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SHORT COMMUNICATION

Is magnesium deficiency the major cause of needle chlorosis of *Pinus taeda* in Brazil?

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Abstract Needle chlorosis (NC) in *Pinus taeda* L. systems in Brazil becomes more frequent after second and third harvest rotation cycles. In a study to identify factors contributing to yellowing needle chorosis (YNC), trees were grown in soils originating from contrasting parent materials, and soils and needles (whole, green and chlorotic portions) from 1- and 2-year-old branches and the first and second needle flush release at four sites with YNC on *P. taeda* were analyzed for various elements and properties. All soils had very low base levels (Ca^{2+}, Mg^{2+} and K^{+}) and P, suggesting a possible lack of multiple elements. YNC symptoms started at needle tips, then extended toward the needle base with time. First flush needles had longer portions with YNC than second flush needles did. Needles from the lower crown also had more symptoms along their length than those higher in the canopy. Symptoms were similar to those reported for Mg. In chlorotic portions, Mg and Ca concentrations were well below critical values; in particular, Mg levels were only one third of the critical value of 0.3 g kg^{-1}. Collectively, results suggest that Mg deficiency is the primary reason for NC of *P. taeda* in various parent soils in Brazil.

Keywords Nutritional deficiency · Forest management · Soil depletion · Pine foliar analysis · Needle chlorosis

Introduction

Magnesium (Mg) has been called the "forgotten element in crop production" due to its low profile among macronutrients in plant nutrition (Cakmak and Yazici 2010). Among several functions, Mg is a component of the chlorophyll molecule that can influence photosynthesis, and a major symptom of deficiency can be foliar chlorosis of older leaves (Chaudhry et al. 2021). The occurrence of chlorosis associated with Mg deficiency can also be directly related to light intensity (Cakmak and Marschner 1992; Ende and Evers 1997; Cakmak and Yazici 2010), which could be impacted by climate and foliar position within tree canopies. In addition, Mg is well known to have antagonistic interactions with K (a major nutrient applied to crops), which can increase needs for Mg (Beets and Jokela 1994; Sun and Payn 1999; Chaudhry et al. 2021; Xie et al. 2021).

In a review of Mg deficiency in coniferous forests, deficiencies in the *Pinus* genus were initially reported in Europe

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followed by North America (Ende and Evers 1997). In addition, Meiwes (1995) indicated that Mg deficiency was widespread in many parts of Europe. Acidification from acid rain, especially in European forests, has increased base leaching and intensified Mg deficiency (Meiwes 1995; Huber et al. 2006; Pavlů et al. 2021). The combined deficiency of Mg and K was called a new kind of forest decline by Fink (1991). Indications of long-term acidification of forest soils in China could further drive the lack of Mg (Zhu et al. 2016). In New Zealand, Mg deficiency has been amply shown to intensify with harvest cycles (Beets and Jokela 1994; Mitchell 2000; Mitchell et al. 2003).

Pinus spp. is the second most-planted tree in Brazil, especially in southern regions where subtropical climatic conditions are very favorable for economically important *Pinus taeda* plantations (IBGE 2021). The traditionally high mean yields in Brazil suggest adequate tree nutrition and management in the majority of these systems. However, trees at many sites are starting to grow more slowly and develop yellow chlorosis, which may be a sign of nutrient exhaustion due to multiple harvest cycles. Deficiency in bases such as Mg has been related to poor soils and rapid exhaustion of soil bases from their removal over several rotational cycles of tree harvests without fertilizer additions (Berthrong et al. 2009). José et al. (2023) working with eucalyptus found decrease of soil quality index for one cycle when whole residue was taking out. However, residue from clear-cutting can release large amount of base from residue which can enhance soil nutrients in the first stage of forest regeneration or planting (Gustienė et al. 2022). In addition, since the initial expansion of forest plantations, very low base concentrations in soil were also suggested to cause chlorosis in tropical pine (*P. caribaea*; Goor 1966). Chlorosis in *P. taeda* is associated with very low soil fertility (Reissmann and Zöttl 1987), and Chaves and Corrêa (2005) noted that intense chlorosis and tree death were probably related to Ca and Mg deficiency in *P. caribaea*. Mg levels could also be influenced by fertilizer and lime applications (Batista et al. 2015; Adam et al. 2021; Consalter et al. 2021a).

In several countries, chlorotic symptoms related to Mg deficiency were referred to as "upper mid-crown yellowing (UMCY)" in the *Pinus* genus (Ende and Evers 1997; Mitchell et al. 2003). Severity of Mg deficiency can be described in eight steps (Beets and Jokela 1994), varying from yellowish needles to needle retention and branch death. Mg deficiency in seedlings grown in sand cultures begin with yellowing of needle tips, which progresses to the middle of the needles, then the tips turn brown, then necrotic (Sucoff 1961). In addition, Mg concentrations (young to old needles) were found to be an effective tool to evaluate tree nutritional status. The reduction in Mg with age can be explained to a large degree by the redistribution of Mg in the tree (starting from needle tips), which can reach 58% for *P. taeda* (Viera and Schumacher 2009).

The critical Mg concentration for *P. taeda* needles appears to be ~ 0.8 g kg^{-1} (Reissmann and Wisniewski 2000; Albaugh et al. 2010). Similar values were reported in *P. radiata* by Sun and Payn (1999), they found that photosynthesis decreases more when Mg concentration is less than 0.6 g kg^{-1}. For the same species, Will (1978) reported critical, marginal, and satisfactory Mg concentrations of $<$ 0.7, 0.7 to 1.0, and $>$ 1.0 g kg^{-1}, respectively. However, some variation exists among *Pinus* species and locations. For example, Sucoff (1961) reported a Mg concentration range of 0.5 to 0.8 g kg^{-1} for severe chlorosis in *P. taeda* and 0.3 g kg^{-1} when the tips had browned; these findings suggest a possible need for establishing degrees of deficiency. In a hydroponic system, Laing et al. (2000) found that *P. radiata* growth response to Mg addition when needle Mg concentrations were above 0.20–0.25 g kg^{-1}. In the field, Chaves and Corrêa (2005) reported Mg deficiency in *P. caribaea* below 0.4 g kg^{-1}. Despite the importance of a single critical level, one should be cognizant of site variations and interpret needle analysis results with caution.

