Near-real time detection and monitoring of water stress for sustainable wood production using sap flow and solar radiation in-situ sensors, IoT and geoinformatics.

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Addressing water stress in poplar plantations is critical due to the climate's variable impact on forest health and productivity. This study assesses the potential for near real-time detection and monitoring of water stress in hybrid poplar plantations.
In June 2024, 20 'Raspalje' (*Populus x generosa*) and 20 'I-214' (*Populus x canadensis*) trees were selected in a 10-year-old plantation in Fresno de la Vega, León, Spain. This plantation has experienced varying degrees of water stress since its establishment. Water stress was monitored weekly from June 26th to August 31st, 2024, through growth measurements of the diameter at breast height (DBH) and the assessment of trees' health status (percentage of yellow leaves and defoliation). Additionally, nine eco-physiological sensors, Tree Talkers (TT) were installed on nine trees to record hourly sap flow density and under-canopy solar radiation.
Time series trend analysis of sap flow and solar radiation data revealed significant differences between stressed and non-stressed trees. The trees identified as stressed showed significantly smaller DBH growth and by the end of July >50% yellow leaves and >5% defoliation. The sap flow analysis indicated a significant negative trend in the stressed trees, while no significant trend was observed in the others. The sap flow trends differed significantly between

the stressed and unstressed trees. Solar radiation measurements showed a significant positive trend for the stressed trees, and trends differed significantly between the stressed and unstressed trees. These results demonstrate that near real-time monitoring using sap flow sensors, IoT, and time series analysis is effective for early water stress detection. Solar radiation measurements are also informative but less sensitive in early stages. Such monitoring may improve early detection of stress and allow early adoption of adaptation strategies to enhance the resilience and growth of poplar plantations.

Keywords: Water stress monitoring, IoT, geoinformatics, wood production, poplar, Sap flow monitoring, in-situ sensors, Introduction

1 Introduction

Addressing water stress in poplar plantations is crucial due to increasing climate variability and its impact on forest health and productivity. Different types of forest ecosystems, from tropical to boreal, have different vulnerabilities to water stress. Some tree species are more resilient than others, and changes in species composition can have long-term effects on ecosystem dynamics. Given the importance of forests for carbon sequestration and biodiversity, it is crucial to understand how trees respond to water stress in order to predict the impacts of climate change and select species that are better adapted to it [1, 2].

These issues affect commercial poplar plantations, which cover 7.6 million hectares in China, followed by France (236,000 ha), Turkey (125,000 ha), Spain (105,000 ha), and Italy (101,430 ha). In Castilla y León, there are 44,000 hectares of poplar plantations (1.10% of the regional forested area), and their harvests account for 40% of the economic value of roundwood harvesting, making this the forest species with the highest economic value [3]. This wood has high commercial value and generates high value-added products, such as plywood. One of the main limitations in the poplar wood processing sector is the lack of available raw material.

There is significant variability in water stress resistance among different poplar species and cultivars. For example, cultivars such as I-214 and Kocabey have been shown to be more suitable for water stress conditions, exhibiting less leaf loss and better resistance to fungal diseases compared to other cultivars [4]. However, further research is needed to understand the physiological processes that enable certain clones to better survive water stress conditions. Despite advances in poplar hybridization to improve their quality and productivity, much remains unknown about how drought affects their performance and physiology

[4]. Identifying cultivars that are more suitable for growth in areas with limited water availability is crucial.

In this context, science and technology have a critical role to play in mitigating water stress. Remote sensing and ecophysiological monitoring have emerged as essential tools for assessing the impacts of climate change on forest ecosystems, allowing accurate and real-time assessment of plant water status. These tools are essential for the sustainable management of forest resources in the face of increasing climate change [5, 6].

