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SHORT COMMUNICATION

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# Water consumption and preliminary crop coefficients of two Populus ×canadensis clones ('I-214' and 'I-488') grown at low planting density

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## Abstract

*Aim of study:* The productivity of poplar plantations in Mediterranean climates might be reduced due to lower precipitations in a climate change scenario. Therefore, understanding the water consumption in these plantations is essential for their management. The objective of this study was to estimate water consumption and preliminary crop coefficients (kc) of two universally used poplar clones (Populus x Canadensis 'I-214' and 'I-488').

*Area of study:* Central Chile (36º 05 'LS; 72º 47' LW; 470 m.a.s.l.).

*Materials and methods:* Commercial stands of poplar clones established in 2009 and 2010 at low density (6×6 m) were used to experiment during the 2016-2017 growing season. In each of them, water balance was measuring, by determining evaporation using micro lysimeters and transpiration using the sap flow. Additionally, the water status and the leaf area index (LAI) were measured to understand the behaviour of both clones.

*Main results:* Although the water supplied to both clones was the same, the transpiration (T) was higher for 'I-488' than 'I-214', at those moments in which the evapotranspiration (ETr) and the vapour pressure deficit (VPD) was higher. On the other hand, differences were observed in plant water status, 'I-488' had more negative xilematic water potential (Ψx) compared to 'I-214'. In turn, I-214 proved to have a higher Leaf Area Index (LAI) than I-488 and grew more during the season, refuting its greater efficiency.

*Research highlights:* These results allow characterizing the water behaviour of both clones in Mediterranean climate condition, but it is necessary to extend the study to more seasons and different age ranges.

**Keywords:** Crop coefficient; water consumption; water balance; poplar.

**Authors' contributions:** PCS was in charge of collecting information in the field, analyzing the data and creating the article. FZ, MY, HVG, CE, JG were part of the evaluation commission in charge of the review and improvement of the article. JV, LR were counterpart of the company in which the investigation was carried out, who provided various information and collaborated in carrying out the measurements. CAO was the thesis director of the first author and main reviewer for the final writing of the document.

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# Introduction

Poplar plantations are highly productive in the Mediterranean zone of central Chile (Yáñez *et al.*, 2019; Cañete-Salinas *et al.*, 2019). There is the potential of obtaining roundwood and non-structural wood derivatives with high added value from these plantations, which represents an interesting option for the forestry industries (Marron *et al.*, 2002; Monclus *et al.*, 2006; O'Neill *et al.*, 2010; Sevigne *et al.*, 2011). However, the productivity of poplar plantations may be limited by their high-water consumption (Marron *et al.*, 2003; Monclus *et al.*, 2006; Silim *et al.*, 2009; Sevigne *et al.*, 2011; Xi *et al.*, 2017; Cañete-Salinas *et al.*, 2019). A decrease in rainfall and an increase in extreme temperatures are expected in Mediterranean areas such as central Chile (IPCC, 2019), which will likely impact the productivity and extension of poplar plantations. Therefore, there is an urgent need to optimize the water use of poplar plantations without affecting the growth and wood quality (Monclus *et al.*, 2006; Xi *et al.*, 2017; Cañete Salinas *et al.*, 2019).

The few studies in water use in poplar plantations have been made in natural forests and short rotation coppice systems (SRS) at high-density plantations (Hou *et al.*, 2010; Fischer *et al.*, 2011; Gao *et al.*, 2016; Cañete Salinas *et al.*, 2019). For example, in a mature poplar plantation of 6 to 7 years old in a medium planting density of 833 trees ha$^{-1}$ with a surface drip irrigation system (SRS), Xi *et al.*, (2017) found maximum crop coefficient ($k_c$) values of 1.2 to 1.3. Otherwise, Gochis & Cuenca (2000) found $k_c$ values between 0.2 and 0.8 for poplars at the age of 1 to 3 years growing under SRS, planted 3.04 x 1.22 m (2,687 trees ha$^{-1}$). These values are low, mainly due to the age of the trees, because the peak of leaf growth has not been reached.

