DIEBACK IN HIGH SITE QUALITY *PINUS RADIATA* STANDS — THE ROLE OF SULPHUR AND BORON DEFICIENCIES

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ABSTRACT

Several forms of dieback of **Pinus radiata** D. Don within otherwise highly productive forests on the eastern highlands of New South Wales, Australia, are attributed here to physiological deficiencies of sulphur or boron, separately or in combination. Over this area there is a strong correlation between the incidence of dieback and soils (usually derived from extrusives or weathered granites) which are deficient in either or both of these elements.

Marginal deficiency of either element could lead to the usual dieback symptoms; directly, by degeneration of the vascular system; indirectly, as in the case of sulphur by increased susceptibility and improved trophic conditions for pathogens such as **Diplodia pinea**. Both the level of deficiency, and the resulting symptoms, are subject to seasonal effects.

INTRODUCTION

Dieback, designated here as "high site quality" (HSQ) dieback, has occurred periodically in some *P. radiata* D. Don plantings. It is generally found within highly productive forests with relatively high rainfalls and often on deep soils. Symptoms have, over a long period, been attributed by various observers to drought, drying winds, frost, rabbits, waterlogging, boron deficiency, fungal infection (e.g., *Diplodia pinea* (Desm.) Kickx. or *Phytophthera cinnamomi* Rands) or to combinations of these. The symptoms are quite distinct from those associated with events such as hailstorms and bird (particularly cockatoos in Australia) or insect attack.

No study of production losses from HSQ dieback has been published and it is almost impossible to delineate the matter quantitatively since outbreaks have been attributed to a variety of causes. The phenomenon is related to weather patterns, and the age and development of the stand. Losses from new plantings are a very different economic problem from losses and malformations in more mature stands. Dieback of this type has been reported in Australia (Queensland, New South Wales, the Australian Capital Territory, Victoria and South Australia), New Zealand, southern Africa and in North and South America.

In eastern Australia, specific areas extending from the Northern to the Southern Tablelands have been affected periodically. These include Mt Topper, Armidale, Nundle, Vulcan, Canobolas, Dog Rocks, Mannus, Green Hills, Wee Jasper, Buccleuch, Bago, Murraguldrie I, Carabost, Bondi and Nalbaugh in N.S.W. and plantations at Ovens Valley, Bright, Stanley, Beechworth and Tallangatta in Victoria.

Elsewhere, parts of the Tarawera and Kaingaroa Forests as well as some other smaller

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areas in New Zealand have also been affected by dieback which may be the HSQ form. In Tanzania, because of the incidence of dieback, and later because of a severe needle blight, the proportion of *P. radiata* has been steadily reduced.

Description of HSQ Dieback

In N.S.W., HSQ dieback is most severe during the first winter frosts, or during the second dry season in the life of the tree, usually about 2 years after planting. Deaths occur in large patches (0.5 ha +) and due to dieback of buds and growing shoots, extensive areas of surviving trees sustain deformities. Typically in these areas, more than 40 percent of the seedlings have sustained permanent deformities. It has been noted that HSQ dieback is often more common in plantations with high weed competition.

The first sign of the problem in young trees is the wilting and bending over of the apical region of the main stem. The tree at this stage almost invariably shows symptoms of moisture deficiency, that is, the needles assume a brown or orange colour. Wilting may be general throughout a plantation, but in many of the trees the symptoms do not progress further. Trees at this stage are usually of quite healthy internal appearance, although some may show patches of brown discolouration in the inner bark. Soon after, the young growing points commence to turn dry and brown, and this is followed by death of the bud and young tissue. Subsequently the whole tree may die off rapidly, or more commonly, chlorosis develops in the foliage. There are also often patches of dark discoloured tissue on the stem. At this stage the most severely affected trees die. In peripheral areas, surviving trees have bud deformities and brown needles in the current and/or older foliage.

In older trees (5 to 15 years) HSQ dieback most frequently occurs during the times of most rapid growth in spring and late summer. Crown dieback occurs with death of the apical meristem leading to subsequent deformities, and there is often shedding of the unopened fascicles and twisting of the soft new growth. There is also pith breakdown, and below the dead zone needles are usually sparse with yellow or necrotic tips. Resin flow (resinosis) indicating lesions in the bark, is common.

Although rainfall and exposure have an important bearing on the incidence of HSQ dieback, it should be clearly differentiated from the effects of drought. Drought causes foliage to wilt and gradually die evenly over the entire tree, with the bark dying uniformly, with both the apical dieback and cambial necrosis of HSQ dieback being absent. Similarly, the effect of frost alone may usually be distinguished from HSQ dieback because normally frost results in overall scorching of the foliage.

HSQ dieback has been observed by ourselves and other workers (for example, Boomsma, 1949; Millikan and Anderson, 1957; Windsor and Kelly, 1971) to be associated with soil characteristics, sulphur and boron nutrient deficiencies, water relations, and genetic variability.

