Woody tissue analysis using an element ratio technique (DRIS)

K. H. RIITTERS[1]
ManTech Environmental Technology, Inc., Research Triangle Park, NC 27709, U.S.A.
L. F. OHMANN
USDA Forest Service, North Central Forest Experiment Station, Grand Rapids, MN 55744, U.S.A.
AND
D. F. GRIGAL
Department of Soil Science, University of Minnesota, St. Paul, MN 55108, U.S.A.

Received December 5, 1990
Accepted March 22, 1991

RIITTERS, K. H., OHMANN, L. F., and GRIGAL, D. F. 1991. Woody tissue analysis using an element ratio technique (DRIS). Can. J. For. Res. **21**: 1270–1277.

The Diagnosis and Recommendation Integrated System (DRIS) was used to describe the variation of 12 elements in woody tree tissue of balsam fir (*Abies balsamea* (L.) Mill.), sugar maple (*Acer saccharum* Marsh.), jack pine (*Pinus banksiana* Lamb.), red pine (*Pinus resinosa* Ait.), and aspen (*Populus tremuloides* Michx.) across Minnesota, Wisconsin, and Michigan, United States. DRIS indices of elemental balance for the growth decades 1956–1965 and 1966–1975 were compared with standards developed from the growth decade 1976–1985. The DRIS analysis indicated that older wood of most species was relatively depleted of N, P, K, S, Fe, Cu, and Al. In at least one of the five species, however, K, S, Cu, or Al was relatively more abundant in older than in younger wood. The older wood of all species was relatively enriched in Ca, Mg, Mn, B, and Zn. Sulfur in older wood became relatively more enriched from west to east across a gradient of wet sulfate deposition; the trend was strongest for hardwood species. These results support the potential use of DRIS for monitoring stoichiometry of tissue from woody increment cores as an indicator of environmental stresses such as air pollution.

RIITTERS, K. H., OHMANN, L. F., et GRIGAL, D. F. 1991. Woody tissue analysis using an element ratio technique (DRIS). Can. J. For. Res. **21** : 1270–1277.

Le système intégré de diagnostic et de recommandation (DRIS) a été utilisé pour décrire la variation de 12 éléments dans le bois du sapin baumier (*Abies balsamea* (L.) Mill.), de l'érable à sucre (*Acer saccharum* Marsh.), du pin gris (*Pinus banksiana* Lamb.), du pin rouge (*Pinus resinosa* Ait.) et du peuplier faux-tremble (*Populus tremuloides* Michx.) à travers le Minnesota, le Wisconsin et le Michigan aux États-Unis. Les indices DRIS pour la balance des éléments pendant les décennies de 1956–1965 et 1966–1975 ont été comparés à des valeurs standard développées pour la décennie de 1976–1985. L'analyse avec DRIS a montré que le bois plus vieux était relativement dépourvu en N, P, K, S, Fe, Cu et Al chez la plupart des espèces. Chez au moins une des cinq espèces, par contre, soit K, S, Cu ou Al était relativement plus abondant dans le vieux bois que dans le jeune. Le vieux bois de toutes les espèces était relativement riche en Ca, Mg, Mn, B et en Zn. Le vieux bois devenait relativement plus riche en S d'ouest en est, suivant le gradient des dépôts humides de sulfate. Cette tendance était la plus marquée chez les feuillus. Les résultats confirment l'utilité de DRIS pour suivre l'évolution stoechiométrique de carottes de bois qui constitue un indicateur de stress environnementaux comme la pollution de l'air.

[Traduit par la rédaction]

Introduction

Element cycles within forests are important indicators of ecosystem functioning and could be monitored to describe the status and trends of regional forest conditions. Regional monitoring is complicated, however, because large-scale and long-term patterns of changes in element concentrations are sometimes complex and not well understood. Elemental concentrations may also be measured within plant tissues, because most element cycles include plant uptake, storage, and release. In this case, data analyses must consider smaller scale patterns and processes such as translocation in woody plants. Despite the potential complexity, there is evidence that elemental analyses of woody tissue from increment cores can be used in monitoring. For example, elements in woody tissue have been related to regional patterns of anthropogenic influences such as pollution (Baes and Ragsdale 1981; Robitaille 1981; Baes and McLaughlin 1984; Bondietti et al. 1989; Ohmann and Grigal 1990). If this type of monitoring is to be useful, reliable and general indices of wood elemental status that signal abnormalities in relation to normal, or base line, conditions are needed.