The estimation of $k_c$ is a difficult task to perform at field level (Xi *et al.*, 2017). The most common method is the one proposed by Allen *et al.*, (1998), in which $k_c$ corresponds to the ratio between actual evapotranspiration ($ET_a$) and reference evapotranspiration ($ET_r$) (Gochis *et al.*, 2000; Fischer *et al.*, 2011). $ET_a$ is typically obtained by adding the transpiration measured employing sap flow sensors (T) and the loss of soil water through evaporation (Ev), which is measured by micro-lysimeters (Allen *et al.*, 1998). Otherwise, $ET_r$ is calculated through the Penman-Monteith equation using climatic information from automatic weather stations (Allen *et al.*, 1998, Hou *et al.*, 2010, Fischer *et al.*, 2011; Alves *et al.*, 2013).

Besides, to know the water consumption of a species, it is also interesting to know the effect of water consumption on the growth and productivity of the plant (Yin *et al.*, 2005, Monclus *et al.*, 2006). In this sense, we hypothesize that knowing variables such as the Leaf Area Index (LAI), xylematic water potential ($\Psi_x$) and growth in diameter allow finding differences between poplar clones of similar varietal origin and managed under equitable conditions.

To improve the information for water management in poplar plantations, the present work aims to assess the water consumption of poplars established at low planting densities, generating $k_c$ values for two widely used poplar clones.

# Materials and method

## *Study site*

The study was carried out in commercial stands of two of the most planted clones in the Mediterranean area of Chile during one season (2016-2017). The clones belong to *Populus ×canadensis* Moench. (*P. deltoides* × *P. nigra*) (‘I-214’ and ‘I-488’), established by the Company name “Agrícola y Forestal El Álamo”, near the town “Retiro” in the Maule Region, Chile (36º 05 'LS; 72º 47' LW; 470 m.a.s.l). Both clones were established in 2009 and 2010, respectively. The soil was prepared with a disc plough, and the poplars were planted at a density of 6 m x 6 m. Fertilizers were not applied due to the high fertility of the soil (over 10% organic matter). Homogeneous trees in excellent sanitary conditions were selected for the study.

This area has a Mediterranean climate with a prolonged dry season between November and March (Table S1 [suppl.]). The scarce rain in spring and summer months made it necessary to irrigate the poplar stands, which is carried out by a furrow method. This an efficiency between 50 and 70% depending on the water transport system, which for this test is high, due to the use of Californian pipes to transport the water to each groove. According to the amount of water used by the company and the results of Cañete-Salinas *et al.*, (2019), both clones for this trial were well irrigated and did not present stress conditions.

$ET_r$ was estimated using climatic information from an automatic weather station (AWS) (Adcon Telemetría, model A730, Klosterneuburg, Austria) located in reference conditions 2.5 km away from the study site. The AWS measured radiation (W m$^{-2}$), air temperature (°C), relative humidity (h), precipitation (mm), wind speed (km hr$^{-1}$) and direction in 15-minute intervals. $ET_r$ was calculated from this information by using the Penman-Monteith equation (Allen *et al.*, 1998). T was obtained using the sap flow methodology (Tranzflo New Zeland ltda). Sap flow sensors were installed in 4 trees per clone representative of the stand. For this, homogeneous trees (height and average foliar mass) and in excellent sanitary conditions were selected, in which two temperature sensors were installed asymmetrically on and under a heater (Green *et al.*, 2003). Each of these sensors has 3 transmitters located at 5, 10 and 15 mm. Each of the sensors was coated with aluminium foil to avoid the effect of radiation. The sensors delivered information every 15 minutes. Clone ‘I-214’ was measured for 25 days between November and December. Then the same sensors were put in ‘I-488’ for 41 days between January and February. The same sensors were used since the research was a preliminary test, so resources were limited.