DIEBACK AND SOIL CHARACTERISTICS

Overall, we observe that HSQ dieback occurs on soils derived from particular parent materials, usually extrusive rocks such as basalt, but also volcanic ash and strongly weathered granites. Thus, in Queensland, dieback has occurred on krasnozems derived from basalt (I. Bevege, *pers. comm.)* and mesozoic Stanthorpe granite (Bryan, 1954); in the A.C.T. on soils derived from granitic and volcanic rocks (Snowdon, 1971); in Victoria on soils derived from basalt (Marks and Minko, 1969); and in South Australia on soils derived from metamorphic rocks (Boomsma, 1949).

In New South Wales the authors have observed HSQ dieback on soils derived from basalts, diorites and strongly weathered granites. Dieback was reported in the 1930s in the early *P. radiata* plantings at Vulcan State Forest on basalt-derived soils, and also in second-rotation plantings on these same soils. Based on first assessment data (at age 9 years) from Continuous Forest Inventory plots, there have been substantial losses at Vulcan compared with plots established with the same nursery stock in the same planting years at the nearby Jenolan State Forest. The 1959, 1960, 1961 and 1962 plantings at Vulcan contain 28%, 7%, 21% and 47% respectively of plots which have less than 50% of the expected stocking. By contrast, the plots established in the same years at the Jenolan State Forest all contain more than 80% stocking. Extensive dieback was reported by Windsor and Kelly (1971) at Green Hills State Forest on soils derived from strongly weathered granite.

In all the Australian locations, despite their very high N, P, K and usually Ca and Mg status, a general property of the soils is a very low available sulphur and boron status which arises either intrinsically from the parent material composition, or as a result of intensive weathering. There is evidence in the case of basalts (MacNiven, 1972), that volatilisation of sulphur and boron (with variation depending on the magma temperature) occurred at the time of extrusion. Boron concentrations in igneous rocks (Rankama and Sahama, 1950) are generally low, ranging from 1-10 ppm boron compared with those of marine argillaceous sediments, 20-300 ppm boron. This difference is reflected in the soils derived from these parent materials and subsequently in the trees growing on these soils (*see* Table 3).

DIEBACK AND NUTRIENT DEFICIENCIES

Sulphur Deficiency

Dieback associated with sulphur deficiency has been observed by the authors in N.S.W. at Nundle, Nalbaugh, Buccleuch and Bondi State Forests (cf. Table 4). Gentle (1970) reported that extensive and sporadically occurring dieback in N.S.W. *P. radiata* plantations was linked with sulphur deficiency. Moderate sulphur deficiency is associated with overall winter yellowing, especially on cold exposed sites. When severe deficiency occurs, one to two metres of the leading shoot, or sometimes merely the terminal buds, die back, often with spectacular brownish-red or red-orange colourations. Needle bases are frequently much yellower than the remainder of the needle and Gentle (1970) regarded this as the best single visual diagnostic symptom available in *P. radiata.* Lyle (1969) reported that in solution culture, sulphur-deficient *Pinus taeda* L. seedlings developed a greenish-yellow colour beginning with the terminal needles. No part of the needle became pure yellow but some colour changes appeared to begin at or near the needle base rather than at the tip.

Sulphur is an essential element, if only because it is present in the amino acids, cysteine, cystine and methionine. Among other functions it has been suggested that the concentration of sulphydryl groups may be related to cold resistance (Coleman, 1966).

Sulphur is obtained not only from mineral soil and litter decomposition, but by foliar absorption of atmospheric sulphur dioxide (Mayer and Ulrich, 1974). However there is no atmospheric input in many *P. radiata* plantations in the eastern highlands, which are beyond the range of maritime influence or industrial effluents, and serious sulphur deficiencies may be found (Humphreys *et al.,* 1975).

Sulphur/Nitrogen relationships

In the foliage of *P. radiata*, a constant ratio has been found between organic nitrogen and organic sulphur (Kelly and Lambert, 1972). This was found to be the same as that in the foliar protein. Any sulphur in excess of that required to balance the nitrogen was accumulated as inorganic sulphate. Hence the inorganic sulphur content of the foliage provides an indicator of the sulphur status of the tree and the site, and is much more sensitive than total foliar sulphur. Sulphur ratings based on foliar sulphate levels (Turner *et al.,* 1977) have been derived for *P. radiata* (Table 1). For all samples in the field situation, total nitrogen was equal to organic nitrogen. If nitrogen is available in excess of the sulphur supply, sulphur becomes limiting for protein synthesis, and an induced sulphur deficiency is possible.