Here we analyzed the chemical composition of chlorotic needles from various commercial *P. taeda* plantations to identify the element or elements associated with symptoms.

Materials and methods

Site characterization, soil sampling, and tissue collection

Samples of *P. taeda* needles exhibiting characteristic chlorotic symptoms were collected from contrasting sites in southern Brazil. In total, trees from four sites were analyzed, one in the state of Paraná and three in the state of Santa Catarina. All four sites have a subtropical climate. The site in Paraná

Table 1 Tree age and site attributes for areas with chlorotic trees at four sites in southern Brazil

Site	Variable				
	age (year)	Rotation	Soil type	Altitude (m a.s.l.)	Soil texture
Bituruna	14	Second	Regosol and Cambisol	1192	Clayey
Major Vieira	12	Second	Regosol	740	Very clayey
Água Doce	19	Second	Regosol	1308	Clayey
Rio Negrinho	16	Second	Cambisol	935	Sandy

in the municipality of Bituruna is in the southeastern region of the state with acidic eruptive rock as the soil parent material. The three sites in Santa Catarina are located in Rio Negrinho, Água Doce, and Major Vieira, which respectively have soils derived from sandstone, acidic eruptive rock, and shale parent materials (Table 1). Soil samples were collected for each soil horizon at three sites (Bituruna, Água Doce, and Major Vieira) and at depths of 0–20, > 20–40, and > 40–60 cm for Rio Negrinho.

At Bituruna, two trees with chlorotic symptoms were harvested on 16 October 2020 (spring season). Twelve branches were collected per tree, six from the lower third and six from the upper third of the crown, and kept separate. In the laboratory, samples were separated by first needle flush (from a branch of the year reflective of spring budding, which usually occurs between July and December) and second needle flush (from a branch of the previous year reflective of summer budding, which usually occurs between December and May). Needles from the first and second flushes were divided into two equal parts. Half of the needle sample was kept intact (uncut) and will be referred to as whole needles (Fig. 1a). For the second half, needles were cut along their length based on color change: chlorotic portion (with symptoms [WS] and unaffected green portion (no symptoms [NS]) (Fig. 1b, c). The length of the cuts varied depending on the color change and ranged from 1/5 to 2/3 of the total needle length (Fig. 1c). Some branches immature or juvenile flushes, and in such cases, needles were separated and classified as juvenile (Fig. 1b, c). Juvenile flushes were present in the spring sampling since budding had recently occurred and thus were not completely reflective of fully formed needles.

At Major Vieira and Água Doce, two trees with chlorosis (yellowing) were harvested at each site, and eight branches from the upper third of each tree crown were collected to obtain second flush needles. At Rio Negrinho, one tree with chlorotic symptoms was harvested and then the tree canopy height was determined and divided into four equal segments (1/4, 2/4, 3/4 and 4/4). Eight branches with first and second flushes were collected from upper segments (3/4 and 4/4), and eight branches were collected from the lower segments (1/4 and 2/4), which contained only first flush needles because the second flush had already fallen.

All needle samples were washed in running water and rinsed in deionized water. Samples were oven dried (65 °C) until constant mass before grinding with a Wiley knife mill. Fresh needles were also selected and photographed with a camera (Axiocam ERc 5S) through a stereomicroscope (Zeiss Stemi 508) to observe chlorotic spots in detail.

Needles and soil analyses

Foliar tissues samples were dry digested in a muffle furnace as described by Martins and Reissmann (2007). Elements were analyzed using inductively coupled plasma optical emission spectroscopy (ICP-OES, radial view). Nutrient results were interpreted based on information from specific publications on *P. taeda* grown in the United States (Table 2).

All soil samples were analyzed for fertility in terms of pH $CaCl_2$–0.01 M (1:2.5 soil solution), exchangeable Al^{3+}, Ca^{2+}, and Mg^{2+} (extracted by KCl 1 M), and available P and K^+ (extracted by Mehlich I). Carbon was determined by chemical oxidation with dichromate. According to the methodology described by Marques and Motta (2003), the following equipment or methods were used to determine extracted elements: atomic absorption, Ca and Mg; spectrophotometry, P; flame spectrophotometry, K; and NaOH titration, Al^{3+} and (H + Al). The following were also determined: sum of