Previous studies have shown that sap flow density is a reliable indicator of water stress, showing significant correlations with tree diameter growth, especially under water deficit conditions [7]. In this sense, [8] showed that sap flow can replace stomatal conductance in irrigation scheduling and transpiration models, further reinforcing its usefulness as an indicator of plant water status. Furthermore, [9] concluded that monitoring sap flow, along with other indicators such as minimum diameter and daily stem contraction, is an effective way to assess tree transpiration and water status, highlighting the importance of this approach in irrigation management and early detection of water stress.

This work evaluates the possibility to detect and monitor the response to water stress of ‘Raspalje’ (*Populus x generosa*) and ‘I-214’ (*Populus x canadensis*) clones, two of the most planted poplar clones in Spain for wood production, using a near real-time approach and in the early stages, based on sap flow and solar radiation in-situ sensors, Internet of Things (IoT) and geoinformatics.

2 Materials and Methods

2.1 Data gathering

In June 2024, 20 Raspalje poplars and 20 I-214 poplars were selected in a 10-year-old plantation in Fresno de la Vega (León, Spain) (Fig. 1). Since its establishment, this plantation has experienced varying degrees of water stress due to changes in the water table. The effects of water stress were monitored by weekly measurements of diameter at breast height (DBH) growth, recorded from 26 June to 31 August 2024 using permanent tapes marked with vernier scales with a resolution of 0.1 mm. We also recorded the health status of each tree on a weekly basis (% yellow leaves, % defoliation) (Table 1 shows the records for the last weeks of July and August). In the initial health status visual assessment (26th June 2024) none of the trees showed symptoms of water stress.