TABLE 1—Deficiency and sufficiency sulphate-S levels in **P. radiata** foliage (from Turner **et al.,** 1977)

Sulphur status	Foliar Sulphate-S levels (ppm)
Deficiency to incipient deficiency	0-80
Marginal to adequate	80-200
Adequate to high	200-400
High (possible N deficiency)	400+

Sulphur deficient trees have been found most frequently in N.S.W. in fast-growing plantations on soils derived from basalts and granites (Humphreys *et al.,* 1975). The data from *P. radiata* plantations presented in Table 2 and arranged in ascending order of mean sulphate-S, shows that while there is no evidence of sulphur deficiency in some forests (for example at Lidsdale and Newnes where atmospheric sulphur dioxide is available from the adjacent coal-burning Wallerawang Power Station), the range of foliar sulphate-S levels in most other forests is very large, varying from deficiency to sufficiency. On soils derived from sedimentary materials, the mean foliar sulphate-S levels are adequate with few deficient areas, while the levels from granitic soils depend more on the state of weathering and the closeness of unweathered (and thus relatively sulphur-rich) material to the surface. The foliar levels from soils derived from extrusive materials are generally low with a few areas in the adequate range.

Sulphur deficiency and fungal susceptibility

Our field observations suggested a relationship between sulphur deficiency and subsequent infection by a pathogen. In the majority of cases, the fungus has been identified as *Diplodia pinea* (Desm.) Kickx. (D. W. Edwards, *pers. comm.*).

In order to study a possible mechanism linking sulphur deficiency and fungal infection, some glasshouse solution culture experiments were carried out (Lambert *et al.,* 1976). *Pinus radiata* seedlings were grown in solutions with a constant level of ammonium nitrogen and with nitrate and sulphate levels varied by mutual substitution. All other nutrients were adequate. The most significant result from analyses of the seedlings was the presence of high levels of free arginine in the needles, stems and

TABLE 2—Foliar sulphate sulphur (ppm) and number of trees sampled, for **Pinus radiata** on soils derived from different parent materials; in order of increasing mean sulphate-S

Forest	Soil Parent Material	Foliar sulphate-S Mean	Range	S.D.	Sample
Wee Jasper	Basic extrusives	16	0-95	27	24
Clouds Creek	Tertiary basalt	20	0-60	24	12
Canobolas (er. A)	Tertiary basalt (eroded A horizon)	25	0-50	30	11
Mount Topper	Tertiary basalt	26	0-60	22	8
Mundaroo	Ordovician (O.) quartzite	26	5-120	43	11
Mannus	Mixed granites, O. quartzite	29	0-190	50	30
Green Hills (D)	Diorite	29	0-110	31	26
Green Hills (M.G.)	Mixed granites	35	0-145	39	20
Nundle (B)	Tertiary basalt flow B	43	0-120	39	11
Nundle (A)	Tertiary basalt flow A	43	0-180	49	28
Murraguldrie II	Ordovician sediments	45	0-145	46	23
Green Hills (G)	Granite	50	0-390	96	44
Bago	Basic extrusives	51	0-125	37	22
Bondi	Ordovician sediments	66	0-215	54	29
Nalbaugh	Devonian granite	80	0-470	100	28
Mullions Range	Rhyolite	83	0-370	79	38
Gurnang	Ordovician sediments	90	5-275	74	21
Carabost	Ordovician sediments	91	0-365	91	48
Uriarra	Granite	106	5-395	146	7
Mellong Range	Hawkesbury sandstone	110	60-190	49	12
Penrose	Hawkesbury sandstone	119	10-285	71	26
Murraguldrie I	Coarse-grained weathered granite	134	5-295	93	13
Jenalon	Silurian sandstone	135	25-320	94	15
Canobolas (in. A)	Tertiary basalt (intact A horizon)	141	0-425	127	23
Billapaloola	Basic extrusives	200	20-370	111	8
Sunny Corner	Silurian-upper D. s/stone-m/stone	209	0.445	124	36
Belanglo	Hawkesbury sandstone	211	65-445	110	17
Wingello	Hawkesbury sandstone	216	35-440	142	12
Newnes	Triassic sandstone	252	100-525	134	27
Vulcan	Permian granodiorite, O. volcanics	262	95-430	102	14
Old Depot	Tertiary basaltic sediments	282	85-650	171	12
Lidsdale	Permian sediments	356	120-740	164	27
Mount Gambier	Quarternary sands	518	270-850	199	6

TABLE 3—Foliar boron (ppm) for **P. radiata** on soils derived from different parent materials (see Table 2) in order of increasing boron levels

Forest	Foliar boron (ppm) Mean	Range	S.D.	Sample
Canobolas (er. A)	4	2-9	2.0	19
Wee Jasper	6	4-10	1.6	29
Vulcan	7	3-14	2.8	30
Billapaloola	8	4-15	3.1	11
Nundle (A)	8	5-13	2.0	36
Bago	10	4-16	3.4	15
Green Hills (D.)	10	4-27	5.7	29
Green Hills	13	5-26	4.9	31
Carabost	15	7-49	8.2	30
Mullions Range	16	8-27	4.5	34
Nundle (B.)	16	8-29	6.8	28
Clouds Creek	16	10-27	5.7	12
Wingello	16	10-28	4.5	12
Jenolan	17	7-40	6.5	35
Sunny Corner	17	8-32	5.3	40
Mundaro	17	10-23	4.8	11
Burnang	19	3-39	8.2	49
Murraguldrie I	19	5-32	9.0	14
Canobolas (in. A)	19	8-27	6.7	9
Old Depot	19	9-28	5.3	11
Mannus	21	4-36	9.7	30
Mellong Range	21	13-38	6.4	17
Murraguldrie II	24	18-45	8.4	23
Lidsdale	24	19-29	3.7	20
Belanglo	25	14-46	9.4	24
Uriarra	26	4-37	10.5	24
Green Hills (G)	26	10-46	8.9	46
Mount Topper	26	16-47	8.9	10
Newnes	26	20-37	4.6	24
Bondi	30	17-46	7.4	11
Penrose	31	16-45	7.8	15
Nalbaugh	39	20-62	11.2	28
Mount Gambier	41	36-45	3.4	6

