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RECOMMENDATION OF SOIL FERTILITY LEVELS FOR WILLOW IN THE SOUTHERN HIGHLANDS OF SANTA CATARINA⁽¹⁾

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SUMMARY

The species *Salix x rubens* is being grown on the Southern Plateau of Santa Catarina since the 1940s, but so far the soil fertility requirements of the crop have not been assessed. This study is the first to evaluate the production profile of willow plantations in this region, based on the modified method of Summer & Farina (1986), for the recommendation of fertility levels for willow. By this method, based on the law of Minimum and of Maximum for willow production for the conditions on the Southern Plateau of Santa Catarina, the following ranges could be recommended: pH: 5.0–6.5; P: 12–89 mg dm⁻³; Mg: 3.2–7.5 mg; Zn: 5.0–8.3 mg dm⁻³; Cu: 0.8–4.6 mg dm⁻³; and Mn: 20–164 mg dm⁻³. The Ca/Mg ratio should be between 1.2 and 2.9. For K and Ca only the lower (sufficiency level), but not the upper threshold (excess) was established, with respectively 114 mg dm⁻³ and 5.3 cmol_c dm⁻³. It was also possible to determine the upper threshold for Al and the Al/Ca ratio, i.e., 1.7 cmol_c dm⁻³ and 0.28, respectively. For maximum yields, the clay in the soil surface layer should be below 320 g dm⁻³.

Index terms: *Salix x rubens*; nutritional diagnosis; cropping system.

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RESUMO: *CLASSES RECOMENDÁVEIS DE FERTILIDADE DO SOLO PARA A PRODUÇÃO DE VIME NO PLANALTO SUL CATARINENSE*

A espécie Salix x rubens é cultivada no Planalto Sul Catarinense desde a década de 1940, porém ainda não estão estabelecidas suas exigências quanto da fertilidade de solo. O presente trabalho é o primeiro a avaliar o perfil produtivo dos vimais dessa região, com a aplicação do método adaptado de Summer & Farina (1986), para a recomendação de fertilidade para o cultivo do vimeiro. Esse método, baseado na Lei do Mínimo e na Lei do Máximo, permitiu estabelecer as seguintes faixas recomendadas para a produção de vime nas condições do Planalto Sul Catarinense: pH – entre 5,0 e 6,5; P – 12 a 89 mg dm⁻³; Mg – entre 3,2 e 7,5; Zn – 5,0 a 8,3 mg dm⁻³; Cu – 0,8 a 4,6 mg dm⁻³; e Mn – 20 a 164 mg dm⁻³. A relação Ca/Mg deve estar entre 1,2 e 2,9. Para o K e o Ca foi possível estabelecer apenas o nível de mínimo, mas não de excesso, respectivamente de 114 mg dm⁻³ e 5,3 cmol_c dm⁻³. Foi possível ainda definir o nível de excesso para Al e para a relação Al/Ca: 1,7 cmol_c dm⁻³ e 0,28, respectivamente. O solo deve apresentar ainda teores de argila na camada superficial inferiores a 320 g dm⁻³ para que a expectativa de produção seja máxima.

Termos de indexação: Salix x Rubens, diagnóstico nutricional, sistema de cultivo.

INTRODUCTION

Since the 1940s or even before, willow has been grown on the Southern Plateau of Santa Catarina, although cultivation for commercial purposes only began in the 1970s (Epagri, 2008). So far, the crop requirements for soil fertility on the Santa Catarina Plateau were not determined. Even in countries where willow cultivation is a tradition, e.g., in the UK, little information on the pH and the nutritional requirements of the commonly used varieties is available (Heaton et al., 2000).

Consequently, cultural practices related to liming and fertilization, planting density, rod length and diameter, soil tillage and others are being used empirically. This may affect the yield, willow quality and longevity of plantations.

The determination of the appropriate nutrient levels in soil and plant tissue is usually based on dose-response curve experiments, testing increasing doses of one or more nutrients (calibration tests) (Raij, 1981). However, these methods are somewhat limited, e.g., experiments have to be carried out with combinations of two or three nutrients together to assess individual responses and interactions between them, with restricted ability to assess other co-called controlled/constant factors or interactions among more than three factors (Sims, 2000; Summer & Farina, 1986).

A graphical method proposed by Cate Jr. & Nelson (1965) separates soils in two classes, i.e., soils with high or low probability response to a particular nutrient. Although the arbitrariness in the definition of these classes can be contained by a

statistical procedure proposed by the same authors (Cate Jr. & Nelson, 1971), the results allow no more than a first approximation (Raij, 1981).