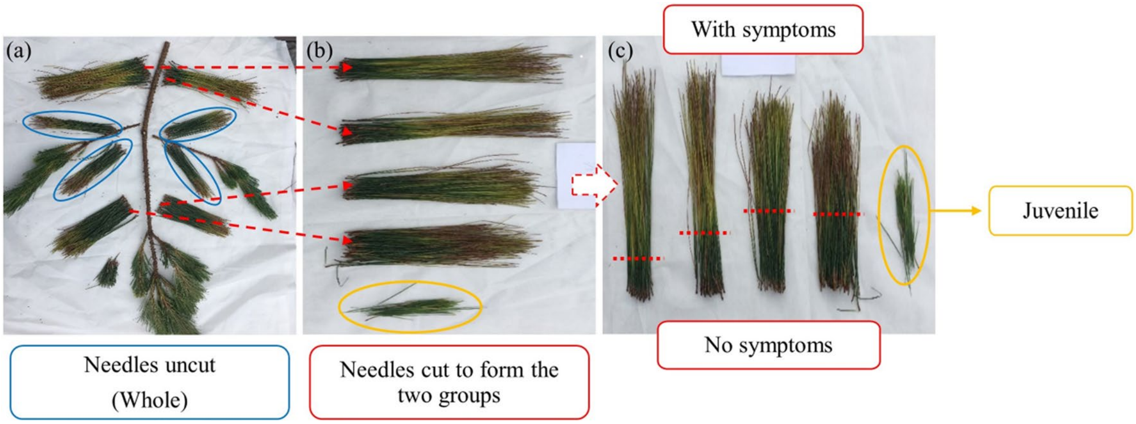

Fig. 1 Separation of *Pinus taeda* needles with chlorosis into portions of the first and second flush, then into the three sample groups: whole needles, needles with and without symptoms of chlorosis. **a** Branch divided into first and second needle flushes. Blue outlines indicate needles that were not cut (whole); red arrows indicate needles that will be cut **b** to separate the two sample groups (with and without symptoms); dotted lines **c** indicate the cut site to divide the needles into groups with chlorotic symptoms and without chlorotic symptoms

Table 2 Critical reference levels and adequate nutrient ranges for *Pinus taeda* in the United States and Brazil

Element		P g kg^{-1}	K g kg^{-1}	Ca g kg^{-1}	Mg g kg^{-1}	Cu mg kg^{-1}	Fe mg kg^{-1}	Mn mg kg^{-1}	Zn mg kg^{-1}	B mg kg^{-1}	Ni mg kg^{-1}
Brazil	Reissmann 1981	1.3	4.0	0.5	0.8	5–7	133–165	210–363	10	15–29	–
USA	Sypert 2006	1.2	4.0	1.5	0.8	3	20	40	20	10	–
	Albaugh et al. 2010	1.2	3.5–4.0	1.5	0.8	2–3	–	20–40	10–20	4–8	–
	Forest Service NC 2012	1.2	3.5	1.2	0.7	2–3	–	–	–	4–8	–
Considered critical level in present study		1.2	3.5	0.5	0.7	2	20	20	10	4	0.3

bases (SB = Ca^{2+} + Mg^{2+} + K^{+}); cation exchange capacity (CEC) effective (CEC eff. = SB + Al^{3+}); CEC pH 7.0 (CEC pH 7.0 = SB + (H + Al)); base saturation (V % = SB/CEC pH 7.0 × 100); and aluminum saturation (m % = [Al/CEC effective] × 100). Soil analyses were interpreted according to the Paraná State manual for fertilization and liming (Pauletti and Motta 2019).

Results and discussion

Deficiency symptoms

In the field, chlorosis can vary widely in intensity, with trees in the same location displaying low, high, or no symptoms (Fig. 2a–e). Chlorotic symptoms varied from needle yellowing to crown loss as also reported by Mitchell et al. (2003) in *P. radiata*. Chlorotic patterns within the crown were more intense on lower branches (Fig. 2c).