roots of the sulphur-deficient plants. Accumulation of particular amino acids (such as arginine, asparagine and/or aspartic acid which are high nitrogen, non-sulphur-containing amino acids) has been reported in a number of sulphur deficient crop plants and appears to be a common mechanism for storing excess nitrogen when protein synthesis is limited by the absence of sulphur-containing amino acids such as methionine and cystine (Mertz *et al*, 1952; Coleman, 1957; Stabursvik and Heide, 1974). Therefore it appears likely that a build-up of particular amino acids occasioned by nutrient deficiency could provide an enhanced source of nitrogen for an infecting fungus (such as *D. pinea*) which has gained entry to the xylem through bark already weakened by the nutrient deficiency (Afzal, 1972).

In New Zealand, vigorous trees with plentiful nitrogen appeared to be much more susceptible to dieback (caused by *D. pinea*; Chou, 1976a; 1976b) than those that were nitrogen deficient (New Zealand Forest Service, 1971; p. 31).

In a study of the significance of *D. pinea* in Victorian plantations, Eldridge (1961) found that despite the presence of the most favourable conditions for damage by *D. pinea*, there was no conclusive evidence that the fungus alone had caused the deaths of any trees and he postulated that there was some other causative factor. Stahl (1968) reported that very little dead-topping occurred on sites where *P. radiata* was growing well. He suggested that *D. pinea* invaded only moribund tissue or a host that was in a weakened physiological condition, and that the defence mechanism of *P. radiata* tissue towards *D. pinea* broke down under heat or water stress. Peterson and Wysong (1968) reported severe damage to exotic pines by *D. pinea* in eastern Nebraska. Treatment with Bordeaux mixture reduced the infection by approximately 50 percent. This fungicide, as with most fungicides, has sulphur as well as copper as a major component (Schweitzer and Sinclair, 1976). It is possible that apart from the fungicidal action of copper, fungal infections can be controlled in some cases by improving the sulphur nutrition of the tree.

Boron Deficiency

Boron deficiency is involved in some but not all HSQ dieback sites. A deficiency of this element has frequently been associated with leader dieback and abnormal growth habits in *Pinus* species under a considerable variety of environmental conditions. Thus, for example, boron deficiency has been reported by Vail *et al.* (1961) in south east Africa for *P. patula* Schl.etCham. and *P. taeda.* White (1964) for *P. caribaea* Morelet and *P. patula* in the Territory of Papua and New Guinea, Van Goor (1966) for *Pinus elliottii* Engelm., *P. caribaea, P. patula* and *Pinus khasya* Royle in Brazil and Humphreys (1972) for *P. caribaea* in Fiji. Stone and Will (1965) have given a detailed description of the occurrence and symptoms of boron deficiency in *P. radiata* and *Pinus pinaster* Loud. in New Zealand. For *P. radiata,* it has also been described by Will *et al.* (1963) in New Zealand and Proctor (1967) in Tanzania, and in Australia by Smith (1943), Gentle (1966) and Snowdon (1971).

Severe boron deficiency in *Pinus* species results in repeated dieback of the apical meristems, and a failure to develop mature needles. Also the roots are reduced in size and number. As a consequence, such plants develop as bushes rather than as trees. Marginal boron deficiency leads to the growth of more or less normal trees which are subject to occasional leader dieback. Severe deficiency is usually associated with boron levels in *P. radiata* of 8 ppm or less, with marginal deficiency in the range 8-12 ppm boron. Both Snowdon (1971) and de Lanuza (1966) noted growth responses to boron with foliage levels up to 15 ppm.

There is a relationship between low foliar boron levels and soils derived from basalts and other extrusive rocks (Table 3). The wide range to be found at most of the locations reflects the considerable variability in the boron content of the parent materials. This variability occurs both intrinsically (different flows) and because of different weathering rates. The wide range also occurs because as discussed below, individual trees of *P. radiata* vary genetically in their ability to take up boron from the soil. We have found *P. radiata* wood from boron deficient sites to have approximately 1-4 ppm boron, not substantially less than the corresponding foliar boron levels. From these data, total boron immobilised in mature trees is of the same order as the total available soil boron on these sites (S. W. Gentle, *pers. comm.*).

