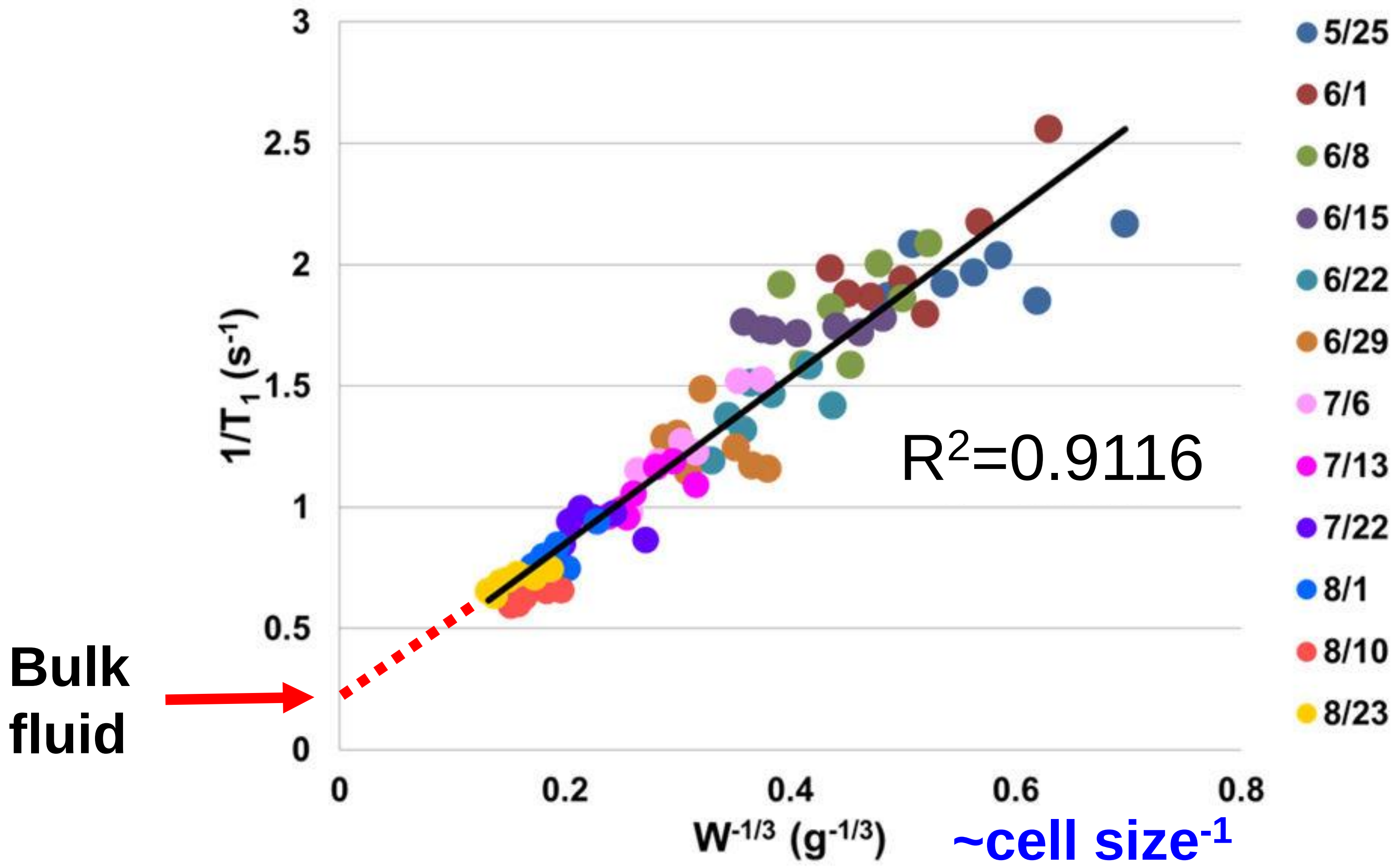






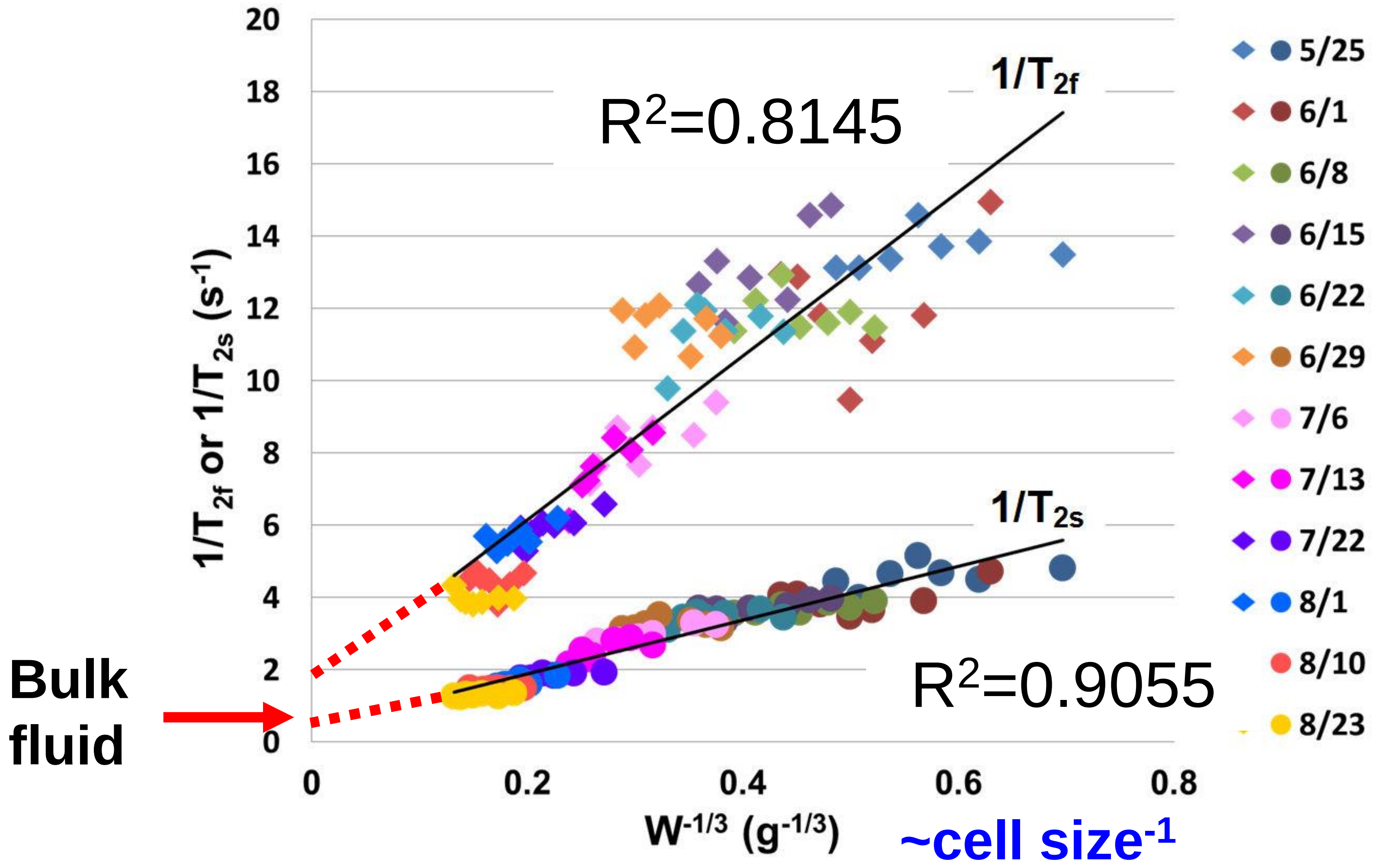
Ex vivo and ***in situ*** results show **good agreements**. T_2 was not decomposed for ***in situ*** measurements.

