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# Generating fuzzy rules by learning from olive tree transpiration measurement – An algorithm to automatize *Granier* sap flow data analysis

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ABSTRACT

The present study aims at developing an intelligent system of automating data analysis and prediction embedded in a fuzzy logic algorithm (FAUSY) to capture the relationship between environmental variables and sap flow measurements (*Granier* method). Environmental thermal gradients often interfere with *Granier* sap flow measurements since this method uses heat as a tracer, thus introducing a bias in transpiration flux calculation. The FAUSY algorithm is applied to solve measurement problems and provides an approximate and yet effective way of finding the relationship between the environmental variables and the natural temperature gradient (NTG), which is too complex or too ill-defined for precise mathematical analysis. In the process, FAUSY extracts the relationships from a set of input–output environmental observations, thus general directions for algorithm-based machine learning in fuzzy systems are outlined. Through an iterative procedure, the algorithm plays with the learning or forecasting via a simulated model. After a series of error control iterations, the outcome of the algorithm may become highly refined and be able to evolve into a more formal structure of rules, facilitating the automation of *Granier* sap flow data analysis. The system presented herein simulates the occurrence of NTG with reasonable accuracy, with an average residual error of 2.53% for sap flux rate, when compared to data processing performed in the usual way. For practical applications, this is an acceptable margin of error given that FAUSY could correct NTG errors up to an average of 76% of the normal manual correction process. In this sense, FAUSY provides a powerful and flexible way of establishing the relationships between the environment and NTG occurrences.



## 1. Introduction

The need for improved irrigation management and better understanding of plant water relations led to the development of several methods for estimating water flow in plant stems. The whole plant transpiration can be estimated by sap flow measurement methods. The heat dissipation method is one of those methods that performs a direct measurement in a trunk section using simple physical principles. This method is often identified as the *Granier* method (Granier, 1985; Lu et al., 2004; González-Altozano et al., 2008).

The *Granier* method bases upon the heat flux provided by means of an adjustable source of electrical energy and constant power through a probe inserted in the trunk, which is correlated to the heat removed by sap flow. For this purpose, two probes are used to determine the temperature difference ($\Delta T$, [°C]) between the upper heating point and an unheated probe placed in a lower point. The $\Delta T$ value is introduced into the equation:

$$k = (\Delta T_{max} - \Delta T)/\Delta T \quad (1)$$

where $\Delta T_{max}$ is the maximum value of $\Delta T$ and $k$ is the flux index. The flux is calculated from $k$ with a relationship admitted to be species independent (Granier, 1985; Granier et al., 1990; Valancogne and Granier, 1997) based on empirical calibrations:

$$u = 118.99 \times 10^{-6} k^{1.231} \quad (2)$$

where $u$ is the sap flux density [$m^3\ m^{-2}\ s^{-1}$]. On a daily course, the maximum temperature difference $\Delta T_{max}$ between both probes in a sensor indicates the minimum or null sap flux rate for that specific day. The sap flux $F$ [$m^3\ s^{-1}$] can be calculated as:

$$F = u \cdot A \quad (3)$$

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**Nomenclature**

| | |
|---|---|
| $A$ | area of the conducting xylem section ($m^2$) |
| $a_j$, $b_j$ and $c_j$ | parameters of a triangular membership function for the $j_{th}$ FS |
| DOY | day of year |
| $e$ | event |
| $ET_o$ | reference evapotranspiration |
| $F$ | sap flux ($m^3\ s^{-1}$) |
| $F_{adj}$ | adjusted sap flux ($m^3\ s^{-1}$) |
| $f_c$ | fraction of ground covered by vegetation |
| $F_{na}$ | not adjusted sap flux ($m^3\ s^{-1}$) |
| $F_{pred}$ | predicted sap flux ($m^3\ s^{-1}$) |
| $FS_j$ | fuzzy set |
| FV | explicative fuzzy variables |
| $f_w$ | fraction of soil surface wetted by irrigation |
| $f_{\Delta j}$ | triangular membership function |
| GN | reference sensor |
| $k$ | flux index (Granier coefficient) |
| $k_{adj}$ | adjusted flux index (Granier coefficient) |
| $k_{na}$ | not adjusted flux index (Granier coefficient) |
| $k_{pred}$ | predicted flux index (Granier coefficient) |
| MSE | mean square error |
| $n_{fr}$ | number of fuzzy regions |
| $NTG_{pred(t)}$ | NTG predicted via algorithm at $t$ time (°C) |
| NTG | natural temperature gradient (°C) |
| $NTG_{obs(t)}$ | observed temperature difference of GN at $t$ time (°C) |
| PFC | the percentage of FAUSY contribution (%) |
| RE | residual error |
| $RE_f$ | residual error of sap flux predicted ($m^3\ s^{-1}$) |
| $RE_{na}$ | residual error of sap flux not adjusted ($m^3\ s^{-1}$) |
| $RH$ | relative humidity (%) |
| $R_s$ | solar radiation ($W\ m^{-2}$) |
| $t$ | time variable. |
| Time | fraction of day (1/48, 12/48, ..., 48/48)) variable |
| $u$ | sap flux density ($m^3\ m^{-2}\ s^{-1}$) |
| $u_{ad}$ | adjusted sap flux density ($m^3\ m^{-2}\ s^{-1}$) |
| UD | universe of discourse |
| $u_{na}$ | not adjusted sap flux density ($m^3\ m^{-2}\ s^{-1}$) |
| $u_{pred}$ | predicted sap flux density ($m^3\ m^{-2}\ s^{-1}$) |
| Vd | the output relative to each event $e$ |
| $x$ | actual value of a variable |
| $x_{max}$ | maximum normalized value of a variable |
| $x_{min}$ | minimum normalized value of a variable |
| $x_n$ | normalized value of a variable |
| $\Delta T_{na(t)}$ | not adjusted temperature difference at $t$ time (°C) |
| $\Delta T$ | temperature difference (°C) |
| $\Delta T_{(t)}$ | temperature difference at $t$ time (°C) |
| $\Delta T_{adj(t)}$ | adjusted temperature difference at $t$ time (°C) |
| $\Delta T_{max}$ | maximum temperature difference (°C) |
| $\Delta T_{max\_adj}$ | maximum adjusted temperature difference (°C) |
| $\Delta T_{max\_na}$ | maximum not adjusted temperature difference (°C) |
| $\Delta T_{pred(t)}$ | predicted temperature difference at $t$ time (°C) |