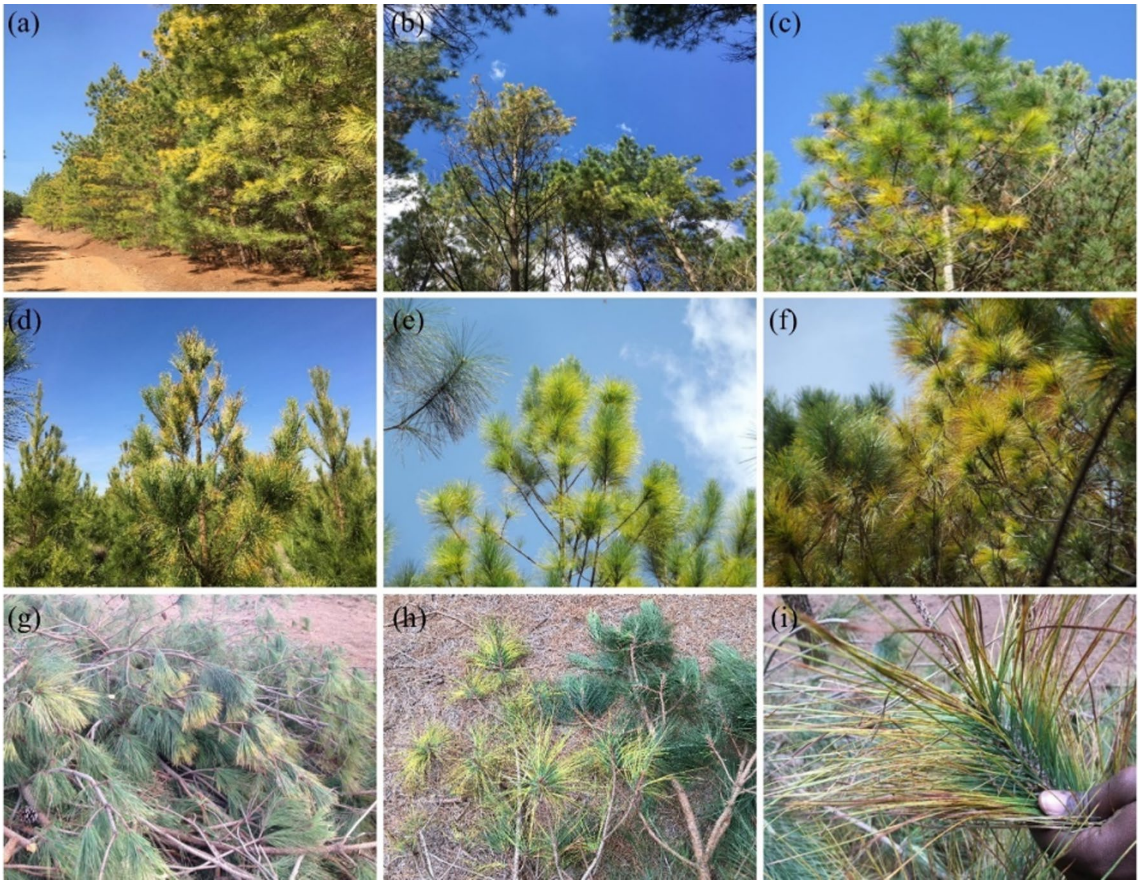

Fig. 2 *Pinus taeda* trees and branches with chlorosis in southern Brazil. **a** Trees with chlorosis exposed to sunlight. **b** Trees with crown loss (severe) and yellow chlorosis (low effect). **c**, **d** Young tree with chlorosis. **e**, **f** Branches with chlorotic needles. **g** Branches of felled tree with chlorosis. **h** Branches of felled tree with and without chlorosis. **i** Chlorotic with some necrosis needles

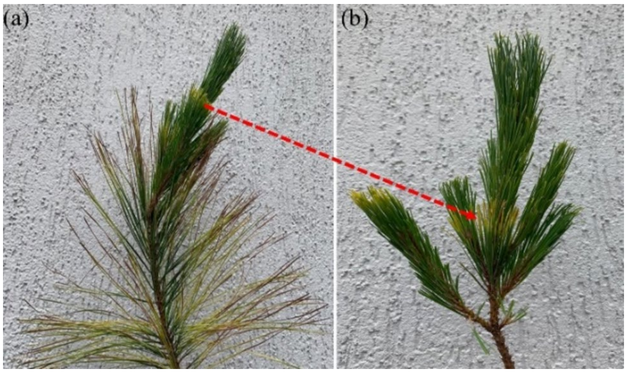

Fig. 3 Initial chlorotic symptoms on juvenile needles of *Pinus taeda* in southern Brazil. **a** Older branch with initial symptoms and advanced chlorosis with the onset of necrosis at needle tips. **b** Young branch with initial yellowing tips on needles

The yellowing of the needle tips (Fig. 2g–i) is similar to previous observations describing Mg deficiency (Sucoff 1961; Reissmann and Zöttl 1987; Beets and Jokela 1994; Ende and Evers 1997; Mitchell et al. 2003; Chaves and Corrêa 2005). Like we saw in the field, Ende and Evers (1997) described that older needles on conifers commonly developed an initial yellowing, while younger needles remained green) (Fig. 3a, b), then the chlorotic needles and eventually part of the upper crown was lost (Fig. 2b). In our study, small yellow or orange spots initially appeared on needle tips, then on other areas of the needles (Fig. 3a, b). In two controlled experiments with *P. taeda* in pots of sand, Sucoff (1961) observed the following Mg deficiency symptoms in seedlings: When young needles are 1/4 or 2/3 of their mature size, tips become yellowish; yellowing progresses quickly to encompass a third to half of the needles; and needles progressively turn brown while the base remains green. In addition, light can accentuate symptom onset in conifers with needle yellowing, generally intensifying in branch parts exposed to light (Ende and Evers 1997). Sucoff (1961) found that on hot and clear days, tips of *P. taeda* primary needles turn yellow, and the chlorosis progresses rapidly toward the base until half of the needle length is yellow. Although effects of light intensity have been consistently observed in the field and reported recently, deficiencies of other elements may cause chlorosis when light intensity is high.

Enlargements of the needles show yellow, brown, and green bands on the needles (Fig. 4a–f). Similar to observations by Sucoff (1961), this yellowing quickly extended to half of the needles, and the entire needle tended to become brown except for the basal 1 or 2 cm. Sucoff (1961) also noted that a yellow band in the middle separated green areas from the terminal portion, which was a mosaic of brown, green, purple, and yellow, indicative of severe K deficiency (1.6–2.6 g kg^{-1}).

Chlorotic severity often varied among needles on the same tree and was usually more severe on 2-year-old needles (vs 1st year) and in first flush needles than in second flush (Fig. 5a–f). Growing needles may develop symptoms when branches in a higher positions act as a sink. At more advanced stages, 10 to 20% of the needle tips became necrotic, and consequently, 70 to 80% of the central part of the needle turned yellow, and only ~ 10% of the needle close to its base remained green (Fig. 5f). Thus, yellowing needles along with necrosis could be an important tool in diagnosing the degree of Mg deficiency as suggested by Sucoff (1961).