Relaxation rate ($1/T_1$) vs (weight)$^{-1/3}$



The T_1 relaxation rates plotted against the inverse of **the cubic root of the weight (~cell size)** shows good linear relations.

Relaxation rate ($1/T_2$) vs (weight)$^{-1/3}$

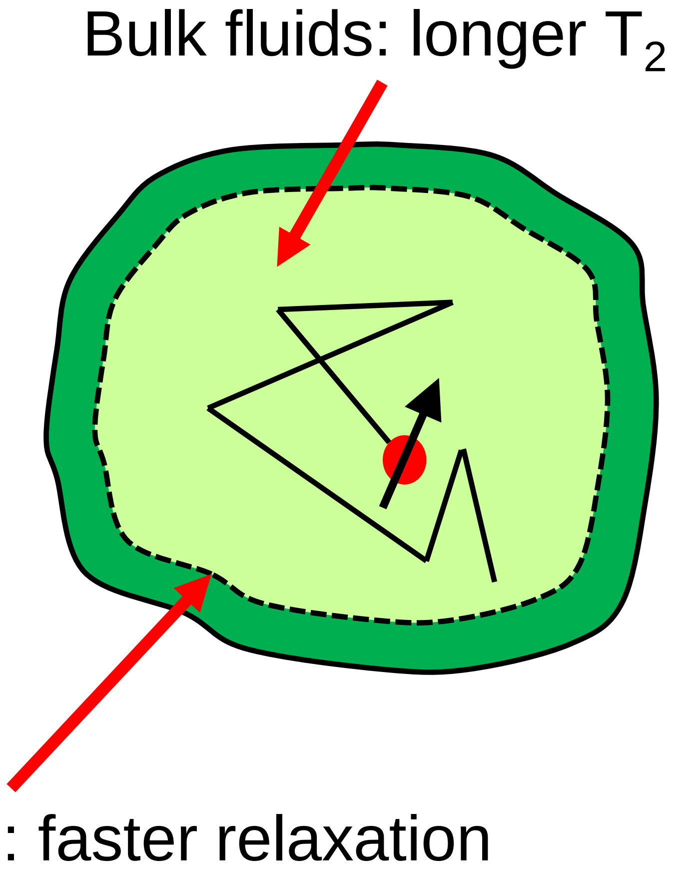


The T_2 relaxation rates plotted against the inverse of **the cubic root of the weight (~cell size)** shows good linear relations.

Relaxation mechanism for the pear fruit cell

$$\frac{1}{T_1} = \frac{1}{T_{1bulk}} + \frac{1}{T_{1surface}}$$

$$\frac{1}{T_2} = \frac{1}{T_{2bulk}} + \frac{1}{T_{2surface}} + \frac{1}{T_{2diffusion}}$$



Relaxation times in plant cells are dominated by the surface relaxation mechanism.

Relaxation mechanism for the pear fruit cell

$$\frac{1}{T_{1surface}} = \rho_1 \left(\frac{S}{V}\right)_{pore}$$

$$\frac{1}{T_{2surface}} = \rho_2 \left(\frac{S}{V}\right)_{pore}$$

ρ_1: T_1 surface relaxivity

ρ_2: T_2 surface relaxivity

$\left(\frac{S}{V}\right)_{pore}$: ratio of surface area to fluid volume

$$\left(\frac{S}{V}\right) \propto \frac{1}{L} \propto W^{-1/3}$$

Because the surface relaxation rate are proportional to the ratio of the surface to the volume of the pore, or the inverse of the linear dimension of the cell. This is the reason why the relaxation rate linearly changes with the inverse of the cubic root of the fruit weight.

Summary for *In situ* & *ex vivo* NMR/MRI of pear fruit

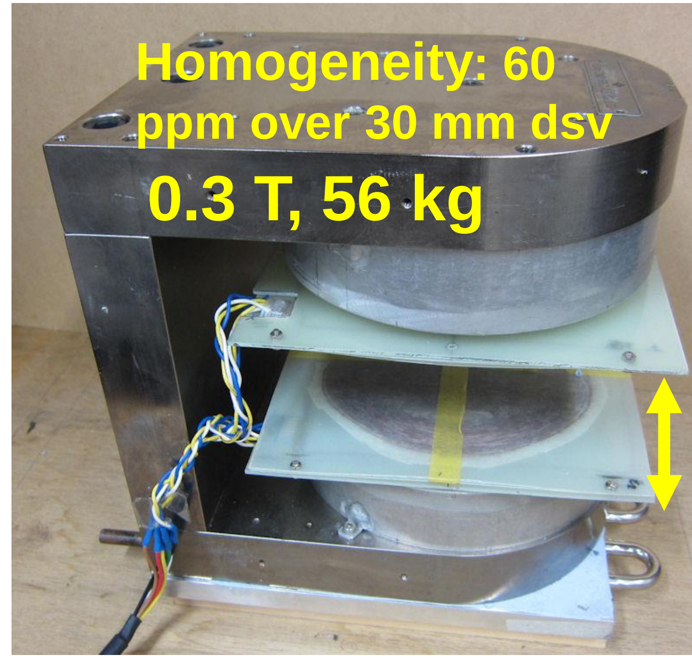
1. Relaxation times of pear fruit measured ***in situ*** and ***ex vivo*** showed good agreements. T_1 decreases in the ripening stage maybe due to sugar production.

2. The relaxation times in the cell enlargement period (late May to August) in pear fruit are shown to be mostly determined by the size of the cell.

Outline

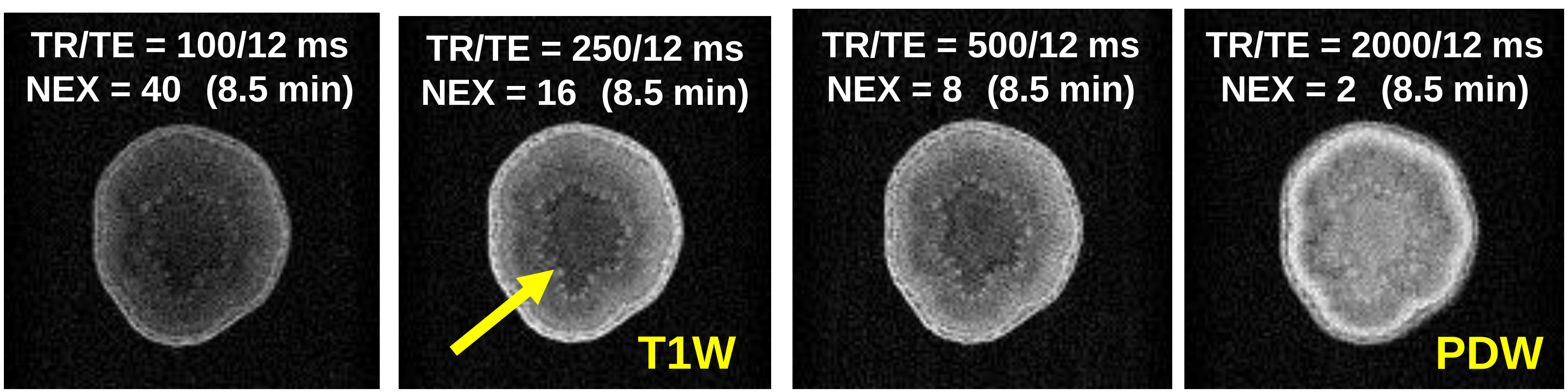
1. Introduction : **outdoor MRI for plants**
2. In situ & ex vivo NMR/MRI of **pear fruit**
   in situ MRI, in situ NMR, ex vivo NMR
3. In situ MRI of **tree** branches and trunks
   branches of pear tree (~20 mm dia.)
   Challenge for larger trees (>60mm dia.)
4. Conclusion