where $A$ is the area [$m^2$] of the conducting xylem section. This method has been successfully used in numerous studies, including in Portugal (Ferreira et al., 2004; Silva et al., 2008; Paço et al., 2009, 2012).

In theory, the *Granier* method is functional and measurements are easily automated. However, it requires heavy data processing and analysis for its systematic use while these tasks are difficult to automate (Do and Rocheteau, 2002a; Bush et al., 2010) since they require frequent user intervention. Beyond, it is assumed that the temperature measurements are not changed by the occurrence of natural temperature gradients (NTG, [°C]) in the trunk. Nonetheless, a NTG occurrence is easily verified by turning off the probe heating. The NTG are most likely originated by factors such as the azimuth of the probes inserted into the trunk, the distance between probes and the effect of radiation, soil and air temperature in the vicinity of the trunk. The variations of the $\Delta T$ circadian curve induced by the NTG contribute to errors in $\Delta T_{max}$ and consequently in sap flux calculation since the error is propagated to $k$. These errors are difficult to be detected and corrected in automatic calculus (Lu et al., 2004; Allen et al., 2011); thus, the process frequently needs a human decision, which constitutes an obstacle to automation. This is particularly pertinent for long temporal series.

Correction techniques for *Granier* sap flow measurements have been applied in order to eliminate or reduce inaccuracy introduced by NTG (Lundblad et al., 2001; Regalado and Ritter, 2007). Two general methodologies are referred in literature: the shutdown of the heating probe during specific periods (Lundblad et al., 2001; Do and Rocheteau, 2002a; Silva et al., 2008) and the use of unheated probes specifically for this purpose (Köstner et al., 1998). Cabibel and Do (1991) proposed a more elaborated correction method, which involves correlations between natural gradients for each probe and micrometeorological measurements. A temperature measurement close to the heated and unheated points, but apart enough to avoid any interference with the heat source, can also be performed as a proxy to infer NTG (Cermák and Kucera, 1981). However, this is not exact information since the measurement points do not coincide. The correction methods mentioned above are usually adequate to specific applications, but do not provide a universal adjustment. The NTG is spatial and temporally variable, not only changing among different trees but also when different sensor installations are used in the same tree. The alternative of combining switched on and switched off sensors to remove NTG bias is limited because it requires that the NTG variability around the trunk is negligible, which is occasional in practice, and that the heating sensor does not affect the NTG occurrences, meaning that the method is restricted to large trees only (Lu et al., 2004). Do and Rocheteau (2002b) tested a new measurement approach employing cyclic heating just in particular situations, where significant natural temperature gradients (NTG > 0.2 °C) are expected and the residual error is possibly diluted. Beyond that, this solution delivers a lower time resolution, needs more expensive equipment to provide for cyclic heating and makes the system far more complex. Additionally, Lubczynski et al. (2012) concluded that the cyclic method in its current state of implementation is not yet optimized with respect to species and variability of environmental conditions, and that data processing is also not fully automated.

Recently, Vandegehuchte and Steppe (2013) reported the *Granier* method as being the most cited concerning NTG occurrence, contrarily to other methods where the influence of NTG on measurements has not been reported yet (e.g., heat field deformation method, Nadezhdina et al., 1998, 2012), although it is expected to be smaller, given the shorter distances to the heat source. Corrections have also been suggested for the tissue heat balance (THB) method (Cermák et al., 1973, Kucera et al., 1977) as reported by Köstner et al. (1998) but Tatarinov et al. (2005) have further