One possibility for such indices is the Diagnosis and Recommendation Integrated System (DRIS), a method developed for constructing indices of plant nutritional status from foliar nutrient analyses (Beaufils 1973). The DRIS index of a nutrient describes its status relative to other nutrients in comparison to its status in a reference (normal or optimal) population. Walworth and Sumner (1987) summarize experiences with DRIS in agronomy; forestry applications are presented by Truman and Lambert (1980), Leech and Kim (1979, 1981), Ward et al. (1985), Kim and Leech (1986), Schutz and de Villiers (1987), Svenson and Kimberley (1988), Hockman and Allen (1990), Hockman et al. (1989), Lozano and Huynh (1989), and Needham et al. (1990). A general conclusion from these studies is that DRIS can be used to interpret foliar nutrient content for the purpose of recommending fertilizer treatments to achieve high yields.

DRIS has been extended to nutrients in seeds (Hallmark et al. 1985) and soils (Beaufils and Sumner 1976; Evanylo et al. 1987) and could presumably be applied to yet other

[1]Author to whom all correspondence should be addressed.

Printed in Canada / Imprimé au Canada

components of the forest ecosystem. DRIS has also been used to interpret foliar analyses relative to tree quality and decline as opposed to commodity production (Schaffer et al. 1988; Hockman et al. 1989; Lozano and Huynh 1989). These results suggest the potential application of DRIS to plant tissue for monitoring of system states.

DRIS has several features that make it particularly applicable to regional monitoring. It applies to many species and simultaneously considers many elements, but information about particular species and elements can be partitioned in detailed analyses. DRIS stresses the detection of abnormalities as opposed to the explanation of all changes that might occur, yet biological understanding can be applied in a DRIS analysis. The method is flexible with respect to the reference population, and it can accommodate different definitions of normality (e.g., high yield or absence of decline) depending upon the needs for particular assessments of forest condition. Finally, DRIS can be developed solely from survey data, but can be further improved by experimental data that may be available.

To explore some possible applications of DRIS in monitoring forest ecosystems, one objective of this study was to extend DRIS to woody tissue from tree stem increment cores. A second objective was to show that a DRIS analysis reproduces a previously reported spatial relationship between S in wood and sulfate deposition from the atmosphere.

Methods

Field

The data were collected across the forested portions of Minnesota, Wisconsin, and Michigan. Plot selection has been documented in detail (David et al. 1988; Grigal and Ohmann 1989). Briefly, a stratified random sample of USDA Forest Service inventory plots within the three states was selected. Stratification was intended to balance the plots geographically and among five forest types: balsam fir (*Abies balsamea* (L.) Mill.) (n = 26), northern hardwoods dominated by sugar maple (*Acer saccharum* Marsh.) (n = 41), jack pine (*Pinus banksiana* Lamb.) (n = 39), red pine (*Pinus resinosa* Ait.) (n = 27), and aspen (*Populus tremuloides* Michx.) (n = 38).

Forest Service inventory plots are clusters of 10 subplots arranged in roughly an elliptic configuration, with measured trees selected with a probability proportional to their size (Doman et al. 1981). Total area of the 10 subplots is about 0.4 ha. At every other subplot (total = 5), a dominant or codominant tree of the most prevalent species on the plot was selected and used for wood tissue samples. The selected tree was required to have a diameter at breast height within 2.5 cm of the current plot mean diameter and to be representative of the topographic position of the plot. Increment core samples were collected from each sample tree to measure radial growth increment and to determine elemental concentration. At least nine cores from each tree (a minimum of 45 cores per plot) were collected with a stainless steel or Teflon-coated increment borer at breast height to determine N (three cores), S (three cores), and other elements (three cores). The cores included a minimum of 30 years of annual growth rings. Cores were placed in plastic straws labeled by tree and plot and were kept frozen until processed.