The most commonly used procedure to determine critical nutrient levels in the soil is known as calibration (Raij, 1981). The greatest difficulty in comparing results from different calibration experiments is the interaction between the controlled variables, maintained constant, and the non-controlled with the tested nutrients. Two or more variables interact when their individual influence is modified by the presence, concentration intensity or activity of the other factors. When the joint action of factors results in a growth response that is, for example, greater than the sum of their individual effects, the interaction is positive (synergic), when it is lower than the sum of individual effects, the interaction is negative (antagonistic). When the sum of the individual effects of factors is similar to the combined action there is no interaction (Summer & Farina, 1986; Wilkinson et al., 2000). This process, however, requires extensive experimentation. Thus, when there is little or no information about the fertility requirement of a crop, the search for alternatives to determine the critical levels becomes challenging. In a new context, the Law of the Minimum or the limiting factor principle, or minimum law of Liebig can be used, not for the isolation and control of factors, but for the identification of interactions and complex responses (Summer & Farina, 1986; Wilkinson et al., 2000).

The Law of the Minimum determines that the growth of a plant is limited by that soil nutrient found in the lowest proportion of the plant's requirement

The Minimum principle is applied under conditions where the supply of energy, minerals and other factors is balanced, near-optimum or unlimited. Once the deficient nutrient is supplied, it induces additional growth, until another nutrient or factor becomes limiting and so on (Raij, 1981; Sims, 2000, Wilkinson et al., 2000).

The application of the Law of the Minimum is complex because there are often several production-limiting nutrients or factors and interactions. Moreover, as defined by the Law of Mitscherlich, biological responses are normally not linear (Raij, 1981). Thus, the application of a nutrient to the soil in sufficient quantity, as described by Liebig, results in a curvilinear response to additional doses of that nutrient until the production becomes maximum, then a "plateau" is reached, as described by Mitscherlich (Malavolta, 1976).

Voisin (1973) emphasizes the role of interactions and claims that the lack of one nutrient in the soil reduces the effectiveness of other nutrients and, consequently, of crop yields. Therefore, each nutrient is most effective when the others are near-optimum. This author also stated that the excess of one nutrient in the soil reduces the efficiency of others and may therefore decrease yields, which is confirmed by the parabolic shape of the response curves. As foreseen by the Mitscherlich Law, in its first approximation, the yield increases decrease with additional doses of a nutrient until reaching a maximum, a plateau, after which the production decreases. This reduction after the maximum was not predicted by Mitscherlich. For this case, Voisin (1973) proposed the Maximum law, based on the understanding that the excess of a nutrient limits or reduces yields, due to nutrient imbalances or toxic effects.

However, Wallace (1990) proposed the Law of the Maximum in contrast to the Law of the Minimum, somewhat different from the focus and application of the proposal of Voisin. Wallace's Law determines that when the needs for each factor involved in the process are fully met, the rate of this process can reach its full potential, which is greater than the sum of its parts, due to sequential positive interactions. In other words, for each nutrient content or value of a production factor there is a maximum possible yield, which occurs when all other factors and interactions are optimal for the content of this nutrient. In other words, for each level or value of a production factor there is a maximum possible production. This production will only be achieved when all interactions and levels/values of other production factors are not less restrictive than the factor in analysis. Thus, the maximum yield obtained with a certain content or amount of a nutrient or production factor represents

the constraint condition for this factor only. All yields below the maximum represent another factor or interaction contributing to the limitation.

Based on these concepts, Summer & Farina (1986) proposed an interpretation model, by which the increase of the levels of a certain nutrient "X" in the soil or of the ratio "X/Y" in the plant tissue up to a maximum critical value would induce yield increases. This region of plant response is interpreted as the region of X insufficiency or of Y excess. The region in which the increases in the levels of this factor X do not affect the yield, was called region of nutrient balance by Summer and Farina. Increases in the levels of the factor, beyond the region of balance, result in a progressive yield decline. This area is defined as the X excess or Y insufficiency region.

This method allows the identification of regions of insufficiency, balance and excess levels and ratios between nutrients based on yield graphs in response to nutrient contents or the ratio between nutrients studied (Wilkinson et al., 2000).