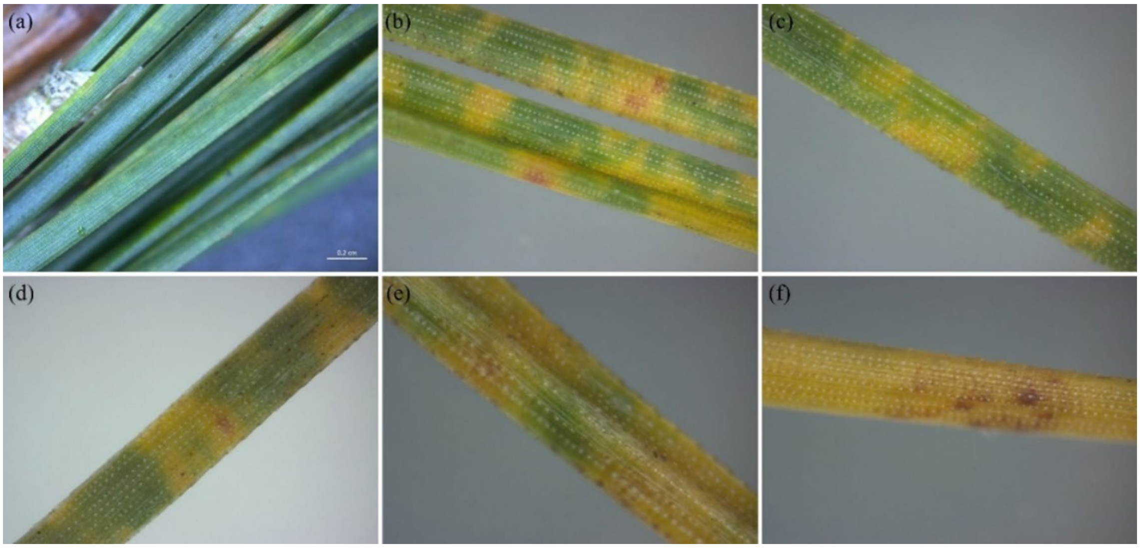

Fig. 4 Different stages of *Pinus taeda* needle chlorosis in southern Brazil. **a** No chlorosis. **b c** Less-severe chlorosis. **d**, **e**, **f** Severe chlorosis

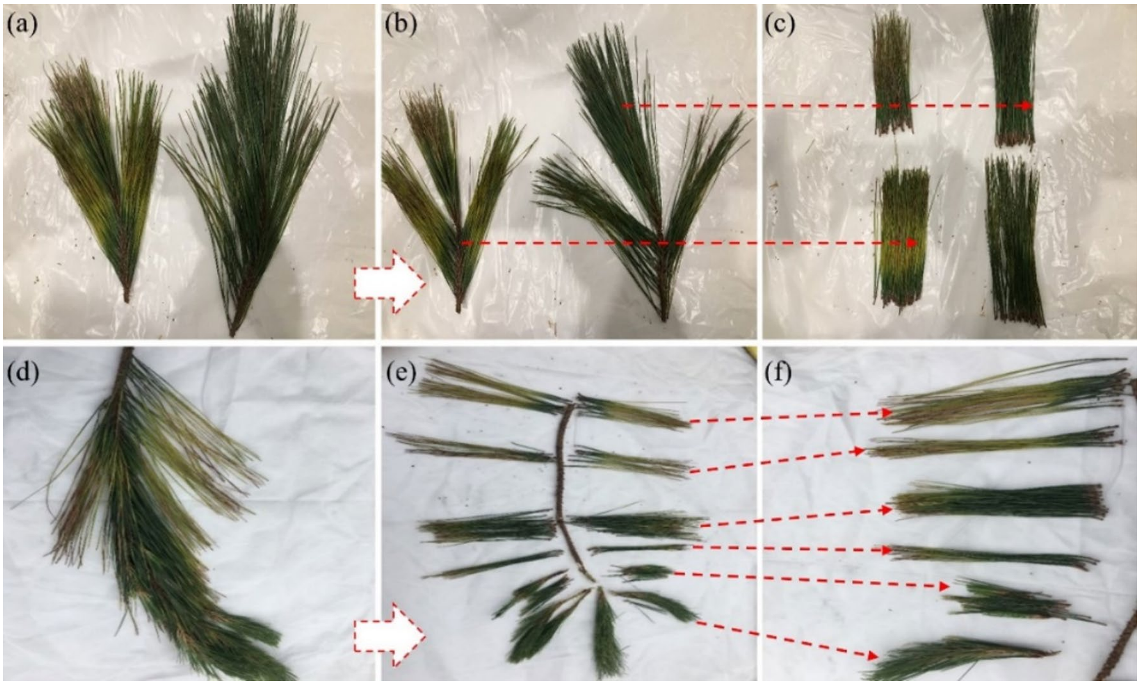

Fig. 5 *Pinus taeda* branches with chlorosis (first and second needle flushes and new flush) for the Rio Negrinho **a**, **b** and **c** and Bituruna **d**, **e** and **f** sites in southern Brazil. **a**–**c** Fascicles from the same branches. **a** Intact branches from the field. **b** Separation of first and second flushes. **c** Branches with (left) and without chlorosis (right) divided into first (top) and second (bottom) needle flushes. **d**, **e**, **f** Same branch. **d** Intact branches from the field. **e** Needles separated into flushes from base to top. **f** From base to top, 2-year-old first flush, 2-year-old second flush, 1-year-old first flush, 1-year-old second flush; bottom two are from juvenile first flush

Table 3 Elemental concentrations in chlorotic *Pinus taeda* needles at Bituruna, Major Vieira, and Água Doce and critical reference levels

Tree		Ca ($g\ kg^{-1}$)	Mg ($g\ kg^{-1}$)	P ($g\ kg^{-1}$)	K ($g\ kg^{-1}$)	Fe ($mg\ kg^{-1}$)	Cu ($mg\ kg^{-1}$)	Mn ($mg\ kg^{-1}$)	Zn ($mg\ kg^{-1}$)	Ni ($mg\ kg^{-1}$)	B ($mg\ kg^{-1}$)	Al ($mg\ kg^{-1}$)
Bituruna	1	0.83	0.21	0.98	4.05	82	5.29	127	9.7	0.91	2.06	510
	2	0.61	0.15	1.14	4.73	156	8.96	140	17.6	1.33	3.12	534
Major Vieira	1	0.51	0.32	1.04	4.87	61	3.09	500	18.0	–	–	–
	2	1.08	0.46	1.04	4.87	66	3.37	733	19.8	–	–	–
Água Doce	1	0.88	0.29	1.18	4.22	136	2.21	196	26.5	–	–	–
	2	0.40	0.16	1.10	4.13	119	2.70	159	18.1	–	–	–
Critical level		0.50	0.70	1.20	3.50	20	2.00	20	10.0	0.20	4.00	