Laboratory

In the laboratory, the tree cores were thawed and the 1956–1985 growth was divided into three 10-year growth periods. Length of each increment was measured, and then increments were grouped with others of the same growth period from each tree (i.e., all 1956–1965 segments aggregated) and oven-dried at 65°C.

We analyzed tissue samples for total S by inductively coupled plasma atomic emission spectrometry (ICP) (ARL model 32000), and for N by semimicro Kjeldahl (Ohmann and Grigal 1990). Samples were analyzed for the other elemental concentrations by ashing (ca. 1 g) them overnight in a muffle furnace at 485°C. Five millilitres of 2 M HCl was added to the ash, and the crucibles were covered and placed on a hot plate at near boiling of the acidic solution for 30 min. After cooling, acid was added to the solutions in the crucibles to restore them to original weight. An additional 5 mL of HCl was then added, and the covered crucibles were allowed to stand overnight. Solutions were then transferred to tubes for analysis of Al, B, Ca, Cu, Fe, K, Mg, Mn, P, and Zn by ICP (ARL model 137). We evaluated our analytical accuracy by comparison of results of samples from the National Bureau of Standards, and our precision by including a standard check sample of wood tissue in the analytical procedure with every batch of samples and by analyzing duplicate samples.

Statistical analyses

Each sample was identified by species, geographic zone, and decade of growth. The concentrations for each element were scaled by a power of 10 such that the resulting values for different elements were of the same order of magnitude. A DRIS analysis (see Walworth and Sumner 1987) was then performed, with modifications as described later. The ratios of concentrations of all 66 possible pairs of elements were formed for each sample (products of concentrations were not considered here). These ratios were then transformed by natural logarithms to normalize their distributions (Svenson and Kimberley 1988) and to obviate the need to consider both a given ratio and its inverse in the DRIS analysis (Beverly 1987).

DRIS norms, standards from which elemental status is evaluated, were selected and estimated for each species by dividing the samples into two populations. The reference population included all samples from the growth decade 1976–1985, and the remaining samples made up the second population. Each element pair was then tested for its ability to discriminate between the two populations. A pair was judged discriminatory either if the means of the transformed ratio differed among populations by the t-test or if the variance of the transformed ratio in the reference population was lower than in the other population by the F-test. A p-value of 0.0001 was used for ascribing significance in both tests. Pairs that failed both tests were dropped from further consideration. DRIS norms were then computed for each of the retained pairs as the mean value of the transformed ratio in the reference population.

DRIS indices for elements were then calculated for each sample. To achieve this, standardized ratios were calculated for the selected pairs of elements by an equation similar to that given by Beverly (1987):

$$[1] \quad \Gamma_{A/B} = [\ln(A/B) - \beta_{A/B}]/\gamma_{A/B}$$

where

$\Gamma_{A/B}$ is the standardized ratio for the element pair (A,B)

TABLE 1. Means and coefficients of variation (CV) for log-transformed ratios of element concentrations in the reference population (entries in boldface type correspond to element ratios retained in the DRIS index calculations for a given species)