In situ MRI of a tree using a permanent magnet



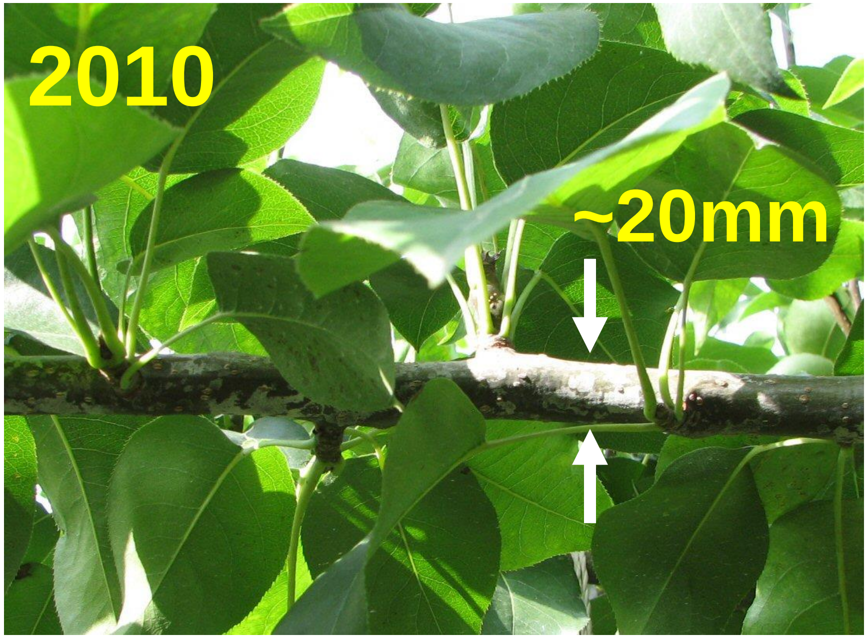
80mm

25.6mm



A maple tree was imaged *in situ* using a 0.3T, 80mm gap permanent magnet.

MRI of normal/diseased branches of a pear tree

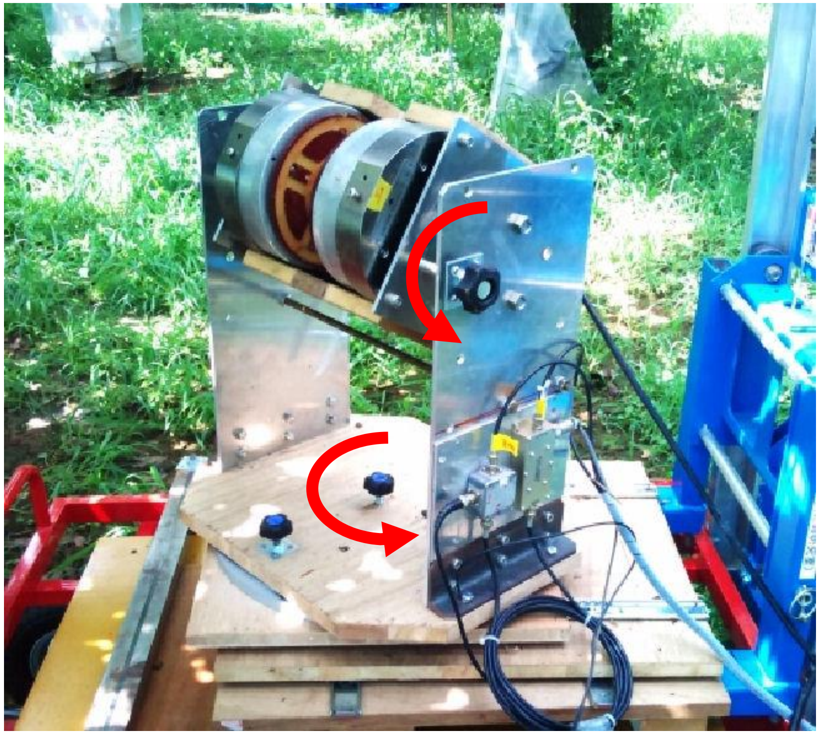


normal branch

diseased branch

The **dwarf disease** is a serious disease in Japanese pear farms, because this disease damages the branches and drastically reduces **yields** of pear fruit. To observe the **function** of the pear branches, we measured MR images of the cross-sections.

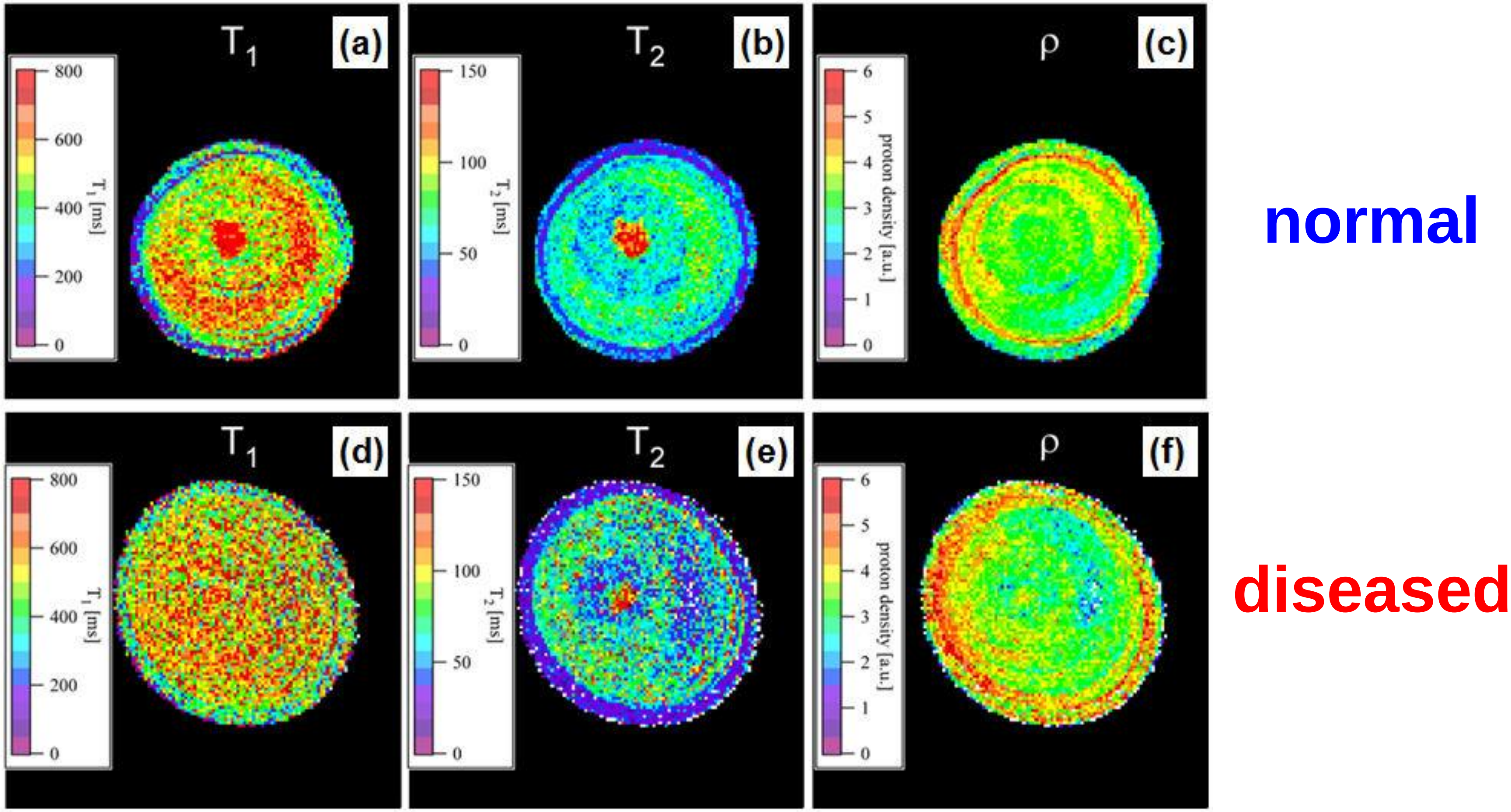
Electrically mobile MRI for a 0.3T/80mm magnet