Oram (1961) in reviewing the agricultural uses of boron, noted that the element has been shown to be closely connected with the movement of sugars, the sugar-starch balance, protein synthesis, respiratory activity, cell elongation, the behaviour of the meristem, and possibly with pectin synthesis. It has also been reported that boron is relatively immobile in plants, is intimately involved in reproduction and water relations of cells and that boron deficiency causes disintegration of terminal meristems (Hacskaylo *et al., 1969).* Snowdon (1971) reported that the earliest symptoms of boron deficiency in *P. radiata* are resin droplets or resin soaked areas on the upper needles and terminal buds. In some cases the terminal needles form a spindle-shaped cluster due to the adhesion of the needle tips to each other with resin. Usually death is restricted to the resin-soaked terminal buds, but deaths due to water stress are also evident in some cases, suggesting that stem damage has occurred. The ends of needles on affected plants are often chlorotic or necrotic and the needles are often distorted, as are many of the newly developing shoots. The pith in the affected area usually has a brown discoloration. He also indicated that damage to the vascular system is incurred where foliar boron concentrations are below 12 ppm. Dieback due to boron deficiency is therefore caused by vascular damage which impairs transport of water to the growing tip. Bud dieback and pith breakdown lead to malformations and to later wood utilisation problems.

Severe dieback symptoms frequently appear after frosts and particularly in hollows and hillside depressions. A connection between low boron levels and severe frost damage in *P. radiata* nursery seedlings was indicated by Gentle (1957). Normally pine growth is seasonal and pines can be expected to be dormant during the period when frost damage can be expected (Kozlowski, 1971).

Combined Sulphur and Boron Deficiencies

Gentle (1966) suggested sulphur and boron deficiencies as possible causes of dieback at Green Hills and Mannus State Forests, N.S.W. Yields were very high but log quality was poor due to multiple branching and leadering each year following bud damage. The two elements can be severely deficient singly or in combination, or marginally so, with a corresponding variation and wider range of symptoms. The variation in the extent of these combined deficiencies in igneous rocks (as discussed earlier) is due to the variability between volcanic flows, leading to high soil variability, and considerable differences can occur over a small forest area. This can be seen for example, at Nundle State Forest, N.S.W. Typical foliar analyses from trees located on soils from three adjoining but distinct basalt flows were (sulphate-S and B respectively) : 0 and 38 ppm; 80 and 6 ppm; 0 and 6 ppm. Thus the first flow was deficient in sulphur, the second in boron and the third in both. Foliar levels of both inorganic sulphur (Windsor and Kelly, 1971; Kelly and Lambert, 1972) and boron (Windsor and Kelly, 1971) fall to a minimum in autumn and spring. Hence in spring when demand is usually high, deficiency symptoms can be produced if these elements are limiting. Severe dieback symptoms also usually occur in spring or late summer, the seasons of greatest nutrient and moisture stress respectively.

The N.S.W. *P. radiata* plantations have been grouped in Table 4 according to the observed frequency and intensity of dieback. The reported values indicate the percentage of samples with deficient sulphur and boron levels (less than 80 ppm sulphate-S and 8 pp B respectively). The combination of these two categories indicates the percentage of samples with sulphur and boron deficiency problems. The forests have been grouped into three categories: (a) very frequent and widespread incidence of dieback; (b) periodic or patchy incidence of dieback; (c) insignificant or no incidence of dieback. The plantations (a) with high incidence of dieback have high percentages of samples with both sulphur and boron deficiency. The second grouping (b) have general deficiency levels of either sulphur or boron, while in the last group (c) the sulphur and boron levels are adequate. Either in combination or singly, sulphur and boron are related to the incidence of dieback over a very large area represented by these *P. radiata* plantations. This simultaneous variation in two elements has almost certainly baffled investigators who have relied primarily on visual symptoms and secondarily on fertiliser response patterns to diagnose dieback and could make many results and observations more readily explicable (see last section *Causes . . . .).*

There is also an increased possibility of dieback during a second rotation of *P. radiata* in those forests with sulphur and boron deficiencies, due to removal of these elements during the first rotation.

Dieback and Water Relations

In the sulphur/boron deficient areas, apart from severely deficient trees, many more trees are marginally deficient and appear to have increased susceptibility to adverse environmental conditions such as drought or frost. In N.S.W. plantations, most severe dieback occurs after periods of drought. Proctor (1965; 1967) reported that severe cases of dieback occurred in Tanzanian *P. radiata* plantations at the end of the first or more usually the second dry season after planting (11 or 23 months). In New Zealand also, increased incidence of dieback has been observed after dry periods (Will, 1971). Dieback does not always occur annually in the same location. Millikan and Anderson (1957) found the occurrence of dieback was related to years of poor rainfall and that the dieback symptoms were overcome by irrigation. Similarly S. W. Gentle *(pers. comm.)* observed a relationship between dieback and rainfall at Vulcan State Forest, N.S.W. Within the area on basaltic soils, severe dieback occurred in 1962 (850 mm rainfall) with little or no symptoms in 1963 (1122 mm rainfall) and 1964 (1045 mm rainfall), but very severe symptoms in the drought year of 1965 (524 mm rainfall).