Element ratio	Aspen		Maple		Balsam fir		Jack pine		Red pine	
	Mean	CV	Mean	CV	Mean	CV	Mean	CV	Mean	CV
S/0.1*N*	**0.354**	**63**	**0.269**	**73**	**0.176**	**107**	**0.141**	**101**	**0.224**	**90**
S/*P*	**−0.228**	**365**	**−0.062**	**374**	**0.030**	**697**	**−0.071**	**173**	**−0.059**	**380**
S/0.1*K*	0.242	131	**0.339**	**40**	−0.221	251	**0.486**	**41**	**0.674**	**39**
S/.01Ca	**2.072**	**11**	**2.556**	**7**	**2.389**	**15**	**2.600**	**7**	**2.510**	**9**
S/0.1Mg	**1.578**	**21**	2.134	10	**1.830**	**274**	**1.778**	**7**	**1.682**	**14**
S/10Al	0.456	95	0.858	39	−0.178	274	−0.350	107	−0.513	68
S/Fe	**0.378**	**210**	**0.665**	**86**	−0.041	3067	0.040	1613	0.395	201
S/0.1Mn	0.340	190	−1.410	58	−1.700	44	**−1.267**	**38**	**−2.147**	**30**
S/Zn	1.464	27	3.094	14	1.992	25	1.692	29	**1.848**	**29**
S/10Cu	1.695	22	**2.223**	**11**	1.933	22	2.178	11	**1.972**	**15**
S/10*B*	0.903	53	1.056	24	0.725	171	**1.452**	**11**	0.928	123
0.1*N*/*P*	−0.581	139	**−0.331**	**83**	**−0.146**	**146**	**−0.212**	**10**	−0.282	96
0.1*N*/0.1*K*	−0.112	328	0.070	310	**−0.397**	**141**	0.355	65	0.450	72
0.1*N*/.01Ca	**1.719**	**18**	**2.287**	**11**	**2.213**	**17**	**2.460**	**10**	**2.287**	**12**
0.1*N*/0.1Mg	**1.225**	**35**	1.865	14	**1.654**	**34**	**1.637**	**9**	**1.458**	**21**
0.1*N*/10Al	**0.102**	**505**	0.590	66	−0.354	119	−0.491	82	−0.737	58
0.1*N*/Fe	0.012	6685	0.396	157	−0.217	594	−0.104	577	0.173	475
0.1*N*/0.1Mn	−0.010	6698	−1.679	52	−1.876	37	**−1.408**	**35**	**−2.371**	**28**
0.1*N*/Zn	**1.110**	**44**	2.825	18	1.816	30	**1.551**	**29**	**1.625**	**35**
0.1*N*/10Cu	1.339	31	1.954	16	1.757	23	2.038	13	1.748	19
0.1*N*/10*B*	0.550	82	0.784	30	0.549	215	**1.311**	**12**	0.704	166
P/0.1*K*	**0.470**	**205**	**0.401**	**52**	**−0.251**	**257**	**0.557**	**25**	0.733	28
P/0.01Ca	**2.300**	**39**	**2.618**	**12**	**2.359**	**20**	**2.671**	**7**	**2.569**	**9**
P/0.1Mg	**1.806**	**52**	**2.196**	**14**	**1.800**	**35**	**1.849**	**6**	**1.740**	**14**
P/10Al	**0.684**	**5**	0.920	46	**−0.208**	**197**	**−0.279**	**133**	−0.455	71
P/Fe	0.609	153	0.727	80	**−0.070**	**1846**	0.104	595	0.457	162
P/0.1Mn	**0.683**	**104**	−1.348	69	**−1.730**	**42**	**−1.197**	**41**	**−2.089**	**28**
P/Zn	**1.691**	**50**	**3.156**	**17**	**1.962**	**31**	**1.763**	**27**	**1.907**	**25**
P/10Cu	**1.917**	**36**	**2.285**	**10**	**1.903**	**23**	**2.249**	**10**	**2.030**	**11**
P/10*B*	**1.131**	**80**	**1.111**	**29**	**0.695**	**182**	**1.523**	**8**	0.987	122
0.1*K*/0.01Ca	**1.830**	**15**	**2.217**	**9**	2.610	12	**2.114**	**9**	**1.836**	**14**
0.1*K*/0.1Mg	**1.336**	**18**	**1.795**	**12**	2.051	12	**1.292**	**13**	**1.008**	**30**
0.1*K*/10Al	0.214	221	0.520	72	0.043	1222	−0.836	48	−1.187	30
0.1*K*/Fe	0.140	601	0.326	176	0.180	586	−0.447	128	−0.279	245
0.1*K*/0.1Mn	0.073	866	−1.749	48	−1.479	31	**−1.754**	**28**	**−2.822**	**23**
0.1*K*/Zn	1.222	38	2.755	18	2.213	26	**1.205**	**44**	**1.174**	**41**
0.1*K*/10Cu	1.451	33	1.884	13	2.154	24	1.692	14	**1.298**	**17**
0.1*K*/10*B*	0.661	98	0.720	38	0.946	165	**0.966**	**18**	0.254	426
0.01Ca/0.1Mg	−0.494	53	−0.422	42	−0.559	37	−0.822	22	−0.829	15
0.01Ca/10Al	−1.616	28	−1.698	19	**−2.567**	**17**	**−2.950**	**13**	**−3.024**	**13**
0.01Ca/Fe	**−1.693**	**47**	**−1.891**	**33**	−2.430	44	**−2.563**	**24**	−2.112	37
0.01Ca/0.1Mn	−1.747	40	−3.966	22	−4.089	15	−3.868	13	−4.658	12
0.01Ca/Zn	−0.609	83	0.538	93	−0.397	92	−0.909	53	−0.662	70
0.01Ca/10Cu	**−0.380**	**112**	**−0.333**	**83**	**−0.456**	**71**	**−0.422**	**50**	**−0.539**	**52**
0.01Ca/10*B*	−1.169	51	−1.499	18	−1.664	85	**−1.148**	**13**	−1.583	71
0.1Mg/10Al	−1.122	41	−1.276	29	**−2.008**	**28**	**−2.128**	**17**	**−2.195**	**18**
0.1Mg/Fe	**−1.191**	**69**	**−1.469**	**41**	**−1.871**	**53**	**−1.738**	**33**	−1.284	64
0.1Mg/0.1Mn	−1.258	49	−3.545	26	−3.530	16	−3.045	16	−3.829	14
0.1Mg/Zn	−0.115	409	0.960	53	**0.162**	**256**	−0.086	516	0.167	292
0.1Mg/10Cu	**0.118**	**386**	**0.089**	**351**	**0.103**	**464**	**0.400**	**46**	**0.290**	**104**
0.1Mg/10*B*	−0.675	104	−1.083	31	−1.105	140	**−0.326**	**45**	−0.754	147
10Al/Fe	**−0.082**	**1028**	−0.194	259	0.137	886	0.376	196	0.893	81
10Al/0.1Mn	−0.131	439	−2.269	40	−1.522	31	**−0.917**	**73**	**−1.634**	**42**
10Al/Zn	1.008	53	2.236	23	2.170	31	**2.042**	**26**	**2.361**	**23**
10Al/10Cu	**1.252**	**42**	1.365	28	2.111	19	2.528	16	2.485	14
10Al/10*B*	0.447	152	0.205	176	0.903	168	**1.802**	**19**	1.441	85
Fe/0.1Mn	**0.017**	**5235**	−2.075	50	−1.659	64	**−1.287**	**55**	−2.570	35
Fe/Zn	**1.069**	**70**	**2.429**	**25**	2.033	54	**1.659**	**44**	1.454	46
Fe/10Cu	1.292	59	1.558	38	1.974	64	2.144	25	1.578	44
Fe/10*B*	**0.534**	**173**	0.389	172	0.766	258	**1.414**	**44**	0.524	258
0.1Mn/Zn	1.114	63	4.505	14	3.692	22	**2.959**	**16**	3.996	15