The purpose of this study was to recommend soil fertility levels, based on field data from willow plantations on the southern plateau of Santa Catarina, using the method proposed by Summer & Farina (1986). This is the first study addressing the recommendation of soil fertility levels for willow

MATERIALS AND METHODS

In 2000, 48 sampling units were installed on willow plantations in the counties Bocaina do Sul, Bom Retiro, Lages, Rio Rufino, and Urubici, in the state of Santa Catarina. Plantation segments with no dead or diseased plants were selected as sampling units. The size of each sample unit was adjusted to the spacing, the possibilities of sampling and the availability of the producer; the goal was to evaluate at least six trees and 1 m² per unit, so the variation was 1–11 m² and 3–27 trees. The branches of each plot were weighed and sampled to determine the moisture content. The samples were oven-dried at 60 °C for 72 h.

In each sampling unit, the water table depth, the presence of a hydromorphic horizon to a depth of 120 cm, and the presence of soil layers impermeable to root penetration were observed.

Soil samples were collected from the 0–20 cm layer, mixed to a composite sample from nine sampling points along a diagonal drawn between the willow rows, of which the first and last points were at the end of opposite rows and the others distributed evenly in-between. Soil samples were

subjected to routine analyses (pH_{water} , P, K, Al^{3+} , Ca^{2+} , and Mg^{2+}) and micronutrients Zn^{2+} , Cu^{2+} and Mn^{3+} , in soil laboratories of Epagri (Empresa de Pesquisa Agropecuária e Extensão Rural de Santa Catarina, 2008) in Chapecó and São Joaquim, and a laboratory of animal nutrition of Epagri/EELages, according to routine methods of the official network of laboratories in Southern Brazil (Tedesco et al., 1995).

In 2001 and 2002, the procedure of soil sampling and analysis and willow production was repeated, wherever possible on the same plots as in the previous year. The plots that had been harvested or could not be repeated for any other reason, were replaced. At each soil sampling, the willow branches in the plot were cut at the trunk and weighed.

The data were analyzed for normality using the Kolmogorov-Smirnov test ($p < 5\%$) (Johnson & Wichern, 1998).

Based on the method proposed by Summer & Farina (1986), the soil nutrient levels and pH values as well as nutrient levels in plant tissue were diagrammed with the respective values of willow yield; each variable was placed on the x-axis, and the willow yield on the y-axis (Figure 1).

By the original method of Summer & Farina (1986), the cloud of points in the graph of each variable is circumscribed with a line joining the points of maximum production for each value on the x-axis. However, considering the limited information available to evaluate willow requirements in this study, two straight regression lines were adopted as alternative to minimize the error or characterize

the inconsistency of the outline of the points of maximum. The ascending line joins the points of maximal responses for each value on the abscissa in the X insufficiency region, where increasing values on the x-axis result in increases in willow yield, on the y-axis (Figure 1). The descending line is to join the points of maximum responses for each value on the abscissa, - X excess region - where increasing values on the x-axis results in decreases in willow yield, on the y-axis.

For each variable evaluated in this study (pH_{water} , P, K, Al^{3+} , Ca^{2+} , Mg^{2+} , Zn^{2+} , Cu^{2+} , and Mn^{3+}), a graph was created with the variable on the x-axis and willow yield on the y-axis. In each graph, a straight line on the left – ascending line – was generated from the leftmost value on the yield graph and the value immediately to the right and above it. The values above and to the right of this segment of the line were gradually added to or removed from the equation in order to obtain the regression with the most significant coefficient of determination R^2 (Table of significance of R^2 values, Steel & Torrie, 1960), without disregarding values to the left and above the generated straight line in the calculation. The absence of significant R^2 in at least 95 % with more than two points in the equation was considered as no adjustment.

To obtain the regression line on the right side of the data set - excess region - the procedure of establishing the descending line was the same. That is, a straight right – descending line - was generated from the rightmost value in the yield graph and the value immediate to the left and above it. The values above and left of that line segment were gradually added to or removed from the equation to obtain the regression with the most significant coefficient of determination R^2 (Significance table of R^2 values, Steel & Torrie, 1960), without disregarding values to right and above the generated straight line in the calculation. The absence of significant R^2 in at least 95 % with more than two points in the equation was considered as no adjustment.