$E_v$ was calculated daily using micro-lysimeters located on the irrigation furrows near the selected trees, using a total of 6 devices. The micro lysimeters were constructed with two PVC pipes, the first worked as a soil container, and the second worked as a container to facilitate the extraction of the first one. The container with soil had a mesh in its lower part that allowed the infiltration of water naturally, which was retained in the second recipient, to obtain the real losses by evaporation. The measurement was carried out every day to obtain the daily weight of the wet soil at each point. Then, the differences in weight from one day to the next were transformed to mm of water. It should be noted that soil conditions are homogeneous throughout the stand, having an almost zero slope, with a large percentage of organic matter and soil depths above 80 cm.

$ET_a$ was estimated by the methodology proposed by Allen *et al.*, (1998) by adding T and $E_v$. Finally, for the calculation of the crop coefficient ($k_c$), we used the equation proposed by Allen *et al.*, (1998), where $k_c$ is the ratio between $ET_a$ and $ET_r$.

### *Characterization of water status.*

Furrow irrigation was applied in both stands from November (2016) to March (2017), once or twice per month. The amount of water applied was measured in each of the irrigations carried out during the season using a Parshall-type flume and multiplying the height of the water by a correction factor of 0.2982 (manufacturer's guidelines) to calculate the flow in megaliters per hectare (WFA; ML $ha^{-1}$). The plant water status was monitored by the xylem water potential ($\Psi_x$) using a pressure chamber (PMS Instrument Co., model 1000, Corvallis, Oregon, USA) with the same methodology used by Cañete Salinas *et al.* (2019). Leaf area index (LAI) was measured using a Nikon Coolpix 4300 digital camera with a Nikon FC-E8 hemispherical converter lens (Macfarlane *et al.*, 2007). A tree calliper was used to determine the diameter of the breast-high increments (DBH-I; the difference of DBH between two consecutive measurements). DBH measurements were performed 3 times during the season, that is, in the beginning, at the middle and at the end of season. Finally, a Water Use efficient Index (WUE-I) was calculated as the ratio between the stem diameter increment (measured by a calliper) and the water applied by irrigation.

### *Data Analysis.*

For the statistical analysis, the t-Student test was used, for independent samples, assuming that both transpiration were measured at different times within the same sensors. This test allowed to determine differences between T and $k_c$ between two clones ("I-214" and "I-488"). For the normality of the independent samples, the Shapiro-Wilk test was used. On the other hand, to make a graphical comparison, the $ET_r$ and vapour pressure deficit (VPD) was used as variables that depend on the climatic conditions and cause modifications on the behaviour of T and $k_c$.

## Results and Discussion

As expected, reference $ET_r$ showed the highest values during December and January and lower demand at the beginning of the season (November) and at the end of the season (March) (Fig. 1). This is normal behaviour because this period has the greatest radiative demand in the southern hemisphere. No differences were observed in $E_v$ between both clones (Fig. 1). This may be because both experimental devices were close in the same stand with a similar soil texture and both were irrigated with the same amount of water. Daily tree T of clone 'I-214' remained relatively constant, between 1- and 3-mm $d^{-1}$, even on the days of greatest water demand (Fig. 1). On the other hand, T of 'I-488' showed values higher than 4.5 mm $d^{-1}$ during the first days of January to then reach values like those registered in 'I-214' (Fig. 1). This behaviour is corroborated by t values (Table S2 [suppl.]), showing that T for I-488 is statistically higher than I-214. Finally, $ET_a$, like the previous variables, remained stable for 'I-214' even