TABLE 1 (*concluded*)

Element ratio	Aspen		Maple		Balsam fir		Jack pine		Red pine	
	Mean	CV	Mean	CV	Mean	CV	Mean	CV	Mean	CV
0.1Mn/10Cu	1.323	53	3.633	25	3.633	19	**3.446**	**12**	**4.119**	**14**
0.1Mn/10*B*	0.547	155	2.495	36	2.425	70	**2.719**	**17**	3.075	45
Zn/10Cu	0.229	202	**−0.871**	**60**	−0.059	912	**0.487**	**84**	**0.124**	**362**
Zn/10*B*	−0.560	116	−2.056	27	−1.267	115	−0.240	179	−0.920	139
10Cu/10*B*	−0.796	77	−1.163	31	−1.208	117	**−0.726**	**34**	−1.044	109

NOTE: The sample sizes for these statistics are as follows. Aspen: 44 for ratios not involving Fe, Mn, or Cu; 43 for ratios involving one of the set (Fe, Mn, Cu); 42 for ratios involving two of the set (Fe, Mn, Cu). Maple: 33 for ratios not involving B, otherwise 32. Balsam fir: 10 for all ratios. Jack pine: 19 for ratios not involving Fe, otherwise 18. Red pine: 71 for ratios not involving Fe, otherwise 69.