Once the ascending and descending straight lines of the target variable were established, the crossing point of both lines was calculated, i.e., the maximum point of the variable. This procedure was repeated for each variable. The value of the studied factor required to achieve the maximum point was considered the optimum value of the factor. That is: $y_a = y_d$, where: $y_a = a_a x + b_a$ and $y_d = a_d x + b_d$, where: y_a = willow yield; a_a = slope of the ascending line, b_a = constant of the ascending line, a_d = slope of the descending line, b_d = constant of the descending line; we have:

$$a_a x + b_a = a_d x + b_d; \text{ so that: } x_{\text{optimum}} = (b_d - b_a) / (a_a - a_d)$$

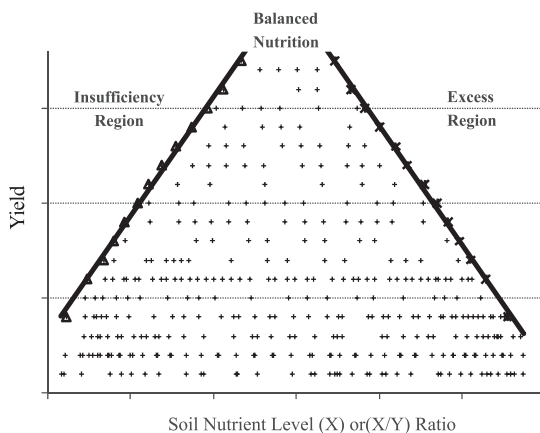


Figure 1. Diagram to determine the regions of insufficiency, balance and excess of nutrient X, or of insufficiency of Y in the ratio X/Y (Adapted from Summer & Farina, 1986).

In the cases where one of the lines was not consistent, i.e., where only a trend to the right or left was observed in the data set, the maximum yield observed in the field was used to calculate the optimum point of the target factor under study.

In addition to the optimal value, a critical range was also defined, limited by the amount of the factor under study needed for yields equivalent to the maximum production observed minus a standard deviation. The value in the ascending line was established as sufficiency threshold, while the resulting value of the descending line was called the excess threshold.

Where: $y_a = a_a x + b_a$ and $y_d = a_d x + b_d$; for: $y_{\text{maximum}-\sigma}$; where: y_{maximum} = maximum yield, σ = standard deviation, so we have: $x_{\text{sufficiency}} = (y_{\text{maximum}} - \sigma - b_a)/a_a$; and: $x_{\text{excess}} = (y_{\text{maximum}} - \sigma - b_d)/a_d$; where: $x_{\text{sufficiency}}$ = sufficiency threshold of the factor under study, and: x_{excess} = excess threshold of the factor under study. Thus, for every variable in the study a balance/sufficiency range was established, where the minimum is the sufficiency value and the maximum the excess value. Values of the target trait below this range in the willow plantations were considered insufficient, and those with values beyond the range in excess for each of the study variables.

RESULTS AND DISCUSSION

The willow yield was responsive to changes in soil pH (Figure 2). The optimal pH values of 5.8 and pH ranges from 5.0 to 6.5 are compatible with the recommendations of Abrahamson et al. (2002) for willow cultivation aiming at biomass production and with the recommendations of the SBCS (2004) for forest species such as black wattle. Since the soils of the region are acidic (Ernani et al., 2000), very high lime doses must be used to adjust the conditions of the soils in the willow plantations.

The highest willow yields were observed in a soil P availability range of 12–89 mg dm⁻³, with a lower limit similar to the range considered sufficient by the SBCS (2004) for “class three” of clay content, i.e., valid for sandy, as well as for medium or clay soils (Figure 3). The upper limit is much higher than the threshold of SBCS (2004) for most crops, however, economic and environmental aspects most likely restrict fertilization of crops (Keoleian & Volk, 2005; Oldham, 2008; Sharpley et al., 2010). This wide range between lower and upper thresholds when another variable interferes with the response, in this case, soil texture and the determination of available P by Mehlich, as observed by Bortolon & Gianello (2008), may be an undesirable feature of the method.