To observe the pear branches, we developed an electrically mobile MRI system with two rotation axes and two sliding tables on the lift.

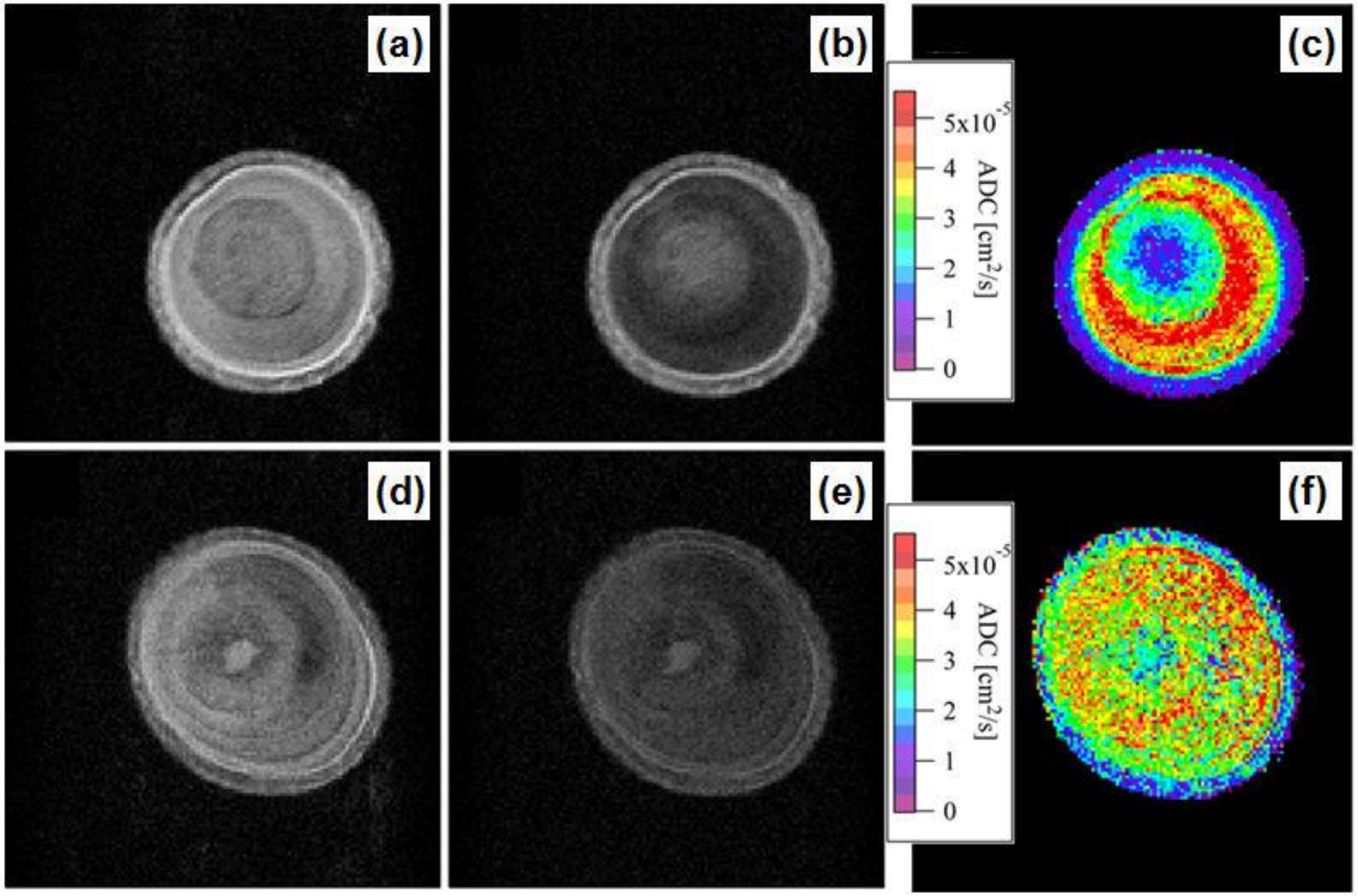
T. Kimura, Y. Geya, Y. Terada, K. Kose, T. Haishi, H. Gemma, Y. Sekozawa, Development of a mobile magnetic resonance imaging system for outdoor tree measurements, **Rev. Sci. Instrum. 82 (2011) 053704**.

NMR parameter mapping



T_1, T_2, and proton density of the normal and diseased branches in the cross sections. Clear difference was not observed.