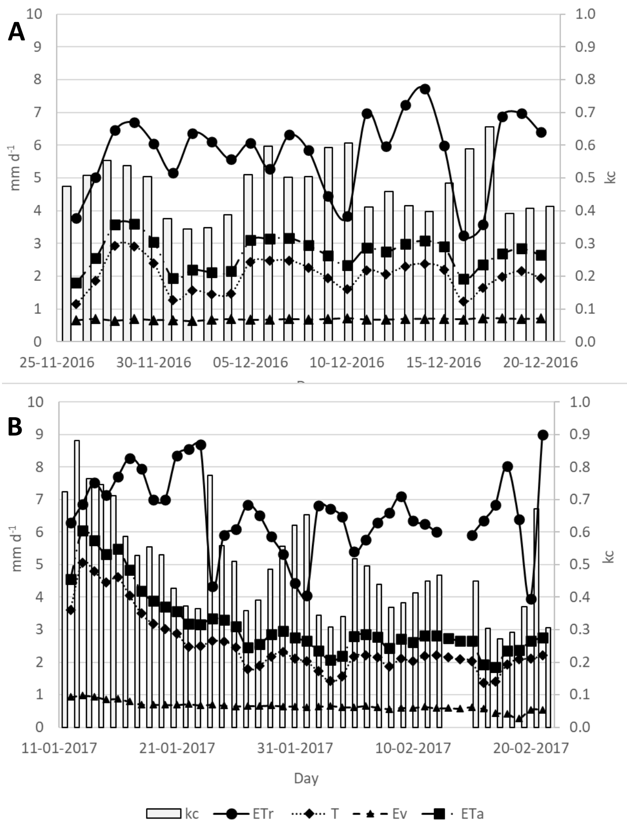


**Figure 1.** Reference evapotranspiration ($ET_r$), transpiration (T), evaporation ($E_v$), actual evapotranspiration ($ET_a$), and crop coefficient ($k_c$), for the clone *Populus ×canadensis* Moench. (*P. deltoides × P. nigra*), 'I-214' (A) and 'I-488' (B).

during the end of December. While for ‘I-488’, it showed a higher value for the first days of January, suggesting the effect of climate demand (Fig. 1).

Regarding $k_c$, the clones showed a different behaviour, thus in ‘I-214’ we observed more stable $k_c$ values than ‘I-488’ (Fig. 1). In this sense, $k_c$ of ‘I-214’ fluctuated within values of 0.3 and 0.6 (Fig. 1). On the other hand, $k_c$ values of ‘I-488’ were higher than 0.7 during the first days of January (high radiation demand). This could be explained by the limited information collected for I-214 (25 days), while for I-488 there was a total of 40 days allowing a better characterization of this variable. This is corroborated by the independent sample test (t-value), which shows no statistical differences between the $k_c$ for both variables, although I-488 is slightly higher (Table S2 [suppl.]).

Although the sample test (t-value) shows differences for T and $k_c$, these may be affected by the climatic conditions that occurred on measurement dates, considering that the data recorded for ‘I-214’ and ‘I-488’ were taken at different times. To solve this, it is necessary to know the behaviour of relevant climatic variables to compare, such as VPD and $ET_r$ (Fig. 2). When the environmental demand is between 6 to 7.8 mm $d^{-1}$, the transpiration of ‘I-214’ does not exceed 3 mm, while that of ‘I-488’ is considerably higher and variable, reaching values above 5 mm. Something similar happens for the evaporative demand of the medium represented by the VPD. When this is between 1 and 1.3 kPa, the transpiration of I-214 does not exceed 3 mm, while for the same range, the transpiration of I-488 is variable and manages to reach values above 5 mm. On the contrary, when $ET_r$ is less than 6 mm $d^{-1}$ and VPD less than 1.3 kPa, no differences are observed between both clones. Therefore, when the environmental conditions are more demanding, ‘I-488’ increases its transpiration to a greater extent, showing to be more sensitive for these types of variations.

To further highlight the differences between both clones, the $\Psi_x$ was studied (Fig. 3). The amount of water applied for both clones was the same, considering some small differences due to the inefficiency of the irrigation system used (furrows). Despite this, the values of $\Psi_x$ indicated that ‘I-488’ always appeared more stressed than ‘I-214’, with differences of 0.2 MPa between both clones (Fig. 3). These differences have already been observed by Cañete Salinas *et al.*, (2019) in experiments with both clones growing under water restriction conditions, showing that ‘I-488’ is more susceptible to lack of water. O’Neill *et al.*, (2010) mentioned that *P. nigra* would grant its descendants a certain tolerance to drought conditions. However, this condition would have been inherited only to clone ‘I-214’. All results mentioned above show that ‘I-214’ not only does it have a better transpiration rate than I-488, but it also looks less stressed.