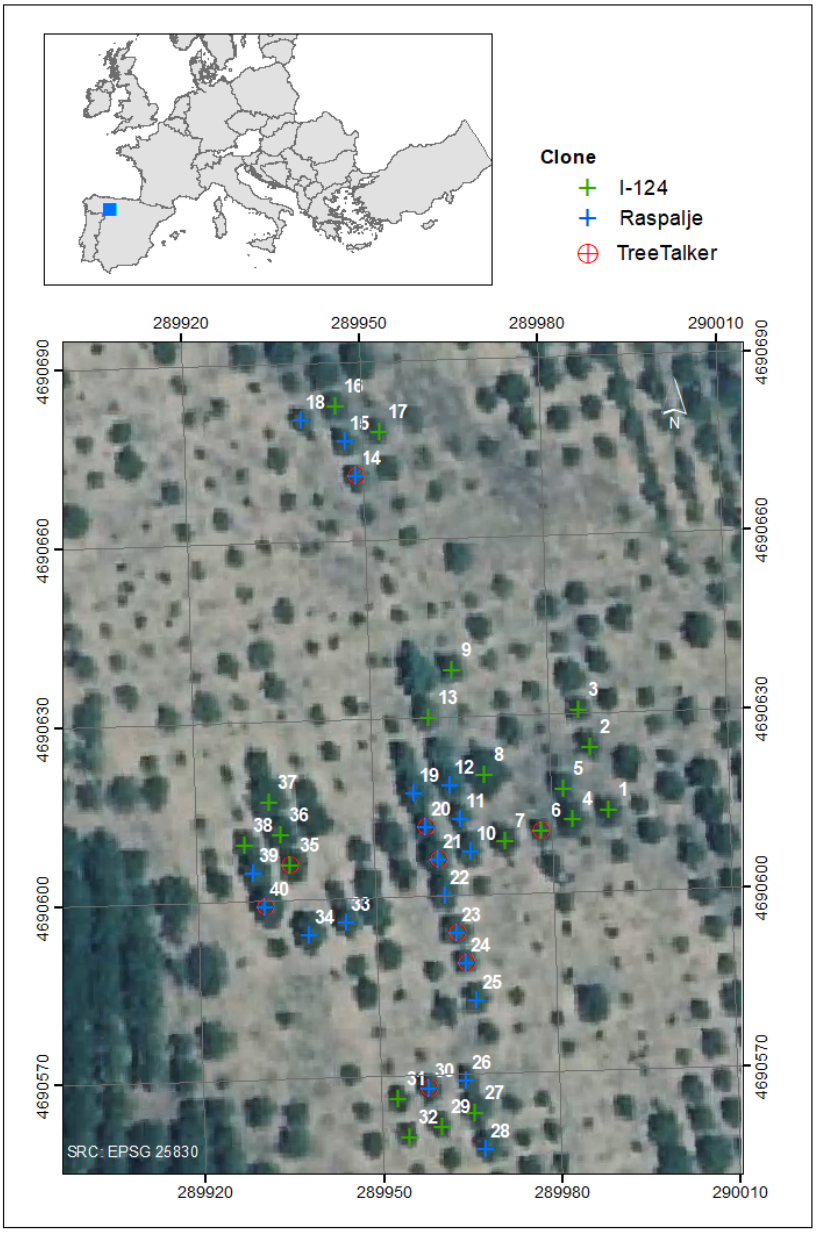

Fig. 1. Location of the field plot and distribution of the monitored trees.

In addition, 9 eco-physiological sensors (Tree Talkers) were installed in nine of the poplars (6 TreeTalker+ version 3.3 (TT+) and 3 TTcyber) (Fig. 1, Fig. 2, Table 1) to record hourly (i) sap flow density and (ii) under-canopy solar radiation in different bands of the electromagnetic spectrum corresponding to each tree. The TT+ were manufactured by the Italian company Nature 4.0. They are IoT devices with microprocessors that work with Arduino 1.8.19 and are based on the ATMEGA328p chip (Atmel Corp). They are equipped with a LoRa transmitter, which allows data transmission to a central portal (gateway) via radio communication. These devices collect information from the trees in which they are installed and transmit it hourly to a receiver/transmitter (TTCloud) via GSM/GPRS technology [6]. The TTcyber devices are a more advanced version of the TT+, also manufactured by Nature, with an NB-IoT connection. All TT+ and TTCyber data can be accessed remotely and in near real-time via an online server [10].

[8].

Fig. 2. Tree talker TT+ and permanent DBH measuring tape placed on one of the monitored trees (right) and TTcloud (with solar panel and GPRS antenna) display in the study plot.

A modification of the code developed by [7], available at https://gitlab.com/erikagarcia96/treetalker, was used to download and process the TT+ data from the server. For the sap flow density, the transient heat dissipation method was used, based on a heating/cooling cycle of 10 minutes per hour, known as the Granier method [11]. Although all TT+ devices are version 3.3, the TTsn 621B039x devices have a different information encoding system to the TTsn 7122900x, so the original code had to be adapted to ensure proper functionality for both types of sensors. In addition to adapting the encoding system, modifications were made to update the formulas related to the electromagnetic radiation received under the canopy in accordance with the latest manuals. The modified code was implemented in a more interactive environment using RMarkdown, designed not only for the study, but also for possible future applications in other plots. This environment allows the results to be exported in HTML format, making visualisation easier. For the TTCyber sensor, code developed by the provider was used.

Sap flow (SF, $l\ dm^{-2}\ h^{-1}$) was calculated for each hour for each tree, but only the values registered between between noon and 4 pm were used in this analysis, since that period should correspond with the maximum in stomatal activity [7] and with when stomatal closure can occur under water deficit conditions

Table 1. Characteristics of the ecophysiological sensor network used in this work. Clone: R: Raspalje, I: I-214, SN: serial number. YL: yellow leaves, LL: leaf loss.

Clone	SN	Model	TT establishment	Health status assessment	
				31/07/2024	28/08/2024
R	621B0397	TT+	25/06/2024	No symptoms	No symptoms
R	71229005	TT+	25/06/2024	No symptoms	No symptoms
R	71229003	TT+	25/06/2024	No symptoms	No symptoms
R	71229002	TT+	25/06/2024	50% YL. 15% LL	70% LL
R	71229006	TT+	25/06/2024	60% YL. 20% LL	70% LL
R	71229008	TT+	25/06/2024	YL (bottom)	YL (bottom)
I	8123A077	TTCyber	27/06/2024	50% YL. 50% LL	75% LL
I	8123A081	TTCyber	15/07/2024	Some YL. 5% LL	20% YL. 35% LL
R	8123A075	TTCyber	15/07/2024	No symptoms	No symptoms