Elemental analysis of needles

First flush needles from the upper medium one-third of live crowns at the three sites (Bituruna, Major Vieira, and Água Doce) were very deficient in Mg (Table 3); values were only half the Forest Service NC (2012) critical level of 0.7 g kg^{-1} (Table 2). Sun and Payn (1999) observed that the onset of Mg deficiency symptoms was strongly influenced by high values of K or K/Mg ratios in needle tissue. However, our needle analysis indicated that K levels were not high and likely did not contribute to the Mg deficiency (Table 3). Although the Ca concentration (Table 3) was below or slightly above the critical level (0.5 g kg^{-1}) proposed by Reissmann (1981) (Table 2), this level could still be considered low since the adopted critical level was much lower than recommendations of other studies (1.2 and 1.5 g kg^{-1}) (Table 2). Concentrations of P and B (Table 3) were slightly below critical levels and possibly indicated deficiency (Table 2). At 10 mg kg^{-1}, Zn was possibly deficient at the Bituruna site (Table 3). Tissue diagnosis indicated that K, Fe, Mn, Cu, and Ni were above critical levels (Table 3). The Al concentrations were high,

Table 4 Elemental concentrations in nonchlorotic and chlorotic parts of needles and in whole needles on *Pinus taeda* tree 1 at the Bituruna site as a function of flush, crown position, and critical reference level

Stage	Crown position	Needle sample [a]	Ca(g kg^{-1})	Mg (g kg^{-1})	P (g kg^{-1})	K (g kg^{-1})	Fe (mg kg^{-1})	Cu (mg kg^{-1})	Mn (mg kg^{-1})	Zn (mg kg^{-1})	Ni (mg kg^{-1})	B (mg kg^{-1})	Al (mg kg^{-1})
First flush	Lower	NS	1.14	0.26	0.86	4.68	142	6.50	202	8.92	0.41	1.74	433
	Lower	WS	0.66	0.13	1.16	4.00	135	7.01	179	9.78	0.39	2.48	588
	Lower	Whole	1.00	0.23	1.00	4.15	84	7.04	128	10.29	0.18	1.96	515
Second flush	Lower	NS	1.40	0.28	0.92	4.74	100	5.81	167	9.17	0.29	1.81	449
	Lower	WS	0.83	0.15	1.15	4.04	132	5.66	266	9.33	0.93	2.33	619
	Lower	Whole	0.96	0.20	0.99	4.05	142	6.35	222	8.49	0.80	2.23	535
Juvenile	Lower	–	0.70	0.32	1.56	8.41	53	10.51	185	22.86	4.76	3.43	196
First flush	Upper	NS	1.06	0.27	0.84	4.63	87	6.24	149	11.36	0.38	2.25	412
	Upper	WS	0.62	0.12	1.18	3.73	121	5.63	178	9.58	0.53	2.04	656
	Upper	Whole	0.83	0.21	0.98	4.05	82	5.29	127	9.75	0.91	2.06	510
Second flush	Upper	NS	1.14	0.29	0.91	4.71	143	6.65	210	11.75	1.44	2.20	487
	Upper	WS	0.56	0.11	1.19	4.07	142	5.60	188	10.15	1.81	2.06	654
	Upper	Whole	0.93	0.21	1.06	4.26	131	6.95	172	10.30	1.49	2.30	549
Juvenile	Upper	–	0.54	0.35	1.58	8.02	61	13.11	159	28.85	6.23	4.15	212
Critical level			0.50	0.70	1.20	3.50	20	2.00	20	10.00	0.20	4.00	–

[a] *NS* Parts without chlorosis, *WS* Parts with chlorosis, Whole: whole needles

Table 5 Elemental concentration in nonchlorotic and chlorotic parts of needles and in whole needles on *Pinus taeda* tree 2 at the Bituruna site (tree 2) as a function of age, flush, crown position, and critical reference level

Age[a]	Needle sample[b]	Crown position	Ca(g kg^{-1})	Mg(g kg^{-1})	P(g kg^{-1})	K(g kg^{-1})	Fe(mg kg^{-1})	Cu(mg kg^{-1})	Mn(mg kg^{-1})	Zn(mg kg^{-1})	Ni(mg kg^{-1})	B(mg kg^{-1})	Al(mg kg^{-1})
First flush													
Of the year	NS	Lower	0.81	0.26	0.83	4.34	113	10.86	123	17.47	1.23	1.81	323
Of the year	WS	Lower	0.54	0.11	1.22	5.62	153	9.00	135	15.37	5.14	3.32	558
Of the year	Whole	Lower	0.68	0.16	1.10	5.12	124	8.92	145	15.84	1.86	2.94	454
Second flush													
Of the year	NS	Lower	0.71	0.27	0.84	3.93	121	9.36	144	14.52	0.76	1.76	310
Of the year	WS	Lower	0.38	0.10	1.11	5.54	140	7.51	109	13.16	1.38	2.71	449
Of the year	Whole	Lower	1.01	0.24	1.10	5.03	117	9.76	156	14.84	0.99	2.50	430
Juvenile													
Lower	–	Lower	0.44	0.28	1.58	8.18	51	12.52	126	23.76	3.64	2.85	210
First flush													
Second	NS	Upper	0.73	0.19	0.87	4.68	106	9.87	112	25.22	0.93	1.72	322
Second	WS	Upper	0.52	0.09	1.38	5.11	143	9.82	130	17.92	2.34	3.50	648
Second	Whole	Upper	0.66	0.14	1.16	4.61	143	8.60	151	18.34	1.50	3.14	550
Second flush													
Second	NS	Upper	0.71	0.21	0.85	4.24	149	8.48	131	24.67	0.76	1.66	362
Second	WS	Upper	0.51	0.10	1.40	5.55	145	9.72	127	17.76	2.71	3.67	627
Second	Whole	Upper	0.58	0.15	1.27	5.77	147	9.39	127	21.74	2.41	3.29	544
First flush													
Of the year	NS	Upper	0.75	0.22	0.86	4.18	113	9.19	105	18.79	0.73	1.56	335
Of the year	WS	Upper	0.59	0.12	1.31	5.09	160	8.86	149	15.35	1.65	3.47	614
Of the year	Whole	Upper	0.61	0.15	1.14	4.73	156	8.96	140	17.60	1.33	3.12	534
Second flush													
Of the year	NS	Upper	0.88	0.28	0.86	4.41	143	8.61	159	19.84	0.75	1.67	360
Of the year	WS	Upper	0.59	0.14	1.37	5.21	161	9.10	153	15.68	1.79	3.18	621
Of the year	Whole	Upper	0.77	0.23	1.05	4.38	115	8.34	133	16.72	1.08	2.51	445
Juvenile													
Of the year	–	Upper	0.49	0.26	1.55	7.44	82	12.35	137	24.71	3.51	2.77	262
Critical level			0.50	0.70	1.20	3.50	20	2.00	20	10.00	0.20	4.00	–