DWI and ADC mapping



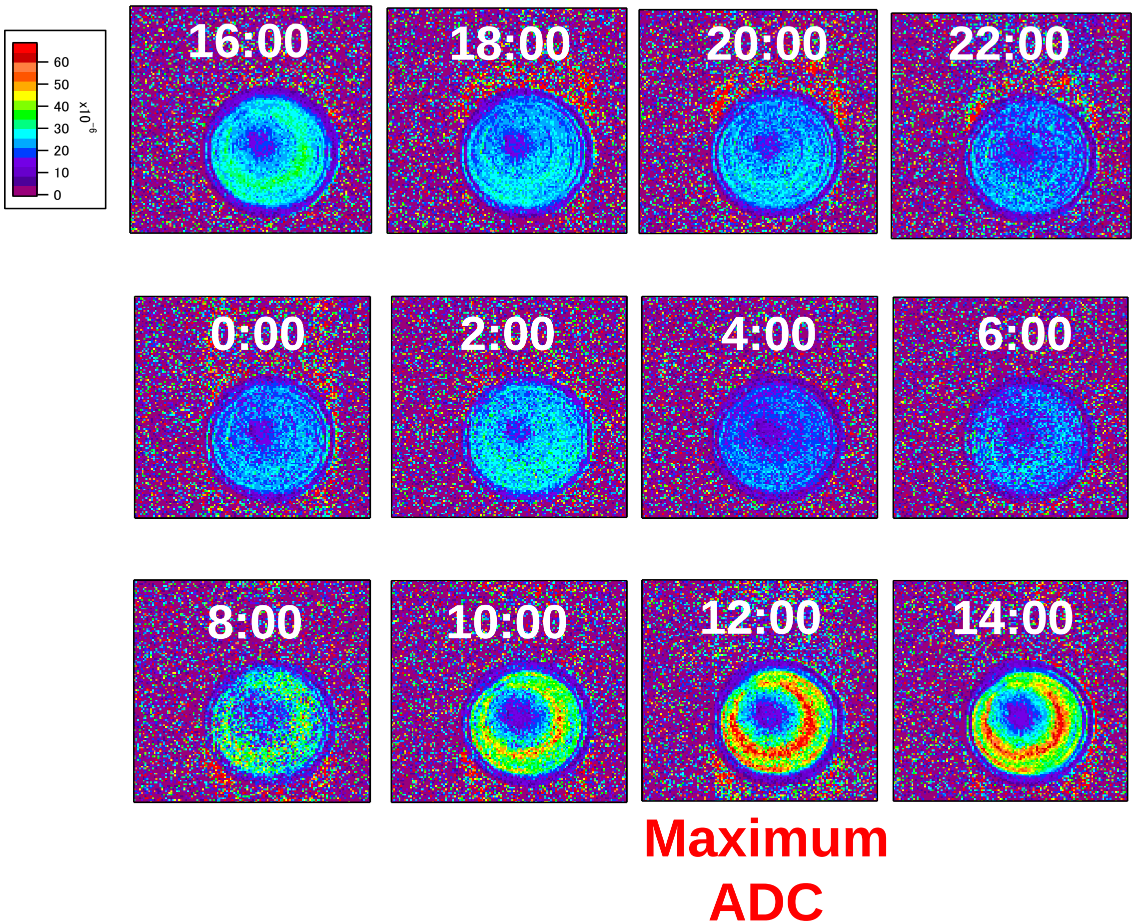
normal

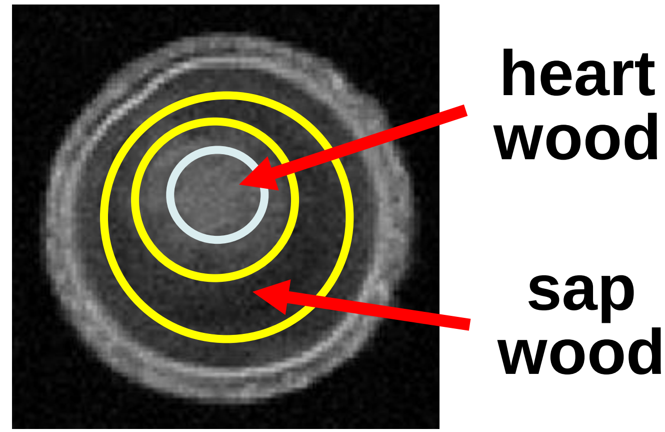
diseased

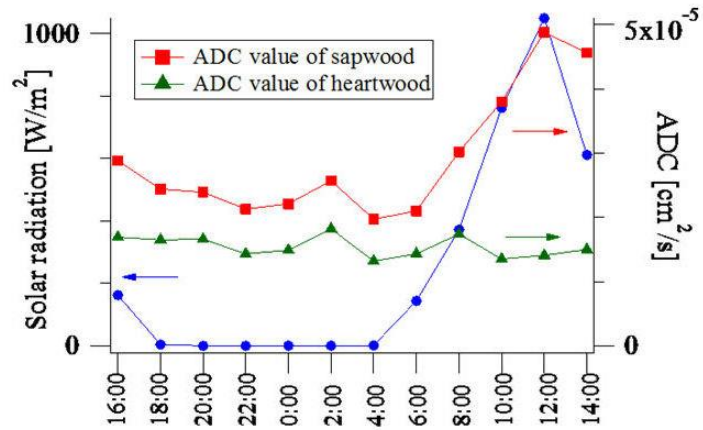
DWI (b = 0 s/mm²) **DWI (b = 314 s/mm²)** **ADC map**

In the ADC map, we can see **very clear structure** in the normal branch but we cannot see such structure in the disease branch.

24-hour measurements (every 2 hours)







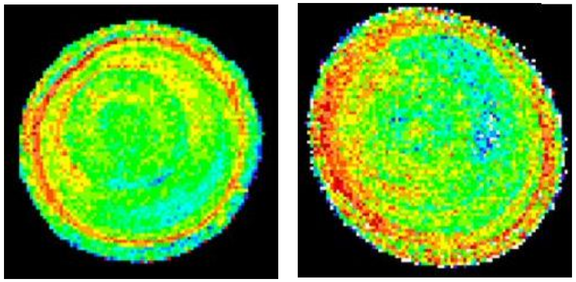
This slide shows ADC map measured **every two hours** for 24 hours. This graph clearly shows that ADC and solar radiation are closely correlated.

Live tree diagnosis in JSMRM meeting (2010)

In the 38th JSMRM annual meeting held in 2010, this system was used to diagnose an **indoor large tree in the conference hall**. The result clearly demonstrated water function of the brach.

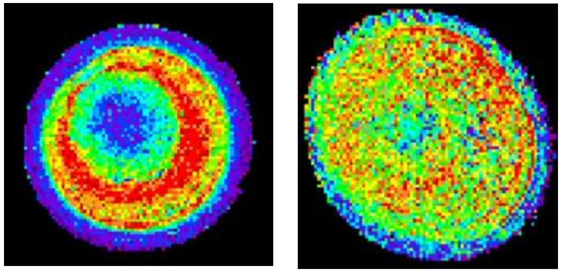
Summry for MRI of pear tree branches

1. Distributions of T_1, T_2, and proton density could not differentiate the diseased from the normal branch.



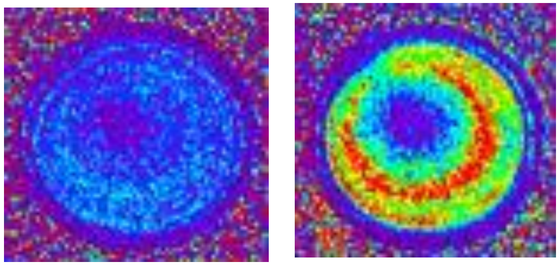
PD: normal diseased

2. The ADC map during daytime clearly visualized the difference.



ADC: normal diseased

3. 24-hour ADC measurements of the healthy branch clearly demonstrate the water function changing with the solar radiation.