2.2 Statistical analyses

In order to demonstrate that sap flows and solar radiation under the canopy of trees under water stress follow a different trend than those of non-stressed trees, time series trend analyses were performed [12]. We analysed the July and August time series for (i) sap flow, calculated as averages between noon and 4 pm, and (ii) daily total solar radiation (wavelength of 550 nm (±20 nm)). Two types of analyses were performed:

(i) Trend modelling for each tree. We fitted a linear regression model to each individual time series to capture the trend (Ec. 1).

$$\textit{Sap flow} \text{ or } \textit{Radiation} = a + (\beta \times \text{time}) \tag{1}$$

where β represents the slope of the trend. Comparing these slopes between trees provides insight into how trends differ between trees with and without water stress. The null hypothesis was that for sap flow, β would be negative (negative slope) for stressed trees, while for unstressed trees it would be positive or have no trend during the study period as it has been found that lower diameter growth caused by water stress is associated with lower sap flow values [7]. The p statistics were calculated for β to test its significance. For solar radiation, the null hypothesis was that β would be positive (positive slope) for stressed trees, while it would be negative or without trend for non-stressed trees, along the study period (July and August), since leaf loss would increase the amount of radiation reaching the sensor (located on the trunk, under the crown). The t and p statistics were calculated for β to test its significance.

(ii) Comparison of trends. We combined a linear regression analysis and a t-test, creating a categorical variable indicating whether a tree was under water stress or not ('stressed' and 'non-stressed') and fitting a linear regression model for the dependent variables (sap flow or solar radiation) and, as independent variables, the time variable, the grouping variable and the interaction term (time × group). If the interaction term was significant ($p < 0.05$), the trends (slopes) differed significantly between the groups. The t and p statistics were calculated for β to test its significance.

The 9 monitored trees were classified as 'stressed' or 'non-stressed' based on two criteria: (a) water stress symptoms on the crown/leaves (yellow leaves/leaf loss) and (b) weekly DBH growth significantly smaller than the average for the other 39 trees in the plot and. Until July 11th 2024 (inclusive) none of the trees showed water stress symptoms in the crown/leaves. After July 25th, the tree corresponding with SN 71229006 showed 60% of yellow leaves and 20% defoliation, while SN 71229002 showed 50% of yellow leaves and 5% defoliation, and SN 8123A077 had 20% of yellow leaves and a slight leaf loss. By the end of July (Table 1) the three of them showed more severe symptoms, which increased during August. Those three trees had a weekly DBH growth close to 0.00 cm (Fig. 3). We used a one-sample t-test to compare each one of these individual growth values with the average of the other 39 values [13]. The null hypothesis was that the individual value was not significantly different from the mean of the other values. The t-statistic was calculated as (Ec. 2):

$$\frac{\bar{x}-\mu}{\frac{s}{\sqrt{n}}} \tag{2}$$

Where $\bar{x}$ is the value to compare, μ is the mean of the other 39 values, s is the standard deviation, and n is the sample size (39). Previously, we used the Shapiro-Wilk test (n<50) to test data normality, obtaining p-values>0.15, which imply that data can be considered normal and that therefore the t-test can be used to compare DBH growths.

3 Results

3.1 Trees under water deficit stress

The results of the t-test for trees 71229006, 71229002 and 8123A077 showed that their DBH growth each week of July was significantly smaller than the average for the trees in the plot (p<0.01). Thus, those three trees from the sample were classified as 'stressed' for the analysis. Regarding tree 8123A081, at the end of August, it showed as well yellow leaves and leaf loss and the DBH growth was lower than the plot average (Fig. 3), so that was taken into account during the discussion of the results.