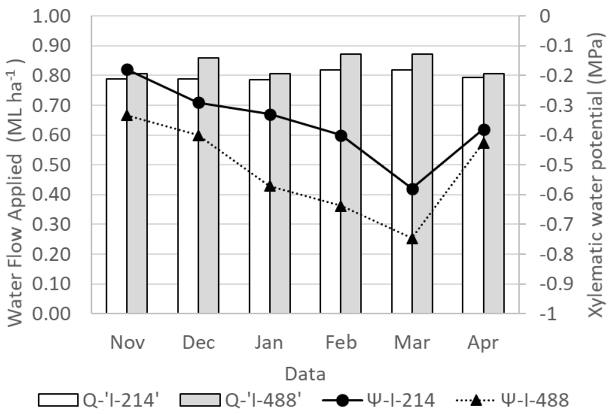


**Figure 3.** Water flow rate per month (Q; $m^3$ $ha^{-1}$) and xylematic water potential ($\Psi_x$; MPa), for two clones of *Populus ×canadensis* Moench. (*P.deltoides × P. nigra*) (‘I-214’ and ‘I-488’).

When comparing the values of $k_c$ obtained in this study with the information collected in the literature, it can be indicated that there are no works carried out in commercial poplar plantations at low densities (6 m x 6 m = 277 trees $ha^{-1}$). As for the existing information, in studies carried out by Xi *et al.*, (2017) in poplar plantations at higher density (833 trees $ha^{-1}$) and five years old, $k_c$ values were observed that exceed the value of 1.0.

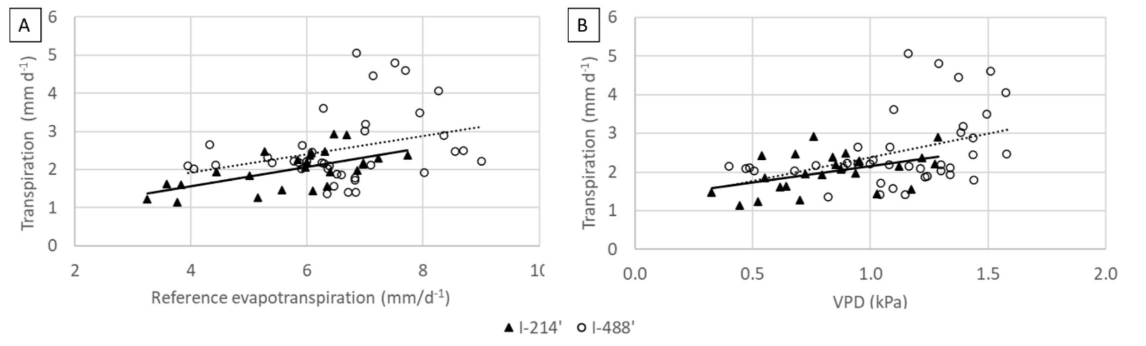


**Figure 2.** A) Relationship between Transpiration and Reference evapotranspiration (ETr) for the clones *Populus ×canadensis* Moench. (*P.deltoides × P. nigra*), ‘I-214’ and ‘I-488’. B) Relationship between Transpiration and Vapour-Pressure Deficit (VPD), for the clones *Populus ×canadensis* Moench. (*P.deltoides × P. nigra*), ‘I-214’ and ‘I-488’.

For similar weather conditions (Mediterranean climates), in Piedmont, Italy, Giovanelli *et al.*, (2007) compared a management situation without irrigation (only contribution by precipitation) and another scenario under irrigation, showing that clone I-214 would be sensitive to lack of water. The $\Psi_x$ values reached were around -0.9 MPa during the period of greatest drought for I-214, which were much higher than those recorded in this trial, where the trees were always kept under irrigation. In turn, the soil moisture, for the management without irrigation, reached 10%, while for our test the lowest was 20% for I-214. Therefore, the conditions of both experiments were different, explaining the dissimilar behaviour for I-214.

