

TECHNICAL REPORT

Applications of a thermal imaging technique in the study of the ascent of sap in woody species

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ABSTRACT

We present applications of infrared thermography to the direct observation of water transport in stems of woody species. Presently, the method gives only qualitative information on the path of sap movement along the stem, and therefore, does not replace any of the common quantitative methods of sap flow measurement. Nevertheless, the thermal imaging technique provides a novel approach to the study of the ascent of sap and could have a role in supporting more quantitative methods. Thermography permits visualization of the thermal variations of a fairly large area of the stem in real time, and hence, is well suited for spatial analysis of sap movement. Three experiments were carried out during the summers of 1991 and 1992, with the following objectives: to define the sap flow distribution in the active annual rings; to identify grain anomalies in the sap wood; and to study the consequences of induced embolism on the path of sap flow. Altogether, we tested more than 10 woody species (broad-leaves and conifers) either in natural conditions or in the nursery. We found considerable differences in the spatial distribution of sap flow not only between species and individuals but also within a single tree. Grain anomalies or embolized zones in the xylem, which are easily demonstrated, often further modify the path of sap flow. The irregularity of sapwood dimensions and of sap flow among tree rings requires careful evaluation of the positioning of the probes when using methods for quantitative measurements.

Key-words: *Populus × interamericana* Bartr.; *Fagus sylvatica* L.; *Abies alba* Miller; *Larix decidua* Miller; *Fraxinus excelsior* L.; *Pinus sylvestris* L.; *Acer pseudoplatanus* L.; *Eucalyptus viminalis* Labill.; infrared thermography; sap flow distribution; grain anomalies; embolism; plant water relations.

INTRODUCTION

The long-distance transport of water in trees is one of the most important problems in tree physiology. Water

ascent can be studied to obtain both quantitative data on sap flow and qualitative information on the path of water movement along the stem.

Quantitative investigations of the global sap flow along the stem have been successfully and extensively carried out in order to estimate transpiration and to study plant water relations in crop and forest plants. The most developed methods are based on the use of heat as a tracer of sap movement, following the work of Huber (1932) and Marshall (1958) who built a sound theoretical foundation for the heat pulse velocity method (HPV). The use of one or more probes to monitor temperature variations of the sap and surrounding xylem allows an accurate estimation of sap velocity (Closs 1958; Cohen, Fuchs & Green 1981) or flow (Čermák, Deml & Penka 1973; Sakuratani 1984; Granier 1985), but is not well suited for a qualitative analysis of the spatial distribution of water ascent in the sapwood. In the case presented here, the movement of heated sap in the xylem is sensed through an infrared thermography system that can visualize, in real time, a fairly large area of the xylem adjacent to the heating element. This novel application of thermal imaging techniques can be used in qualitative studies on the path of sap movement along stems, and could have a role in supporting some methods of quantitative investigation.

This paper presents three experimental applications of infrared thermography with the following research objectives: to define the sap flow distribution in the active annual rings, to identify grain anomalies in the sap wood, and to study the consequences of induced embolism on the path of sap flow.

MATERIALS AND METHODS

Experiments were carried out during the summers 1991 and 1992 in various locations of the Eastern Alps and of the Central Apennines.

The apparatus used in the experiments consisted of:

- (1) a thermocamera (TTC) (AGA 782, AGA THERMOVISION, Sweden) with a 20° field of view with 2 milliradian resolution, an 8–14 µm

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- spectral response, nitrogen-cooled sensor, and a 5° selected thermal range with 128 grey levels;
- (2) a videotape recorder (VTR) connected to the TTC in order to record its analog output signal 'on line', for later processing 'off line' on a personal computer (PC);
- (3) a 220-V, 50-Hz voltage, generated by a 12-V, battery-powered inverter, to supply the VTR and a regulated DC voltage source set between 0.5- and 15-V continuous range for the heaters;
- (4) a heating probe consisting of a 0.2-mm-diameter nichrome wire wound on a 1.5-mm-diameter glass tube, insulated by a coat of varnish, and inserted into a brass tube 3 mm in diameter and 3 cm long (used in experiment 2);
- (5) a thin (0.3 mm) nichrome wire used in experiments 1 and 3; and
- (6) a shielding external structure to prevent wind and direct sunlight from affecting the infrared readings.