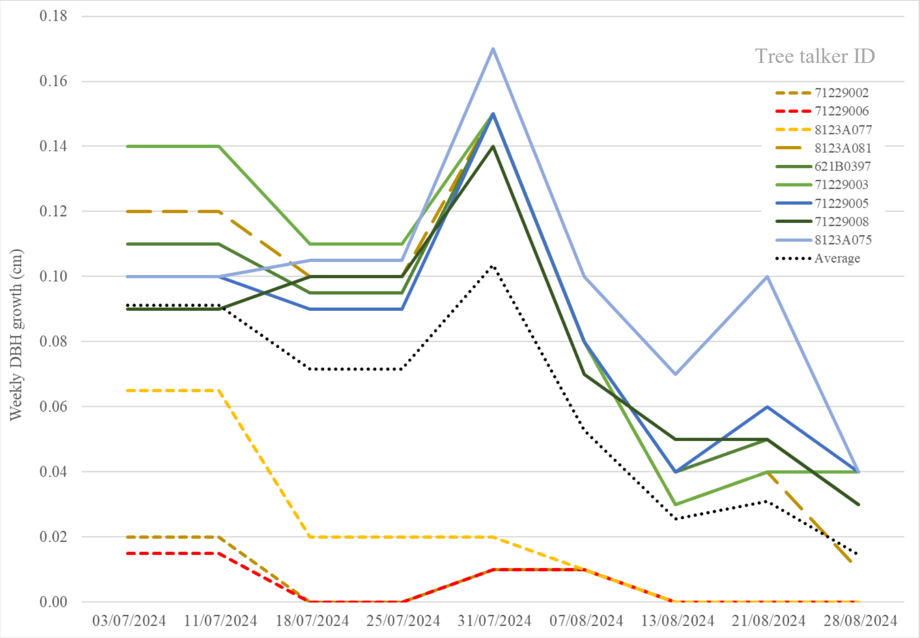

Fig. 3. Weekly DBH growth for each ecophysiologically monitored tree. The black dotted line corresponds to the average growth for the 40 trees under study. Dashed lines correspond to trees classified as "stressed" due to their significantly lower DBH growth or visual assessment (yellow leaves or leaf loss, see Table 1).

3.2 Sap flow to monitor water stress in poplar plantations

The sap flow time series analysis showed a statistically significative negative trend (standardized $\beta<0$; $p<0.001$) for the trees under water stress in July (71229002, 71229006, 8123A077), which involved a decrease in the sap flow during the analyzed period, while for the other trees no significant trend was detected ($p>0.05$) (Table 2). For tree 8123A081, which only showed symptoms of water stress at the end of August, no trend was detected. These results agree with the daily sap flow average values between noon and 4 pm displayed in Fig. 4.

Table 2. Results of the trend analysis for sap flow in July (SFJ) and August (SFA) and solar radiation (SR) for July and August. Independent variable: time. ID: TT serial number; n: number of cases.

Month / ID		71229002	71229006	8123A077	8123A081	71229005	71229003	621B0397	71229008	8123A075
SFJ	β	-0.63	-0.94	-0.89	-0.23	-0.13	-0.007	0.27	0.07	-.16
	p	<0.001	<0.001	<0.001	0.34	0.49	0.97	0.01	0.68	0.53
	n	31	31	16	17	30	31	31	31	17
SFA	β	0.64	-.50	-	-0.53	-0.82	-0.71	0.14	-0.61	-0.50
	p	0.12	0.25	-	0.22	0.02	0.07	0.98	0.14	0.24
	n	8	30	0	31	9	31	22	31	31
SR	β	0.80	0.77	0.70	-0.26	-0.81	0.40	-0.57	0.39	-0.81
	t	10.64	9.23	6.52	-1.79	-10.79	3.32	-4.99	3.27	-10.79
	p	<.001	<.001	<.001	0.079	< .001	0.002	<.001	0.002	<.001
	n	60	60	47	47	61	61	53	61	61

The interaction term 'time × group' was significant ($\beta = 0.36$, $t = 8.5$, $p < 0.001$), so the sap flow trends differed significantly between the stressed and unstressed trees. This difference was registered when using the 3 trees stressed in July and August and when the other tree with visual symptoms at the end of August was included in the analysis. The variable "Time" was not significant in the model ($p>0.05$) and the variable "Group" did not enter in the final linear model. 470 observations were used for this analysis, so the results are robust.