4:00 am 12:00 am

Outline

1. Introduction : **outdoor MRI for plants**

2. In situ & ex vivo NMR/MRI of **pear fruit**

   in situ MRI, in situ NMR, ex vivo NMR

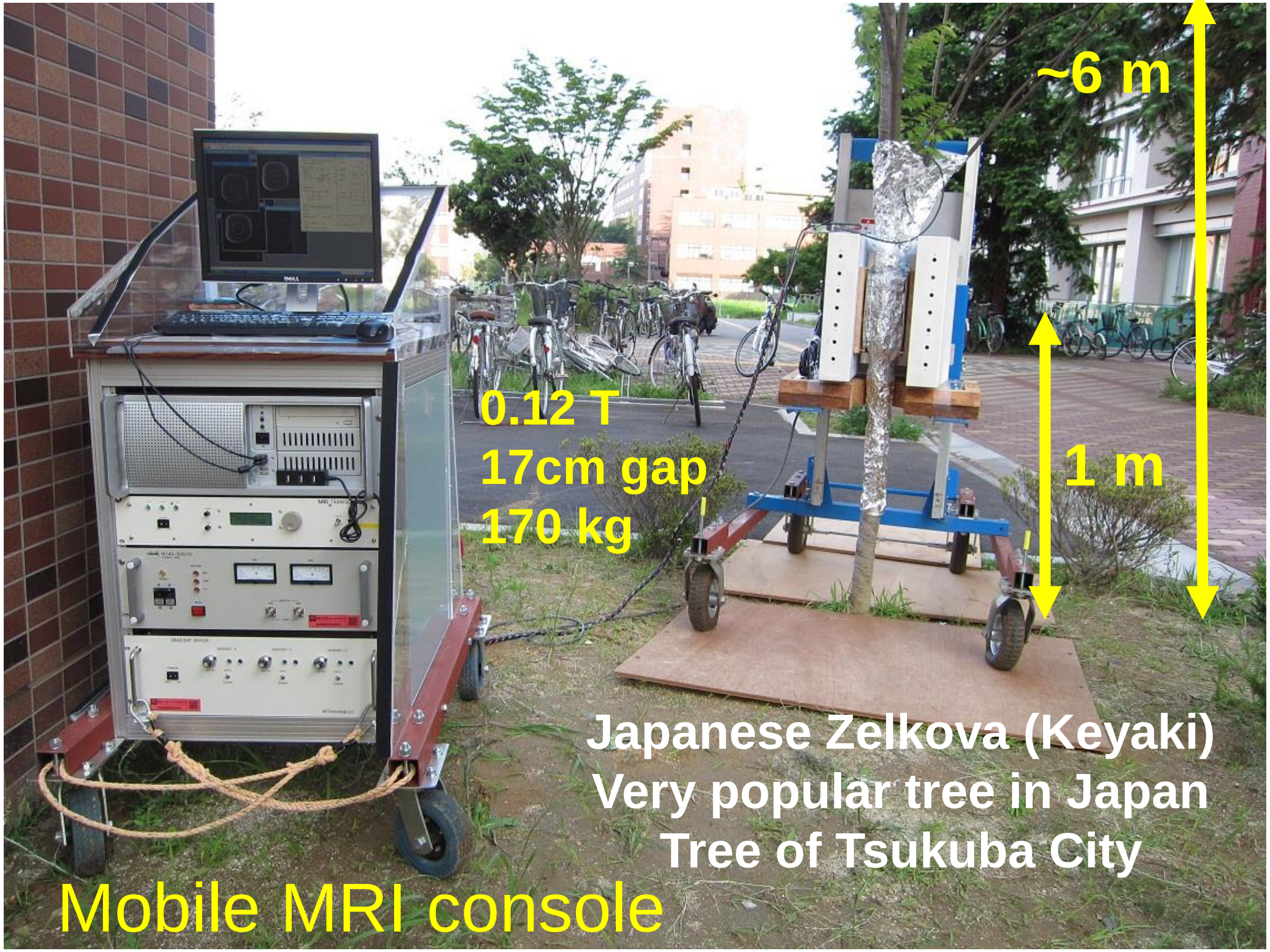
3. In situ MRI of **tree** branches and trunks

   branches of pear tree (~20 mm dia.)

   Challenge for larger trees (>60mm dia.)

4. Conclusion

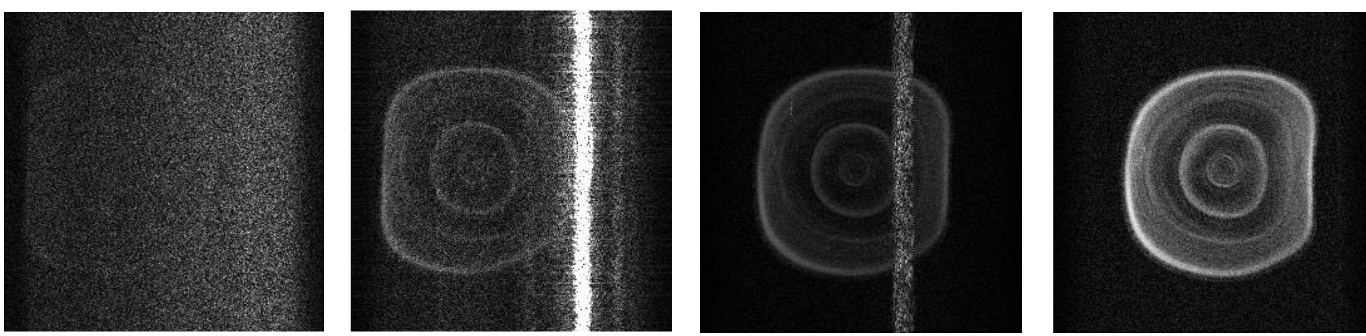
Challenge for MRI of larger trees (>60 mm dia.)



Remote operation using Wireless network

MRI of a tree with a **60 mm diameter** at **0.12 T**.

RF coil and electromagnetic shielding

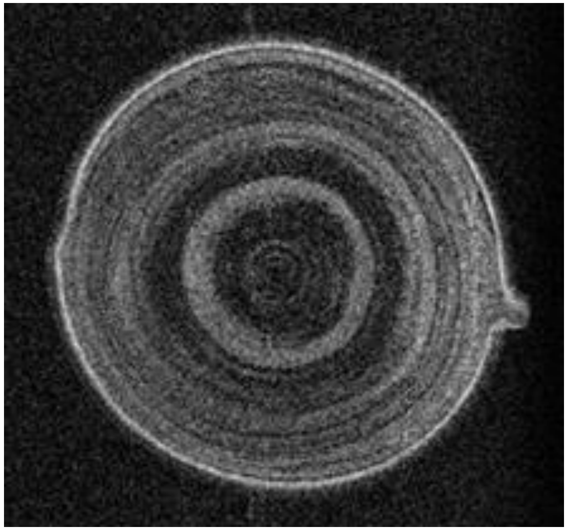


External noise was **absent (switched off)**

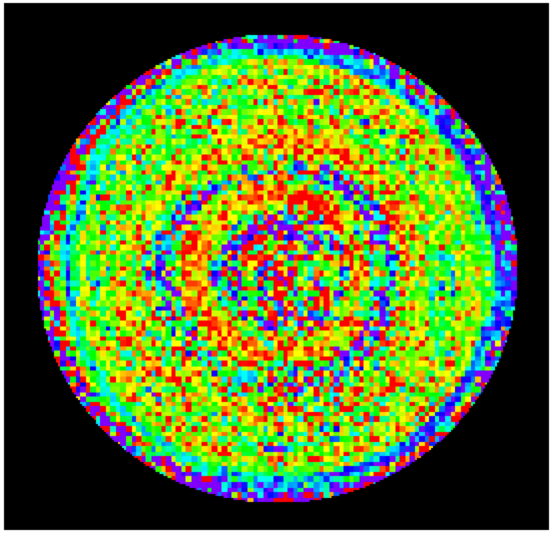
Thickness of Al foil

The RF coil was wound around the tree and shielded with aluminum foils. This technique is **effective for most external noise** but ineffective for powerful one.