Experiment 1

In order to visualize the spatial distribution of sap flow in a continuous longitudinal section of the xylem, it was necessary to expose the xylem by carving away a portion of the stem 25 cm long at breast height. The surface of the section was cut parallel to the stem axis, and was smoothed and levelled; the wound was sprayed with silicon grease to prevent the exposed tissues from drying out. The carving took about 2 h for a tree of 25 cm diameter at breast height (DBH). Undoubtedly, such a wound could have an influence on the velocity of sap ascent, but some of our observations show that the spatial distribution of sap movement and the relative contributions of annual rings to the total transport are not qualitatively modified in a substantial way.

A segment of nichrome wire was placed along the section in a tiny cut near its base. The cut (about 1–1.5 mm deep) had two purposes: to create a lodging for the wire that could be filled with a conductive silicon paste, securing an even contact of the wire to the surface throughout the section; and to allow contact of the wire with a layer of the xylem that was not damaged by the carving (1–2 mm below the cut surface). The thin, superficial layer of damaged xylem does not interfere with the reading since the thermal conductivity of wood allows the conduction of the heat from the sap to the cut surface.

The wire was heated with 1.5 A constant current: the voltage and power varied according to the previously measured length of the wire.

The camera was placed on a tripod at a distance of about 50 cm in order to allow the whole section to be focused in the recording frame, and to ensure a geometrical resolution of 1 mm. The camera was accurately set perpendicular to the cutting plane.

A two-layered tent was erected to shield both the infrared camera and the carved portion of the trunk

from direct solar radiation and wind (since the xylem temperature should be maintained as uniform as possible).

The experiment consisted of a heating and a cooling phase. The wire was kept heated until a thermal steady state condition was reached (after 10–15 min). Once the power was turned off, the cooling phase began; the experiment was completed when the initial thermal conditions in the sapwood were reattained.

The cooling phase lasted about 5 min, and the entire experiment about 20 min for each tree.

The trees examined were chosen either in a nursery (*Populus × interamericana* Bartr.), or in a natural setting within a plot subjected to a forestry management plan in the Dolomites (Eastern Alps) at 1200 m above sea level (*Fagus sylvatica* L., *Abies alba* Miller, *Larix decidua* Miller, *Fraxinus excelsior* L., *Pinus sylvestris* L. and *Acer pseudoplatanus* L.). The trees had all previously been selected for removal by the local forest authority.

Experiment 2

This experiment was developed to visualise sap movement with a non-disruptive technique. Originally, we intended to devise a system to estimate the rate of sap flow from infrared images, but at the present time we are only able to make relative comparisons of variations in flow during a 24-h cycle (Anfodillo *et al.* 1992). The technique used in the experiment permits clear identification of the orientation of vessels in the xylem. The method was based on heating a small portion of the outermost rings using a probe inserted into the stem from the opposite side. A hole was initially cored in the trunk with a 5-mm-diameter increment borer and later bored to the desired depth with a 3.5-mm-diameter power drill equipped with an extension. The depth of penetration was set according to the stem diameter. Since it was essential to preserve the outermost rings of active xylem intact on the side where measuring took place, the hole, initially shorter than the stem diameter, was progressively lengthened until the thermal signal became readable. The thickness of the wood remaining intact did not qualitatively affect the thermal trace.

The hole was thoroughly cleaned from sawdust with a portable vacuum cleaner. The heating power probe (1 W), mounted on an extension, was inserted in the hole, so that the heating element was in contact with the sound xylem. The infrared camera was set up as in experiment 1.

This experiment was done on *Fraxinus excelsior* and *Eucalyptus viminalis* Labill.

Experiment 3

The experiment was done to visualize the influence of an induced embolism on the path of sap in a *Fraxinus excelsior* specimen. This method was based on heating a

large area of the outermost sapwood ring which had been exposed by carefully removing the bark without damaging the xylem. The nichrome wire (approximately 1 m long) was placed around the de-barked stem in a spiral to heat four parallel segments of the xylem, regularly spaced 8–11 cm apart, and 12 W of power were supplied for 30 s. The infrared camera was positioned as in experiment 1 and the cooling phase was recorded.

The experiment was repeated following the interruption of sap flow in a small portion of the outermost ring. This was obtained by making a 2 cm wide and 5 mm deep cut with a chisel at the base of the debarked area in the centre of the stem.

RESULTS AND DISCUSSION

Thermography permits high-resolution detection and visual recording of surface temperature variations. Thermal zones with the same temperatures are identified by the same tone of grey. The grey scale can later be converted into conventional colours on a PC in order to allow an easier interpretation.

In our experiments, when the heating element was turned on, the temperature of the sap in the adjacent xylem was raised, and by recording the surface temperature of the stem, we were able to display the ascent of the heated sap. The xylem cooling pattern further demonstrated the sap flow when the heating element was turned off.