TABLE 4—Frequency of boron and sulphur deficiency (as percentage of sample in each concentration range) in various **P. radiata** plantations grouped according to the observed frequency and incidence of dieback (**see** also Tables 2 & 3)

Forest	Parent material	Foliar boron (ppm)			Foliar sulphur ppm)		
		<8	8-12	<12	<80	80-120	<120
Very frequent and widespread incidence of dieback							
Bago	Basic extrusives	20	40	60	68	27	95
Green Hills	Diorite	45	34	79	92	8	100
Mannus	Mixed granite Ordivician quartzite	7	23	30	80	17	97
Nundle	Tertiary basalt flow A	56	42	98	71	21	92
Wee Jasper	Basic extrusives	79	21	100	92	8	100
Periodic or patchy incidence of dieback							
Billapaloola	Basic extrusives	55	36	91	13	13	26
Bondi	Ordivician sediments	0	0	0	72	21	93
Canobolas	Tertiary basalt (eroded A horizon)	89	11	100	43	4	47
Canobolas	Tertiary basalt (intact A horizon)	0	11	11	84	6	90
Carabost	Ordivician sediments	17	23	40	57	17	74
Clouds Creek	Tertiary basalt	0	33	33	100	0	100
Green Hills	Mixed granites	13	35	48	85	10	95
Green Hills	Granite	0	4	4	84	9	93
Gurnang	Ordivician sediments	8	16	24	57	10	67
Mount Topper	Tertiary basalt	0	0	0	100	0	100
Mundaroo	Ordivician quartzite	0	27	27	82	18	100
Murraguldrie I	Coarse-grained weather granite	21	7	28	38	8	46
Nalbaugh	Devonian granite	0	0	0	71	7	78
Nundle	Tertiary basalt flow B	0	29	29	82	18	100
Uriarra	Granite	8	8	16	71	0	71
Vulcan	Permian granodiorite, Ordivician volcanics	63	33	96	0	7	7
Insignificant or no incidence of dieback							
Belanglo	Hawkesbury sandstone	0	0	0	12	6	18
Jenolan	Silurian sandstone	6	20	26	23	13	36
Lidsdale	Permian sediments	0	0	0	0	0	0
Mellong Range	Hawkesbury sandstone	0	0	0	17	18	35
Mount Gambier	Quarternary sands	0	0	0	0	0	0
Mullions Range	Rhyolite	0	12	12	47	24	71
Murraguldrie II	Ordivician sediments	0	0	0	78	13	91
Newnes	Triasic sandstone	0	0	0	3	10	13
Old Depot	Tertiary basaltic sediments	0	9	9	0	8	8
Penrose	Hawkesbury sandstone	0	0	0	25	32	57
Sunny Corner	Silurian-upper Devonian, sandstone-mudstone	0	20	20	8	14	22
Wingello	Hawkesbury sandstone	0	8	8	8	25	33

HSQ dieback has been observed mainly in specific topographical situations. Snowdon (1971) reported that in the Australian Capital Territory, dieback most frequently occurred in hollows and hillside depressions particularly where the soils had poor internal drainage. The Tarawera Forest dieback in New Zealand was similarly located but without a drainage problem (Chou, 1976). These same topographical features (especially on sites subject to frost, and extremes of seasonal waterlogging and droughting) characterise the areas where HSQ dieback has been most severe in N.S.W.; at Mannus, Buccleuch, Vulcan and Nundle State Forests and on eroded areas of krasnozems at Canobolas State Forest. At this latter location, there are exposed cold areas at high altitudes (above 700 m) which are also susceptible to dieback.

DIEBACK AND MANAGEMENT PRACTICES

Site Preparation

Site preparation practices may accentuate tree boron deficiency dieback problems (G. J. Windsor, *pers. comm.).* Boron deficiency was intensified at Buccleuch State Forest, N.S.W. by removal of topsoil in windrowing. Also ripping and planting in rip lines in low wet sites, reduced root development and intensified tree boron deficiency.

Fertilisers

Nitrogen fertilisers can stimulate the early growth of *Pinus* species under certain circumstances. However because of the biochemical association between nitrogen and sulphur, in situations where sulphur is limiting, nitrogen fertilisation will lead to sulphur deficiency. This is illustrated by the case of a Douglas fir plantation in Washington State (Humphreys *et al.,* 1975) where addition of urea at 450 kg/ha caused reduction of foliar sulphate-S from 560-760 ppm to undetectable levels.

Correction of Deficiencies

Attempts to overcome sulphur and boron deficiencies have encountered technical difficulties because the soil types involved usually have low sulphate and borate sorption capacities. Soluble fertilisers are rapidly leached from the soil and responses are short-lived. Sulphate sorptions for two contrasting N.S.W. soils are shown in Table 5 (from Humphreys *et al.,* 1975). The Buccleuch site (low sulphate adsorption capacity) showed only slight sulphur uptake one year after fertiliser application. By contrast, at Wingello State Forest (high sulphate adsorption capacity) high foliar sulphur levels were maintained. Basalt-derived soils at Vulcan, Buccleuch and Nundle State Forests N.S.W. have very poor sorptive characteristics (J. Kelly, *unpubl.).* Boronated superphosphate gives lasting effects for boron but not for sulphur. Slow release sulphur fertilisers such as iron pyrites (Banath, 1969) and foliar fertiliser sprays need to be further investigated.