PDW image and ADC map at 0.12T



PDW image



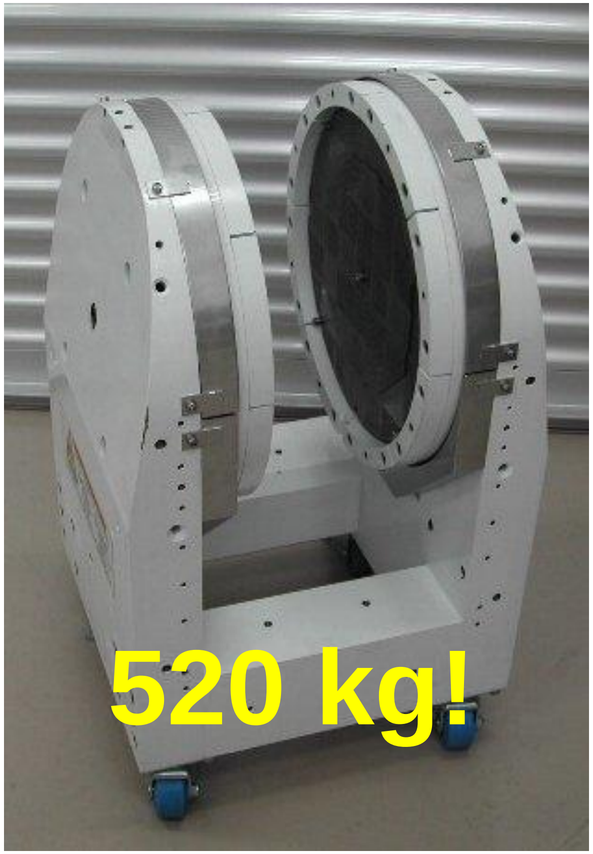
ADC map (parallel to the tree)

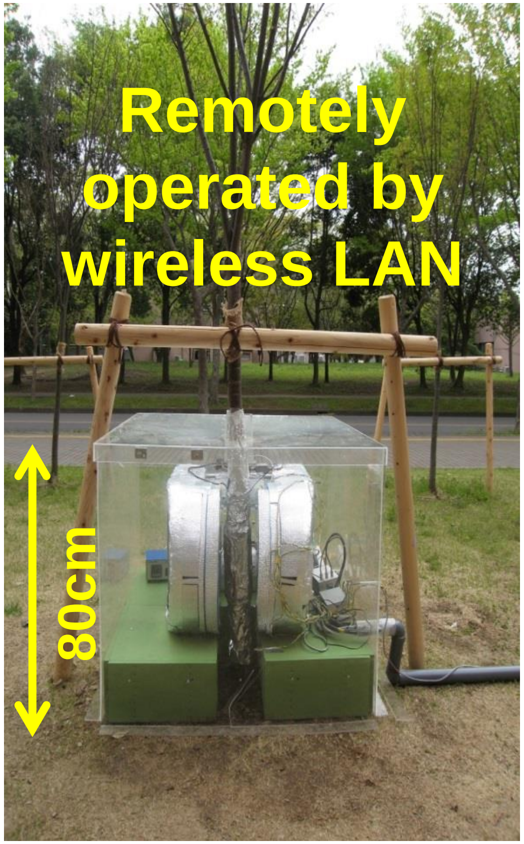
TR/TE = 800ms/20ms
NEX = 1, 256x256x16
FOV $(80\ mm)^3$,Slice 5mm

TR/TE = 800ms/46ms
NEX = 4, 128x128
FOV $(80\ mm)^2$,Slice 30mm

Because the ADC map is measured **in January 2013**, water function was very low. **Much higher SNR is desired!**

Ongoing project : tree measurements at 0.21 T



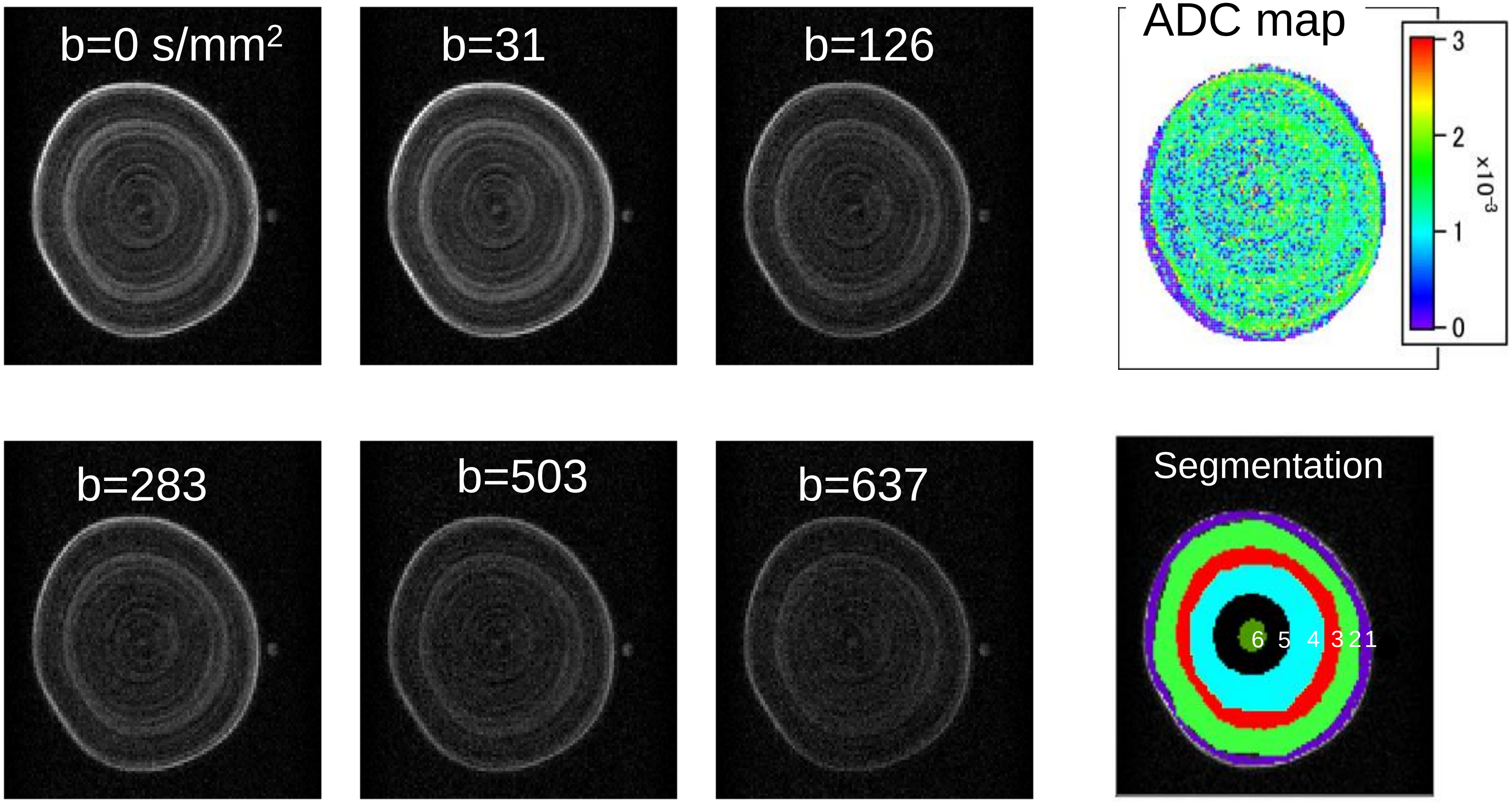


Japanese Zelkova

Field strength: 0.21T, Gap = 16 cm
Homogeneity: 34.6 ppm for $(20cm)^2$ x 12cm dev
Weight: 520 kg (<u>hard to move, but we moved</u>)