To know the water behaviour of different forest species, it is important to know values such as $ET_r$ and $k_c$, but these must be complemented with information such as LAI and increments in growth. The average LAI of both clones during the study season (Table 1), shows that I-214 LAI is higher than I-488. In turn, the growth in diameter (DBH-I) during the season, was double for I-214 and I-488. As previously discussed, I-214 would be more tolerant to adverse conditions in the environment, and it would also be much more efficient, since despite having a higher LAI, it is capable of maintaining a stable water demand concerning the environment and at the same has to maintain high growth rates. Additionally, the WUE-I was calculated, using the amount of water applied through irrigation, concerning the growth in diameter. In this, both clones were applied with similar amounts of water during the season, however I-214, with the same amount of water, was able to grow twice as much (Table 1).

# Conclusions

This study is the first approach towards the determination of kc in commercial poplar clones ‘I-214’ and ‘I-488’ to produce roundwood planted at low density (6 m x 6 m plantation frame). 'I-214' shows a more homogeneous relationship between T, $ET_r$ and VPD, that is, independent of the increase in the climatic demand, the T does not rise in the same proportion. Therefore, 'I-214' would be less demanding for water consumption. On the contrary, 'I-488', at high $ET_r$ and VPD values, shows great variability with high and low T values, that is, it would be more susceptible to changes in atmospheric demand. Additionally, I-214 had a higher LAI, and grew more during the measurement season, proving to be more efficient, achieving twice the growth with the same amount of water applied.

This information should be extended to one or two seasons of continuous measurements and at different age ranges.

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# References

Alves M, Mantovani E, Sediyama G, Neves J. 2013. Estimate of the crop coefficient for Eucalyptus cultivated under irrigation during initial growth. Cerne. 19(2): 247-253. https://doi.org/10.1590/S0104-77602013000200008

Allen R, Pereira L, Raes D, Smith M. 1998. Crop evapotranspiration: guidelines for computing crop water requirements, Irrigation and Drainage Paper 56. United Nations FAO, Rome. http://www.fao.org/docrep/X0490E/X0490E00.htm

Cañete-Salinas P, Zamudio F, Yáñez M, Gyenge J, Valdés H, Espinosa C, Jara-Rojas F, Venegas J, Retamal L, Acevedo-Opazo C. 2019. Responses in growth and physiological traits in two Populus × canadensis clones ('I-214' and 'I-488') submitted to different irrigation frequencies in central Chile. Forest Ecol Manag. 449: 117455. https://doi.org/10.1016/j.foreco.2019.117455

Fischer M, Trnka M, Hlavinka P, Orság M, Kučera J, Žalud Z. 2011. Identifying the Fao-56 crop coefficient for high density poplar Plantation: the role of interception in estimation of Evapotranspiration. Bioclimate: Source and Limit of Social Development International Scientific Conference. Topol'čianky, Slovakia.

Gao G, Zhang X, Yu T. 2016. Evapotranspiration of a Populus euphratica forest during the growing season in an extremely arid region of northwest China using the Shuttleworth-Wallace model. J. For. Res. (2016) 27: 879. https://doi.org/10.1007/s11676-015-0199-5

**Table 1.** Water Flow Applied (WFA; ML $ha^{-1}$), Leaf Area Index (LAI), Diameter of the Breast High Increments (DBH-I; cm), Water Use Efficiency Index (WUE-I; cm $ML^{-1}$), for two clones of *Populus ×canadensis* Moench. (*P.deltoides × P. nigra*) (‘I-214’ and ‘I-488’)

| Clone | WFA (ML $ha^{-1}$) | LAI | DBH-I (cm) | WUE-I (cm $ML^{-1}$) |
|---|---|---|---|---|
| ‘I-214’ | 4.79 | 2.74 | 1.58 | 0. 33 |
| ‘I-488’ | 5.01 | 2.41 | 0.73 | 0.15 |

Giovannelli A, Deslauriers A, Fragnelli G, Scaletti L, Castro G, Rossi S, Crivellaro A. 2007. Evaluation of drought response of two poplar clones (Populus×canadensis Mönch 'I-214' and P. deltoides Marsh. 'Dvina') through high resolution analysis of stem growth. J Experimental Botany. 58: 2673-2683. https://doi.org/10.1093/jxb/erm117