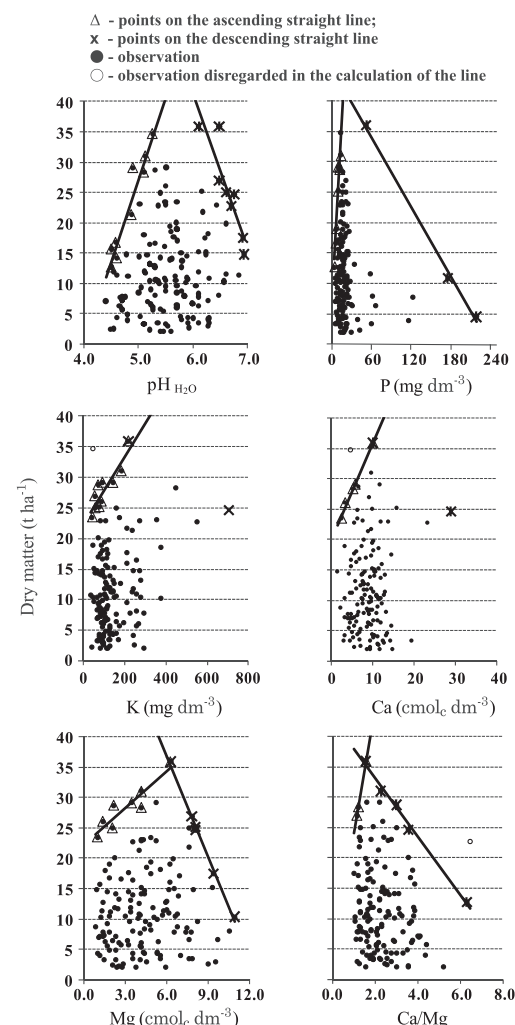


Figure 2. Relationship between the yields of *Salix x rubens* and the pH values, exchangeable contents of P, K, Ca, and Mg and the Ca/Mg ratio of the soil on the Southern Plateau of Santa Catarina.

Potassium availability was less limiting than would be expected, as farmers are not used to applying K or organic fertilizers (Figure 2). The extraction at harvest of this nutrient was estimated at 29 kg ha⁻¹ year for average dry matter yields of 10 t ha⁻¹ for the regional conditions of this study (Rech et al., 2005). Adegbedi et al. (2001) found a removal of 7 to 44 kg ha⁻¹ K in studies conducted in New York State, USA.

The soils had an average K content of 129 mg dm⁻³. As similarly observed for P, the minimum level of K sufficiency (114 mg dm⁻³) was similar to the high

and very high levels of the SBCS recommendations (SBCS, 2004) for soil with medium CEC ($5.1\text{--}15.0\text{ cmol}_c\text{ dm}^{-3}$). However, it was not possible to establish the upper threshold for the surface layer, probably due to the low density of samples with high enough K levels to limit willow yields, be it by nutritional imbalance, or by toxicity or salinity.

The mean Ca content in the soil was $8.4\text{ cmol}_c\text{ dm}^{-3}$ and the sufficiency threshold $5.3\text{ cmol}_c\text{ dm}^{-3}$ for willow production. This value is similar to the limit of the sufficiency range of the SBCS classification (SBCS, 2004). It is also compatible with the levels reported by Adegbedi et al. (2003) and Labrecque et al. (1998) in experimental areas with willow. Similarly as for K, no upper threshold could be established for Ca either.

For Mg it was possible to establish a sufficiency range of $3.2\text{--}7.5\text{ cmol}_c\text{ dm}^{-3}$, while the mean value was $4.4\text{ cmol}_c\text{ dm}^{-3}$ (Figure 2). For the Ca/Mg ratio, the average was 2.3, while the sufficiency range was determined from 1.2 to 2.9. Willow yields were higher in soils with narrower Ca/Mg ratios (Figure 2) than in soils growing *Salix* for biomass production (Labrecque et al., 1998). Still, the value was within an adequate range for many agricultural crops (Camberato & Pan, 2000). This narrow Ca/Mg ratio does not seem to be a problem, because the limestone used in the region is usually dolomitic lime, and therefore, appropriate for the plant requirements. Perhaps for this reason, only few of the sampled plantations were classified in the insufficiency range.

Although willow yields were higher in the absence of Al, the level tolerated for yields of over 90 % of the maximum were obtained with Al contents of up to $1.7\text{ cmol}_c\text{ dm}^{-3}$ (Figure 2). However, Cronan & Grigal (1995) claimed that the relationship between Ca and Al can be a more appropriate indicator for the evaluation of stress in the forest development. Based on the data and procedure adopted in this study, the maximum value of Al/Ca was 0.28. Above this threshold, the Al/Ca ratio may be the main yield-limiting factor.

For the micronutrients (Figure 3), the optimum Zn content was determined at 6.8 mg dm^{-3} and the limits of the sufficiency range 5.0 mg and 8.3 mg dm^{-3} . The average Zn content found in willow plantations was 5.8 mg dm^{-3} . These values are high, compared to the classification of the (SBCS, 2004). However, they are similar to levels reported by Labrecque et al. (1998) in soils of willow plantations for biomass production which were assessed for organic fertilization.