$\ln(A/B)$ is the natural logarithm of the ratio of concentrations of elements A and B in the sample

$\beta_{A/B}$ is the mean of $\ln(A/B)$ from the reference population

$\gamma_{A/B}$ is the coefficient of variation of $\ln(A/B)$ in the reference population

The standardized ratios for each sample were then entered into index equations of the form

$$[2] \quad I_A = n^{-1} \sum_{i=1}^{n} \{\Theta \Gamma_{A/B}\}$$

where

I_A is the DRIS index for element A

n is the number of element pairs retained that include element A

Θ is equal to 1 if element A appears as the numerator in $\Gamma_{A/B}$ and -1 if element A appears as the denominator in $\Gamma_{A/B}$

The summation in eq. 2 is over all pairs that include the element of interest.

A positive (or negative) value for a DRIS index for a given element derived in this way indicates that the balance among elements has shifted towards (or away from) that particular element in the sample, in comparison with the elemental balance observed in the reference population. The changes for any single element are only relative to the other elements in the index equation. A zero value indicates that the balance for that element has not changed.

It is possible to use other reference populations. If, for example, the reference population was defined as the earliest growth decades, then the signs of the DRIS indices for each element would change. But the interpretation would be equivalent because the indices would then be defined relative to older wood rather than younger wood. The DRIS technique is more robust when the reference population is chosen to minimize the variances of element ratios (Beaufils 1973).

When all possible ratios are retained in the DRIS index equations, the DRIS indices for a given sample will sum to zero; the magnitudes of DRIS indices for different elements can then be compared directly (see Walworth and Sumner 1987, p. 163). This occurs because a positive contribution by any ratio to one index (e.g., $+\Gamma_{A/B}/n$ for element A's index) is exactly balanced by a negative contribution to another index (e.g., $-\Gamma_{A/B}/n$ for element B's index). Although all ratios were not retained in the present application, DRIS indices for different elements are still directly comparable under one condition: that the $\Gamma_{A/B} = 0$ for the ratios that were not retained. It is reasonable to assume that the condition has been met on average in our approach, because according to one criterion used to select ratios, a t-test, the differences in means of the ratios in question were not significant.

In any case, the index values for a given element can be related to features such as position within the tree or the geographic zone from which the sample was taken. To compare changes in elemental balance for different positions within trees, the means and standard errors of DRIS indices were calculated for each species by decade of growth, averaging over geographic zones. Analysis of variance was used to test for differences in the mean DRIS S index among geographic zones, and covariance analysis was used to test for an overall relationship between the S indices for all species and wet sulfate deposition (7.5, 10.0, 11.8, 16.3, and 18.3 kg·ha^{-1}·year^{-1} for zones 1 through 5, respectively) as reported by Ohmann and Grigal (1990).

Results and discussion

Table 1 contains the means and coefficients of variation of the log-transformed element ratios by species in the reference populations. Nearly all of the element pairs retained in the DRIS index equations (shown in boldface type) met the t-test selection criterion. In general, these ratios included at least one element that is considered to be relatively mobile in plant tissue, and ratios of pairs of relatively immobile elements were rarely included. The ratios that were retained did not include Al and Mn in sugar maple and Fe and B in red pine. Therefore, DRIS index equations were not estimable for those combinations of species and elements. Of the 66 possible ratios, 28 pairs were retained for aspen, 23 for balsam fir, 45 for jack pine, 22 for sugar maple, and 30 for red pine.