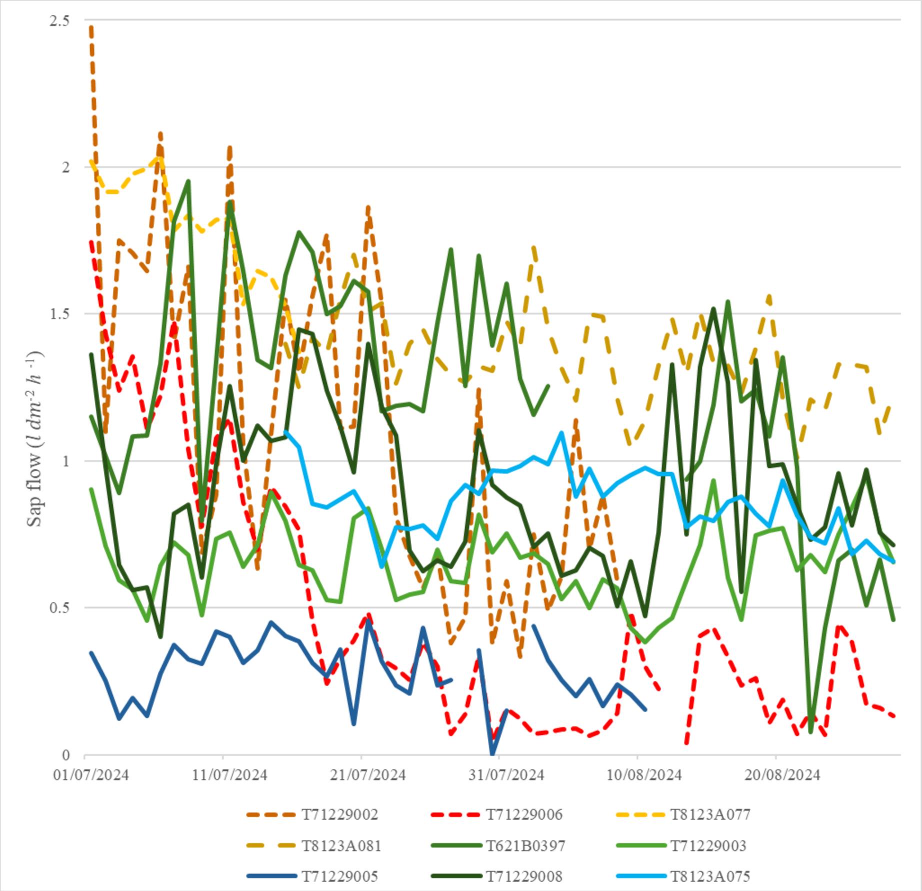

Fig. 4. Daily sap flow averages between noon and 4 pm for each tree. Dashed lines correspond to trees classified as “stressed” due to their significantly lower DBH growth or visual assessment.

3.3 Solar radiation to monitor water stress in poplar plantations

The time series analysis for the daily 550 nm solar radiation received under the canopy showed a statistically significative positive trend (standardized $\beta>0$; $p<0.001$) for the trees with visual symptoms of water stress since July (trees 71229002, 71229006, 8123A077, 71229008), which involved an increase in the light received by the sensor, due to the leaf loss and the change in colour of the leaves (to yellow) (Table 3). For the other trees no trend ($p>0.5$) or a significant decrease ($\beta<0$; $p<0.05$) was found, probably due to a larger amount/size of leaves in the crown and the shorter daylight period. The non stressed tree 71229003 showed a significant but very slight increment of radiation (as $t=3.3$ showed, compared to $t=10.64$ for tree 71229002 (70% leaf loss in August)).