The optimal Cu amount determined based on willow yield was 2.8 mg dm^{-3} , which is considered high (SBCS, 2004). Even the lower threshold of the

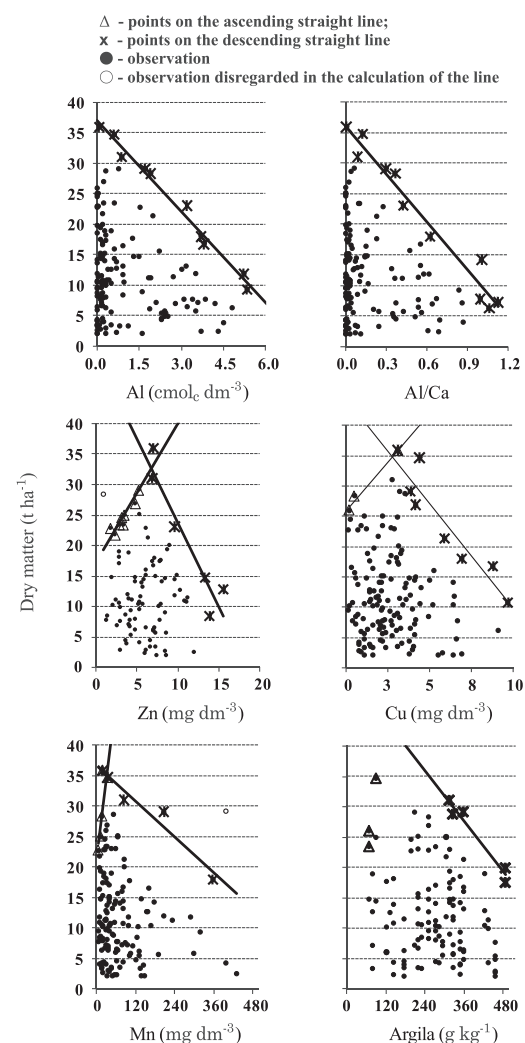


Figure 3. Relationship between the yields of *Salix x rubens* and exchangeable contents of Al, Zn, Cu, and Mn and clay in the soil on the Southern Plateau of Santa Catarina, total observations: 143.

sufficiency range ($0.8\text{--}4.6\text{ mg dm}^{-3}$), was considered high according to this classification. On the other hand, Labrecque et al. (1998) reported higher Cu than observed in this study.

The optimal level of Mn, 34.0 mg dm^{-3} , is far higher than the ranges defined by the classification of SBCS (2004), so that the lower sufficiency limit ($20.0\text{--}163.4\text{ mg dm}^{-3}$) is almost 10 times greater than the lower limit of the upper class of that classification (Figure 3) and higher than the levels presented by Labrecque et al. (1998).

The average clay content in the samples was 270 g kg^{-1} , in both soil layers. It was not possible to determine a threshold of minimum clay content. This may be the result of the presence of organic soils and areas where there is constant replenishment of nutrients through water flow, situations in which the contribution of clay minerals to nutrient replacement may be negligible. However, soils with higher clay content seem limiting, perhaps due to the difficulties of drainage and soil aeration. According to the model, soils with a clay content $> 320 \text{ g dm}^{-3}$ could limit willow yields.

CONCLUSIONS

1. The application of the modified method of Summer & Farina (1986) allows the establishment of recommendations of: a) levels of sufficiency and excess for pH, P, Mg, Zn, Cu, and Mn and the Ca/Mg ratio, b) sufficiency but not excess levels of K and Ca, c) the upper threshold for Al, Al/Ca ratio, and for clay contents.

2. For willow production, soils should have a pH between 5.0 and 6.5 and the following nutrient contents: P $12\text{--}89 \text{ mg dm}^{-3}$, K $> 114 \text{ mg dm}^{-3}$; Ca $> 5.3 \text{ cmol}_c \text{ dm}^{-3}$; Zn $5.0\text{--}8.3 \text{ mg dm}^{-3}$; Cu $0.8\text{--}4.6 \text{ mg dm}^{-3}$; and Mn $20\text{--}164 \text{ mg dm}^{-3}$. The level of Al should not be higher than $1.73 \text{ cmol}_c \text{ dm}^{-3}$, the Ca/Mg ratio should be between 1.2 and 2.9 and the Al/Ca ratio < 0.28 . The soil clay content should be $< 320 \text{ g dm}^{-3}$.

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