[a] Of the year: needles that will turn 1 year old; Second: needles that will turn 2 years old (based on budding times)

[b] *NS* Part of needles without chlorosis, *WS* Part of needles with chlorosis; *Whole* Whole needles

Table 6 Elemental composition of *Pinus taeda* needles exhibiting chlorosis at the Rio Negrinho site as a function of flush, crown position (height), and critical reference level (CL)

Stage position	Ca ($g\ kg^{-1}$)	Mg ($g\ kg^{-1}$)	P ($g\ kg^{-1}$)	K ($g\ kg^{-1}$)	Fe ($mg\ kg^{-1}$)	Cu ($mg\ kg^{-1}$)	Mn ($mg\ kg^{-1}$)	Zn ($mg\ kg^{-1}$)	Ni ($mg\ kg^{-1}$)	Al ($mg\ kg^{-1}$)	Mo ($mg\ kg^{-1}$)	Co ($mg\ kg^{-1}$)	V ($mg\ kg^{-1}$)
First flush													
Upper 3/4	0.97	0.70	1.31	5.79	70	7.76	145	18.60	3.32	372	0.38	0.51	0.27
Upper 4/4	1.23	0.99	1.33	6.53	74	8.17	189	27.60	3.80	402	0.49	0.79	0.19
Second flush													
Lower 1/4	0.63	0.34	1.20	6.56	46	8.04	67	15.40	1.81	256	0.28	0.24	0.22
Lower 2/4	0.82	0.51	1.27	6.60	50	7.36	103	15.10	2.78	282	0.27	0.44	0.20
Upper 3/4	1.04	0.88	1.20	6.29	47	8.09	147	21.60	3.68	288	0.16	0.29	0.12
Upper 4/4	1.30	1.21	1.36	6.86	45	9.39	161	29.00	3.62	413	0.23	0.18	0.32
Critical level	0.50	0.70	1.20	3.50	20	2.00	20	10.00	0.20	–	4.00	–	–

primarily in the chlorotic needles. Similar to signs for Mg deficiency, excess Al and Mn have been reported to cause "gold tip chlorosis" (Hecht-Buchholz et al. 1987). Wit et al. (2010) also found that Mg absorption was reduced in *Picea abies* after field application of Al. However, Al concentrations of 625 mg kg^{-1} in low growth sites and 737 mg kg^{-1} in high growth sites, higher than those in our study, were reported by Reissmann and Wisniewski (2000). Therefore, additional studies are required to further evaluate the influence of Al on chlorotic symptoms.

Fractionation

Regardless of flush, age, or crown position, analysis of chlorotic needle parts revealed that Mg concentrations were approximately half that in green at the Bituruna site (Fig. 1c, Tables 4 and 5). In *P. radiata* needles, Hunter et al. (1986) found Mg values of 0.3 g kg^{-1} in green basal portions of needles and 0.2 g kg^{-1} in yellow middle portions, so the difference was not as great as in the present study. On the other hand, our analysis of whole needles yielded intermediate values as expected, possibly indicating that Mg deficiency is a substantial contributor to the chlorosis (Figs. 1, 2, 3, 4 and 5). Thus, separating tissue into portions with and without chlorotic symptoms (Fig. 1C) could help in diagnosing Mg deficiency in *Pinus*.

Magnesium values of green needle portions ranged from 0.19 to 0.27 g kg^{-1} and 0.21 to 0.29 g kg^{-1} for first and second flushes at Bituruna, respectively (Tables 4 and 5). However, corresponding values of chlorotic portions were 0.09–0.13 g kg^{-1} and 0.10–0.15 g kg^{-1} of Mg for first and second flushes, respectively (Tables 4 and 5). These values were closer to the Mg concentration of 0.3 g kg^{-1} for *P. taeda* needles in the final tip browning stage (Sucoff 1961) and to *P. radiata* (0.20–0.25 g kg^{-1}) grown in controlled conditions (Laing et al. 2000) (Table 2). In field-grown *P. caribaea*, Chaves and Corrêa (2005) reported Mg values below 0.4 g kg^{-1} in chlorotic portions. Thus, 0.3 g kg^{-1} may be indicative of Mg deficiency when chlorotic portions of needles are tested.

The lower Ca values in chlorotic tissue (vs green) also suggest a possible contribution of Ca deficiency to the chlorosis (Tables 4 and 5), and observed Ca concentrations were often close to the critical limit (0.5 g kg^{-1}) (Table 2). In *P. caribaea*, Chaves and Corrêa (2005) found Ca concentrations from 0.6 to 2.0 g kg^{-1} in typical green needles and 0.1 to 0.2 g kg^{-1} in chlorotic needles. However, the lower B values in green tissue suggests little possibility of this element being associated with chlorosis.