Genetic Variation and Inter-Species Competition

Clonal variation

The extent of dieback symptoms varies widely from tree to tree indicating genetic variability. Snowdon (1971) and Windsor and Kelly (1971) have both reported clonal differences in the nutrient status of *P. radiata* trees growing on soils with low boron status. Waring (1973) reported on four clones sampled at seven years of age, finding significant differences between foliar boron concentrations and susceptibility to dieback. Further significant differences for foliar boron and sulphate sulphur have been found between clones at Bago State Forest, N.S.W. (Table 6). Pawsey (1960; 1969) observed

TABLE 5—Effect of sulphur adsorption capacity of the soil on **P. radiata** foliar sulphur uptake after fertilisation (from Humphreys **et al.**, 1975)

Location	Fertiliser treatment	S sorption maximum of soil (μg/g)	Mean sulphate-S (ppm) Years after planting 0.5	1	2	3	7
Buccleuch (Wee Jasper)	N-P-K (25 g S/tree)	0.21	4	57	6	—	—
	Elemental S (25 g S/tree)		1	76	18	—	—
Wingello	Rock Phosphate + S (280 g/tree)	57.06	—	—	—	259	264
	Superphosphate (450 g/tree)		—	—	—	239	216

TABLE 6—Foliar boron and sulphate-S concentrations in **P. radiata** clones at Bago S.F., N.S.W.

Clone No.	Foliar boron (ppm) Tree No. 1	2	3	4	5	6		Mean
E 59	7	10	11	14	12	8		10
E 75	31	17	21	23	19	25		23
E 80	14	9	6	12	9	9		10
E 151	9	6	6	8	6	9		7
E 153	14	17	13	20	13	17		16
							LSD 0.05	5

Clone No.	Foliar sulphate-S (ppm) Tree No. 1	2	3	4	5	6	7	8	Mean
E 62	190	140	135	185	120	260	210	155	174
E 64	60	30	0	150	55	0	45	100	55
E 70	80	165	0	60	180	15	5	0	63
E 80	5	0	0	0	35	0	5	25	8
E 83	110	125	145	155	140	110	175	130	136
E 87	150	235	170	130	65	160	105	215	154
							LSD 0.05		47

differences in dieback symptoms between clones and their progeny on basalt soils and he attributed the differences to moisture stress. It seems possible therefore that stock can be selected or bred which is more efficient at taking up boron and sulphur than that at present routinely planted.

Species variation and competition

When foliar sulphur and boron concentrations in *P. radiata* are compared to those of other forest tree species located on the same soil type in N.S.W. (Table 7), it appears that *P. radiata* is relatively inefficient at obtaining these two elements. On basalt soils at Nundle State Forest, *Pseudotsuga menziesii* (Mirb.) Franco and *Pinus ponderosa* Laws both maintain much greater levels of boron and are significantly higher in total sulphur. At other locations on soil types other than basalts, *Pseudotsuga menziesii* and *P. ponderosa* both have higher boron levels than *P. radiata* but the results are more variable for total sulphur. *Pinus patula* and *P. taeda* usually have lower foliar boron

TABLE 7—Boron and total sulphur (ppm) in the foliage of adjacent species growing in various arboreta in N.S.W.

Location	Species	B (ppm)	Total S (ppm)
Nundle S.F. — 1	**Pinus radiata**	8	1160
	P. ponderosa	31	1360
	Pseudotsuga menziesii	14	1550
— 2	**P. radiata**	6	1170
	Pseudotsuga menziesii	25	1810
— 3	**P. radiata**	10	1170
	Pseudotsuga menziesii	39	1810
— 4	**P. radiata**	6	970
	P. ponderosa	20	1155
	P. patula	8	1105
Green Gap	**P. radiata**	11	1425
	P. ponderosa	25	1300
	Pseudotsuga menziesii	42	1820
Bulga S.F.	**P. radiata**	20	1230
	P. elliottii	32	1200
	P. taeda	11	1176
	P. patula	14	1675
	Pseudotsuga menziesii	45	1290
Camerons Camp	**P. radiata**	48	1330
	P. elliottii	16	970
	P. taeda	25	950
	P. patula	18	1345
Manning River	**P. radiata**	23	1275
	P. elliottii	26	830
	P. taeda	12	1055
	P. patula	15	1290

concentrations than *P. radiata.* The total sulphur concentrations are usually for *P. taeda,* lower than, and for *P. patula* higher than, those for *P. radiata.* The *Pseudotsuga menziesii* seed sources were generally trees located on glacial soils in British Columbia and Washington State. These soils have been found to be low in sulphur and in some cases, boron. The *P. ponderosa* seed sources were from pumice volcanic soils in Washington State. Hence, both these species have adapted to become efficient acquirers and utilisers of these nutrients. However, the *P. taeda* and *P. elliottii* seed sources were from situations where there are high sulphur and boron concentrations and in this respect are very similar to *P. radiata.* Thus, on the problem soils discussed earlier, it appears that species can be selected which are able to obtain sufficient sulphur and boron from the soil. They will thus not be susceptible to dieback and should maintain healthy growth.