Experiment 1

Figure 1a shows a thermal image taken during the heating phase whilst there was a high transpiration rate (1000 h, September 1991) in a 5-year-old specimen. The heat diffusion recorded clearly shows that the sap flow was concentrated in the three outermost annual rings (each annual ring appears twice in the section clearly defined by two symmetrical peaks). The rate of water transport decreased quite strongly towards the centre of the stem, and sap flow was negligible in the two oldest rings, which appeared to have completely lost their function. Such a regular and symmetrical flow pattern was only found in this nursery-grown, diffuse porous specimen.

The cooling phase was important in those experiments done on ring porous species, where the currently used heating system did not lead to well-defined peaks in the thermal image during high rates of water transport. In these species (Fig. 1b), only the area immediately adjacent to the wire appears heated during the heating phase in the thermal image because the temperature of the rapidly flowing sap could not be raised sufficiently, and indeed, the sap cooled off to the initial temperature at a very short distance from the heater. On the other hand, maintaining constant heating power in every experiment allowed us to compare the thermograms.

Moreover, the temperature of the heating wire should be kept as low as possible to avoid damage to the xylem. None the less, two small cooler indentations in the heated area highlight the active annual ring.

The indentations are more evident in the cooling phase (Fig. 1c), clearly identifying the path of sap ascent. In readings taken at sunset, when the sap flow decreased, the thermogram shows two discernible peaks during the heating phase, even in ring porous species (Fig. 1d).

Our observations suggest that thermograms can give a realistic display of the spatial distribution of sap ascent, even though a portion of the stem has been removed. Indeed, repeating the readings after considerable modification of the cut surface did not change the pattern of movement; furthermore, relative sap flow remained unchanged even one month after the cut was made.

We have compared many individuals of different species (conifers and broad-leaf deciduous trees grown in natural conditions), and most of them have shown a particular spatial distribution of sap movement. These differences were particularly pronounced in diffuse-porous species and conifers.

For example, Fig. 2a shows that in a 70-year-old, 16 cm diameter at breast height (DBH) *Picea abies*, the thickness of the conductive xylem appears to be quite different on the southern (right in the picture) and on the northern sides of the tree (left in the picture). The pattern of sap flow is demonstrated well not only by the height of the thermal peaks above the wire, but also by the shape of the heated area below. In a 35-year-old, 18 cm DBH, *Larix decidua*, we found that all the rings in the sapwood transported sap, but that the relative flow was not evenly distributed (Fig. 2b). In a 200-year-old, 32 cm DBH *Abies alba*, water transporting sapwood included about 50 annual rings. However, the distribution of sap flow was clearly asymmetrical across the section. One side of the tree, which was characterized by thicker annual rings, showed a linear decrease in sap flow towards the centre; the other side showed two areas of intense flow, separated by a much less active zone (Fig. 2c).

In an 85-year-old, 18.5 cm DBH *Fagus sylvatica*, irregularity of transport along the section is very evident (Fig. 2d).

In a 40-year-old, 14 cm DBH *Acer pseudoplatanus*, all the annual rings appeared to conduct, even though they showed different sap flow rates (Fig. 3a). *Pinus sylvestris* was the only species that exhibited constant flow rate across the sapwood. The image shows that flow suddenly stops where heartwood begins (Fig. 3b).

In the ring-porous species that we tested [*Fraxinus excelsior* (Fig. 1b, c, d), *Robinia pseudoacacia* L., *Quercus petraea* Lieblein and *Quercus cerris* L.], sap flow was strictly confined to the last annual ring.

A system to visualize the relative distribution of sap flow in the xylem on an intact tree has not yet been developed. Although there are obvious limitations to

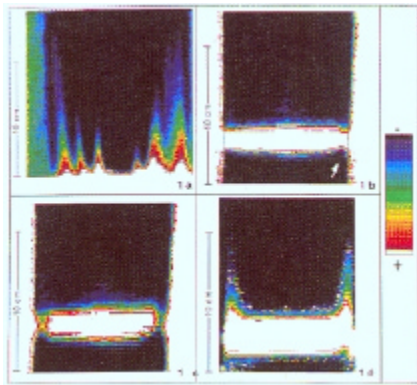


Figure 1. Experiment 1: (a) Heating phase in *Populus × interamericana* Batr. (b) Heating phase in *Fraxinus excelsior* L. taken at 1100h in July with the tree undergoing high transpiration. The arrow points out the cooling of the wire due to the transport in the active xylem. (c) Cooling phase in *Fraxinus excelsior* L. (conditions as above). (d) Heating phase in *Fraxinus excelsior* L. taken at 1900h in July with the tree undergoing low transpiration.

the more general application of our system in sap flow studies at the present time, these observations show that thermography could be a useful tool in calibrating some of the classic sap flow measuring methods.