Table 7 Results of chemical analyses of soils at four sites in Brazil where *Pinus taeda* has needle chlorosis

Sample[a]	pH $CaCl_2$	Al^{+3}	H + Al	Ca^{+2} $cmol_c$ dm^{-3}	Mg^{+2} $cmol_c$ dm^{-3}	K^+ $cmol_c$ dm^{-3}	SB[b] $cmol_c$ dm^{-3}	CEC eff.[c] $cmol_c$ dm^{-3}	CEC pH 7 $cmol_c$ dm^{-3}	C g dm^{-3}	P g dm^{-3}	V[d] mg dm^{-3}	m[e] %
Bituruna													
Ap	3.40	6.47	32.00	0.10	0.20	0.07	0.37	6.84	32.37	50.57	6.12	1	95
Bi	3.70	5.25	17.60	0.20	0.10	0.04	0.34	5.59	17.94	33.56	5.23	2	94
Cr	3.90	2.52	3.00	0.00	0.10	0.04	0.14	2.66	3.14	21.39	10.04	4	95
Água Doce													
Ap	3.80	5.27	16.76	0.10	0.13	0.07	0.30	5.57	17.06	32.48	1.63	2	95
Cr	4.00	6.76	15.51	0.10	0.10	0.00	0.20	6.96	15.71	4.23	1.51	1	97
Major Vieira													
Ap	3.30	9.46	26.14	0.10	0.10	0.07	0.27	9.73	26.41	16.94	1.18	1	97
C	3.82	6.81	20.02	0.10	0.10	0.07	0.27	7.08	20.29	6.50	0.46	1	96
Cr	4.14	4.92	9.51	0.10	0.10	0.06	0.26	5.18	9.77	3.02	1.30	3	95
Rio Negrinho													
0–20 cm	3.50	9.24	29.30	0.40	0.10	0.06	0.56	9.8	29.86	99.80	1.50	2	94
> 20–40 cm	3.50	10.10	32.00	0.30	0.10	0.08	0.48	10.54	32.48	99.80	1.50	2	95
> 40–60 cm	3.70	7.00	24.50	0.30	0.10	0.05	0.45	7.45	24.95	59.30	0.20	2	94
> 60–80 cm	3.80	6.17	16.30	0.40	0.10	0.04	0.54	6.71	16.84	10.20	0.10	3	92

[a] Following the classification criteria of the Brazilian Soil Classification System–SiBCS (Embrapa 2018), for soils horizons – Ap = A horizon with anthropic influence; Bi – incipient development of horizon B; C – C horizon; Cr – C horizon with soft rock,

[b] SB = sum of bases (SB = Ca + Mg + K)

[c] CEC = cation exchange capacity – effective (CEC eff. = Ca + Mg + K + Al) and pH 7.0 (CEC pH 7.0 = Ca + Mg + K + H + Al)

[d] V = bases saturation (V % = SB/CEC pH 7.0 × 100)

[e] m = aluminum saturation (m % = Al/CEC eff. × 100)

Position

Needle concentrations of Ca, Mg, Mn, Zn, and Al were directly related to the site of collection within the crown of trees from Rio Negrinho (Table 6). Except for Mg, all other element concentrations were close to critical values (Table 2). The lower parts of the crown had chlorosis and less Mg. Again, chlorotic needles had Mg values ranging from 0.3 to 0.54 g kg^{-1}. Beets and Jokela (1994) suggested that premature needle fall may be indicative of a deficiency when maintenance of needles in the lower portion of the crown is compromised. The higher Mg concentration in second flush needles confirms the transport of Mg from the first needle flush, which was also reported by Rabel et al. (2020).

Soil fertility and climate

Soils from all evaluated sites had (Table 7) very low nutrient availability and very high acidity but had high buffer capacity and CECs. Low nutrient availability could be related to the parent material at the sites—sandstone (Rio Negrino), acid eruptive rock (Água Doce and Bituruna) and shale (Major Vieira)—and the high degree of weathering, which corroborate findings of Bonfatti (2012) and Kampf and Curi (2012). The high buffer capacity and CEC could be related to the high organic matter levels in these soils; however, more than 90% of effective CEC (m%) and 96% of pH 7.0 CEC (V %) were due to Al^{3+} and (H + Al) because of the very high acidity. The very low levels of bases (especially Mg^{2+}) and very high Al^{3+} in the soil in our study was also reported for a *Picea abies* forest by Wit et al. (2010), who found that high levels of Al^{3+} in the soil decreased Mg concentration in the needles, indicating that the interaction between these two elements must be considered. Since three of our sites had also undergone a second rotation and the fourth site a third rotation (all without fertilization and liming), nutrient exhaustion could further contribute to the low soil fertility status and deficiency in multiple elements (Table 7) (Ferreira et al. 2001; Vidaurre et al. 2020; Consalter et al. 2021b).

The severe droughts in 2014 and 2015 in southern Brazil (Finke et al. 2020) may also have increased the incidence and severity of any nutrient deficiency as described by Goor (1966) for dieback of *Pinus elliottii* in Brazil after a severe drought. Goor suggested that dieback intensity could be related to lack of B and Ca. Clearly, further studies are needed to determine how periodic climatic events such as drought affect tree nutrition.

Conclusions

Our detailed evaluation of soils and trees of *P. taeda* with severe chlorosis in Brazil indicated that Mg deficiency was the most likely cause of the chlorosis; Mg levels were low in the soil and very low in the tree tissues. Variations in tissue Mg concentration reflected the level of chlorosis, and symptoms were similar to those described in previous studies. Low levels of Ca, P, Zn, and B and high Al possibly influenced chlorosis severity. Adding low rates of lime to supply Ca and Mg to the acidic soils in pine forests might help mitigate the deficiency and thus the chlorosis and improve overall tree nutrition.

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