Weed species which grow on boron and sulphur deficient sites, generally have higher tissue concentrations of boron and sulphur than *P. radiata.* The effect this has on decreasing the available nutrients for tree growth can be ascertained from Table 8. These data were compiled from a 2-year-old *P. radiata* plantation located at Nundle State Forest on basalt-derived soil where the associated weed species were primarily blackberry together with grasses and herbs. Three times more sulphur and five times more boron were immobilised in the weed species than in the trees. Thus it may be expected that weed suppression would alleviate some of the boron and sulphur problems.

There are two important implications from this genetic and species variation. Firstly, tree selection within species or species selection alone can be used for plantation establishment on affected sites and secondly, the role of weed species in competing for limiting amounts of sulphur and/or boron can be ascertained and steps taken if necessary to eliminate them.

TABLE 8—Biomass, sulphur and boron contents of **P. radiata** and associated weed species in a 2-year-old plantation located on a basalt derived soil

Species	Component	Biomass (kg/ha)	Sulphur (kg/ha)	Boron (g/ha)
P. radiata	Needles	171	0.25	1.88
	Branches	35	0.02	0.35
	Stem	109	0.07	1.09
	Total	315	0.34	3.32
Blackberry plants	Leaves	96	0.19	3.36
	Stems	307	0.23	3.68
Grasses and herbs		314	0.44	6.28
Litter		210	0.33	4.20
	Total	927	1.19	17.52

CAUSES OF PINUS RADIATA HIGH SITE QUALITY DIEBACK

We thus suggest that the incidence and variation in *P. radiata* high site quality dieback is often the direct result of sulphur and/or boron deficiencies in the trees. Dieback can occur directly as a result of these deficiencies or because these deficiencies have predisposed the trees to other agencies which can cause dieback. The dieback occurs because the vascular system becomes ineffective either directly because insufficient sulphur or boron or both are supplied from the soil (leading to structural weakness in the plant) or indirectly because due to these nutrient deficiencies, the fungus *D. pinea* has successfully invaded the shoot. Infection by *D. pinea can* be initiated in a number of ways but we consider it likely that ability of a tree to limit the entry and development of the fungus is strongly influenced by its sulphur status. Sulphur deficiency produces a metabolic malfunction which leads to apical bud resinosis and (hence facilitates the entry of the fungus into the shoot) and also leads to an accumulation of particular amino acids which would be favourable for the rapid growth of the fungus. Survival of seedlings in the field is apparently dependent on the absence of sulphur deficiency (indicated by presence of foliar inorganic sulphur) and this can be ensured by fertilisation with sulphur, or specific clonal selection. Dieback can be intensified by inappropriate species selection and/or weed competition, possibly by nitrogen fertilisation, by loss of top soil particularly in site preparation, and by accentuation of soil aeration problems by planting in rip or plough furrows in wet sites.

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APPENDIX 1. Materials and Methods

Foliage samples for analysis were taken from experimental plots and a series of nutrient surveys established by the Forestry Commission of N.S.W. For the surveys, co-dominant trees were selected within inventory plots and covered a range of age and productivity classes. The experimental plots were part of trial plantings and fertiliser trials. All foliage samples were taken only from untreated (control) plots. Foliage samples were collected in May-June (late autumn, early winter). They were taken from the full length of the previous twelve month's growth on the second main whorl beneath the leading shoot. Where necessary (for example with very young trees) all shoots on this whorl were included in the sample. Where biomass, total sulphur and total boron of **P. radiata** and associated weed species were determined, all plant material was removed using a grid of one square metre, taken to the laboratory and sorted.

All samples were dried at 70°C in a forced-draught oven for 36 h and ground to a fine powder (approx. 30 mesh or 500 μm). The chemical analyses were carried out according to the procedures described by Lambert (1976). Total nitrogen was determined by a micro Kjeldahl procedure. Boron was estimated using carmine after dry ashing. Total and inorganic sulphur were determined indirectly after precipitation of barium sulphate from an ash solution and dilute hydrochloric acid extract respectively, and estimation of the barium concentration by atomic absorption spectrophotometry.

The broad susceptibility ratings in Table 4 were derived from two sources:

(a) Results of disease surveys carried out by pathologists including specific instances of disease outbreaks.

(b) Field observations and reports on dieback situations and deaths (poor survival) of seedlings at plantings.

After consultation with field foresters, managers, biologists and nutritionists, the grouping of the forests into the three broad susceptibility ratings was agreed to. For those plantations grouped in the "very frequent" category at least one age class was observed to experience dieback annually. For those in the "periodic" category, particular age classes were affected by dieback only once every few years.