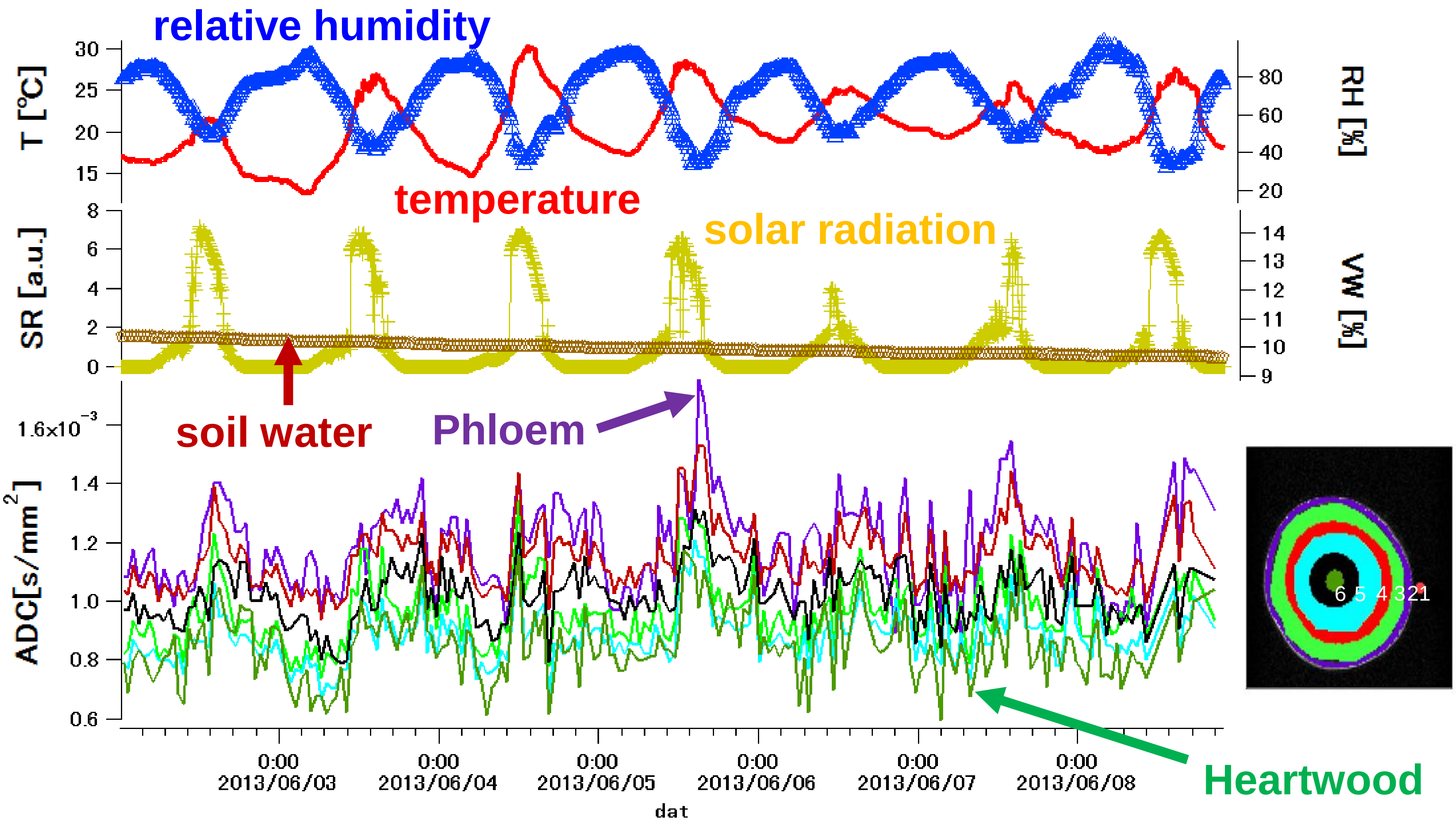
Poster No.79
By Terada et al.

ADC map of the cross section at ~50 cm high



TR = 1200 ms, TE = 50 ms, δ = 18 ms, Δ = 25 ms, matrix = 128 × 128, FOV = 10 cm × 10 cm, slice thickness = 2 cm, NEX = 2, pixel bandwidth = 195 Hz

Long term experiments in the natural condition



ADC map is measured automatically **every 30 minutes** with the climate data.
Water function is not active, but distribution of ADC is correctly measured.

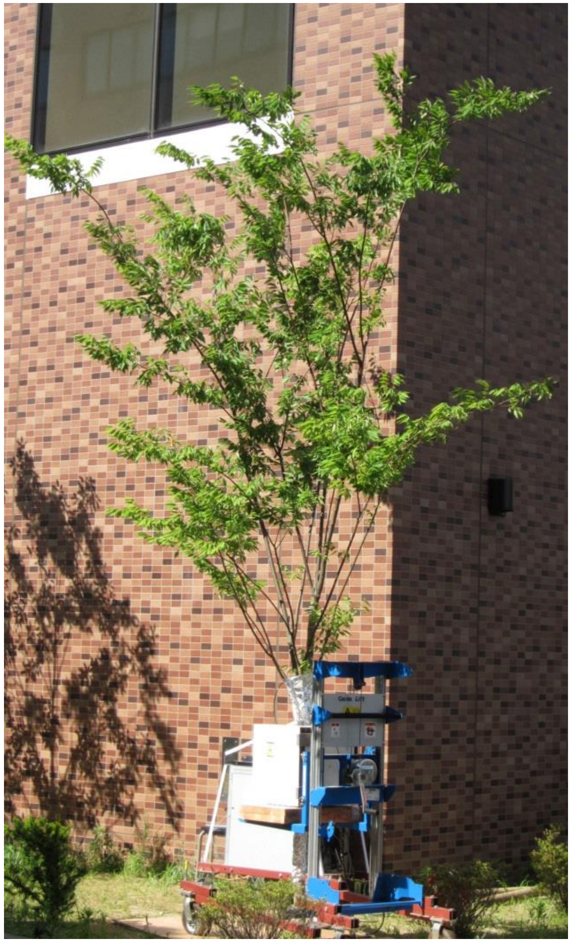
Japanese Zelkova for this year experiments

February 19th, 2013
Tree age is 4 years.

August 23rd, 2013

Because our tree was transplanted in February, the leaves are still small and the water function of the trunk is not so active.

Japanese Zelkova for the last year experiments



The diameter of the trunk is about **85 mm**.

2012: 5~6 years

2013: 6~7 years

Rapidly growing

Our tree will grow to give us better results in future!

Please come to poster No.79.

Conclusion

1. Outdoor plant measurements using compact/portable MRI systems are promising for plant study and evaluation.

2. Permanent magnets, gradient coils, RF coils, and other MRI electronics including computer and wireless communication technology, are essential for the system developments.

Acknowledgements

Prof. Hiroshi Gemma, University of Tsukuba

Dr. Yoshihiko Sekozawa, University of Tsukuba

Mr. Kazuma Togashi, MRTechnology

Graduate students in our laboratory

Ms. Fumi Okada, Mr. Takeshi Kimura

Mr. Daiki Tamada, Mr. Yuto Geya

Mr. Hirotaka Fujisaki, Mr. Atsushi Fukita

Mr. Satoshi Moriwaki

Thank you for attention!