The differences in distribution of sap flow within the xylem and the variability in the thickness of active sapwood—not only between species and individuals but also within a single tree—need to be considered when using sap-flow-rate measurement systems based on either single or multiple heat probes.

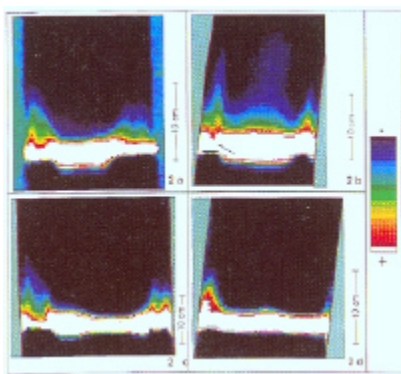


Figure 2. Experiment 1: (a) Heating phase in 16cm DBH *Picea abies* (L.) Karst. at noon in July. Although the thickness of the active xylem was evidently different, the sapwood included 33 annual rings on both sides. (b) Heating phase in *Larix decidua* Miller at 1900h in July. The active sapwood included 15 annual rings. The arrow points out the area, very close to the heartwood, where most of the transport took place. (c) Heating phase in *Abies alba* Miller at 2100h in July. (d) Heating phase in *Fagus sylvatica* L. at noon. The flow was much higher in the southern side of the stem (left in the picture).

Experiment 2

Figure 3c shows the droplet shaped thermograms obtained in a 22cm DBH *Fraxinus excelsior* (I) and a 25cm DBH *Eucalyptus viminalis* (II). They clearly show that in the former the sap flowed straight up while in the latter it flowed at an angle (approximately 10° from the axial direction), presumably as a result of spiral grain which is not infrequent in *Eucalyptus*.

It is known that spiral grain rather than straight growth can be considered a normal growth pattern in many hardwood and softwood species (Panshin & Zeeuw 1980). Therefore, methods for the measurement of sap velocity, such as the HPV method, require careful positioning of the probes if the entire circumference is not sampled. Thermal imaging can be useful in identifying the specific growth pattern of single trees in a non-disruptive way.

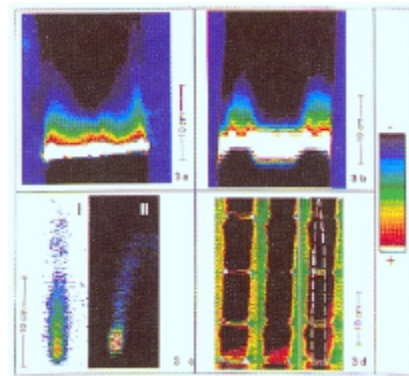


Figure 3. Experiment 1: Heating phase in *Acer pseudoplatanus* L. at 1100 h. (b) Experiment 1: Heating phase in a 70-year-old, 17cm DBH *Pinus sylvestris* L. at 1500h. (c) Experiment 2: Heating phase in (I) *Fraxinus excelsior* L. and (II) *Eucalyptus viminalis* Labill.; the direction of the thermal trace shows the orientation of vessels. (d) Experiment 3: Heating phase in intact xylem (left), and cooling phase in intact xylem (centre) and after a cut was made (right).

Experiment 3

Figure 3d shows three thermograms taken in a 5.5cm DBH *Fraxinus excelsior* before and after the pattern of flow was interrupted by a cut in the xylem. The four parallel segments of wire are very evident in the left thermogram, recorded during the heating phase. In the central thermogram, which displays the cooling phase on the intact stem (5s after the heater was turned off), the simultaneous cooling of the wire segments is clearly shown. After the cut was made, the cooling phase showed a quite different pattern (the right thermogram): the area immediately above the cut cooled down very slowly, since the sap flow had been interrupted. The reversed V-shape of the thermogram clearly shows how the sap flow gradually resumed around the entire ring above the cut. In Fig. 3d (right), the embolised zone is

outlined by two dotted lines superimposed on the thermal image.

CONCLUSIONS

Our observations suggest that infrared thermography can be used in the *qualitative* analysis of sap flow patterns in woody species. We are presently working on the application of this technique to the *quantitative* analysis of sap flow. In ring-porous species, where sap flow is confined in the last annual ring, a method such as described in experiment 2 appears to be promising. A further step could be the development of a system allowing the heating of the sap in an undisturbed stem.

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