Gochis D, and Cuenca R. 2000. Plant Water Use and Crop Curves for Hybrid Poplars. J Irrigation Drainage Engineering. 126 (4): 206-214. https://doi.org/10.1061/(ASCE)0733-9437(2000)126:4(206)

Green S, Clothier B, Jardine B. 2003. Theory and practical application of heat pulse to measure sap flow. Agron. J. 95: 1371-1379. https://doi.org/10.2134/agronj2003.1371

Hou L, Xiao H, Si J, Xiao S, Zhou M, Yang Y. 2010. Evapotranspiration and crop coefficient of Populus euphratica Oliv forest during the growing season in the extreme arid region northwest China. Agricultural Water Manag. 97(2): 351-356. https://doi.org/10.1016/j.agwat.2009.09.022

Intergovernmental Panel on Climate Change. IPCC. http://www.ipcc.ch

Marron N, Delay D, Petit J, Dreyer E, Kahlem G, Delmotte F, Brignolas F. 2002. Physiological traits of two Populus × euramericana clones, Luisa Avanzo and Dorskamp, during a water stress and re-watering cycle. Tree Physiology. 22: 849-858. https://doi.org/10.1093/treephys/22.12.849

Marron N, Dreyer E, Boudouresque E, Delay D, Petit J, Delmotte F, Brignolas F. 2003. Impact of successive drought and re-watering cycles on growth and specific leaf area of two Populus × canadensis (Moench) clones, 'Dorskamp' and 'Luisa_Avanzo'. Tree Physiology. 23: 1225-1235. https://doi.org/10.1093/treephys/23.18.1225

Monclus R, Dreyer E, Villar M, Delmotte F, Delay D, Petit M, Barbaroux C, Le Thiec D, Bréchet C, Brignolas F. 2006. Impact of drought on productivity and water use efficiency in 29 genotypes of *Populus deltoides x Populus nigra*. New Phytologist. 169: 765-777. https://doi.org/10.1111/j.1469-8137.2005.01630.x

O'Neill M, Shock C, Lombard K, Heyduck R, Feibert E, Smeal D, Arnold R. 2010. Hybrid poplar (Populus ssp.) selections for arid and semi-arid intermountain regions of the western United States. Agroforest Syst. 79: 409-418. https://doi.org/10.1007/s10457-010-9286-y

Sevigne E, Gasol C, Brun F, Rovira L, Pagés J, Camps F, Rieradevall J, Gabarrell X. 2011. Water and energy consumption of Populus spp. bioenergy systems: A case study in Southern Europe. Renewable and Sustainable Energy Reviews. 15(2): 1133-1140. https://doi.org/10.1016/j.rser.2010.11.034

Silim S, Nash R, Reynard D, White B, and Schroeder W. 2009. Leaf gas exchange and water potential responses to drought in nine poplar (Populus spp.) clones with contrasting drought tolerance. Trees. 23: 959-969. https://doi.org/10.1007/s00468-009-0338-8

Xi B, Di N, Wang Y, Duan J, Jia L. 2017. Modeling stand water use response to soil water availability and groundwater level for a mature Populus tomentosa plantation located on the North China Plain. Forest Ecol Manag. 391: 63-74. https://doi.org/10.1016/j.foreco.2017.02.016

Yáñez M, Zamudio F, Espinoza S, Ivković M, Guerra F, Espinosa C, Baettig R. 2019. Genetic variation and growth stability of hybrid poplars in high-density short-rotation coppice stands in central Chile. Biomass and Bioenergy. 120: 84-90. https://doi.org/10.1016/j.biombioe.2018.11.011

Yin C, Wang X, Duan B, Luo J, Li C. 2005. Early growth, dry matter allocation and water use efficiency of two sympatric Populus species as affected by water stress. Environ Experimental Botany. 53: 315-322. https://doi.org/10.1016/j.envexpbot.2004.04.007