The results of the trend comparison showed that the interaction term ’Time x stress’ was significant ($\beta = 0.67$, $t = 21,15$, $p < 0.001$), so the under the canopy solar radiation trends differed significantly between the stressed and unstressed trees. A significant positive interaction means the stressed trees have a steeper positive trend compared to non-stressed trees. This difference was registered when using the 4 trees with visual symptoms in July and August. The variable “Time” was as well significant in the model ($\beta = 0.15$, $t = 4.80$, $p < 0.001$), but with a lower influence than the interaction ’Time x stress’ (as showed by the lower values of β and t). The variable “Group” did not enter in the final linear model, which means that there was no difference in the radiation between the two groups at the start. 506 observations were used for this analysis, so the results are robust.

4 Discussion

Our findings indicate that sap flow density is a reliable early indicator of water stress. Trees identified as stressed showed significantly reduced sap flow in July, likely due to physiological responses such as stomatal closure or reduced root uptake. These results are in line with previous research where sap flow monitoring has been successfully applied to assess tree water stress in different forest ecosystems [7, 8]. Similarly, [14] found that the decrease in soil moisture content resulted in a linear reduction in sap flow density in four tree species: *Fagus sylvatica, Acer pseudoplatanus, Tilia cordata, and Carpinus betulus.* During a dry period, sap flow density was reduced by between 44% and 31%, reinforcing the idea that sap flow is a reliable indicator of water stress in various tree species. The interaction term 'time × group' in the linear model further confirms that stressed trees follow a distinct sap flow pattern over time compared to non-stressed trees. This finding is particularly relevant for poplar plantations, where early detection of water stress can help forest managers take timely action, such as adjusting irrigation (where possible). Early detection of stress, particularly in poplar plantations, can aid forest managers in timely interventions like adjusting irrigation [9], contributing to the Sustainable Development Goal (SDG) 12 (Responsible Consumption and Production) by promoting efficient water use. By ensuring that water is used wisely, this study supports both sustainable production and the conservation of vital water resources.

Additionally, increased solar radiation under the canopy of stressed trees offers a near-real-time, non-invasive indicator of water stress. The positive trend in light penetration due to canopy thinning through leaf loss reinforces the ability of solar radiation sensors to monitor stress progression. Stressed trees, such as TT 71229002, showed a marked increase in under-canopy radiation as leaf cover decreased, a phenomenon directly related to water stress. However, radiation measurements are less sensitive to detect water stress in early stages, since they are related to leaf loss or changes in the color leaves, symptoms that appear after DBH growth decrease. Similarly to the sap flow results, the interaction term 'time x stress' highlights the significant difference in radiation trends between stressed and unstressed trees, highlighting how canopy thinning due to water stress can be tracked using these sensors. Previous studies have shown that increased radiation penetration through the canopy can indicate reduced leaf area or health, both of which are associated with drought conditions [15]. By providing real-time insights into tree health, this study supports better management of plantation ecosystems, promoting both environmental sustainability and economic resilience (SDG 15, Life on Land) [5].

5 Conclusions)

These findings show that near-real time detection of water stress using sap flow sensors and IoT technology is an effective method for sustainable management of poplar plantations. The results showed that stressed trees had significant reductions in sap flow, providing early and actionable indicators of water stress. Although solar radiation measurements are also useful, they could only detect stress at later stages. This approach enables forest managers to intervene early to optimize water use and minimize long-term tree damage, thereby supporting sustainable timber production and ensuring healthier, faster growing trees.

The integration of advanced sensor technologies, such as IoT-based SAP flow monitoring, is in line with the SDGs, particularly SDG 13 (climate action) and SDG 12 (responsible consumption and production). These technologies provide real-time data on water stress, enabling climate change adaptation strategies for plantations. By promoting the sustainable use of natural resources, they increase the resilience of forest ecosystems to environmental stressors, benefiting the entire poplar value chain, from plantation companies to wood processing industries.

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