As an example of calculation of a DRIS index, the sugar maple reference norms that include N are $0.1N/P = -0.331$, $0.1N/0.01\text{Ca} = 2.287$, and $S/0.1N = 0.269$ (Table 1). The DRIS N index (I_N) for sugar maple is calculated by using these values and their associated coefficients of variation as

$$[3] \quad I_N = (1/3)[(\ln(0.1N/P) + 0.331)/83 + (\ln(0.1N/0.01\text{Ca}) - 2.287)/11 - (\ln(S/0.1N) - 0.269)/73]$$

where N, P, Ca, and S refer to the concentrations of those elements in the particular sample.

Figure 1 illustrates the DRIS indices in relation to decade of growth for each species and element. By definition, the indices for the decade 1976–1985 are near zero. All indices

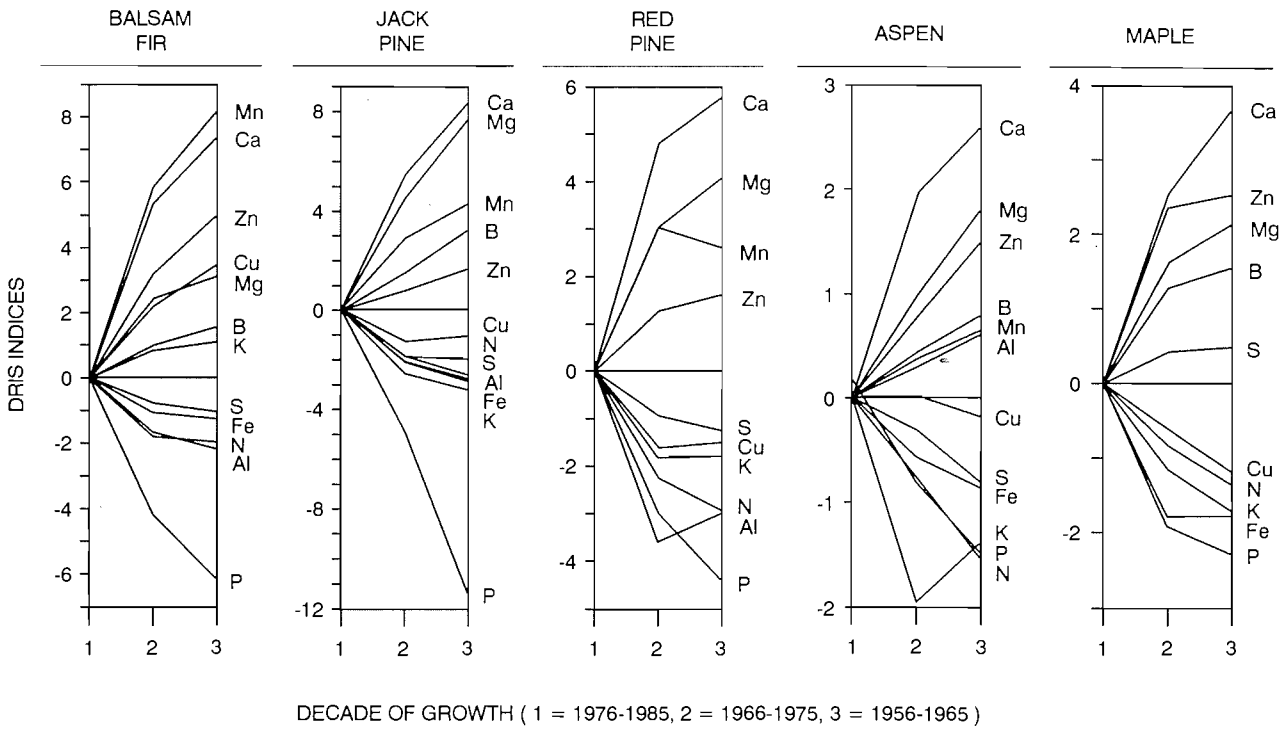

FIG. 1. Elemental DRIS indices (which have been multiplied by 0.01) in relation to decade of growth for five species. See text for derivation of DRIS indices.

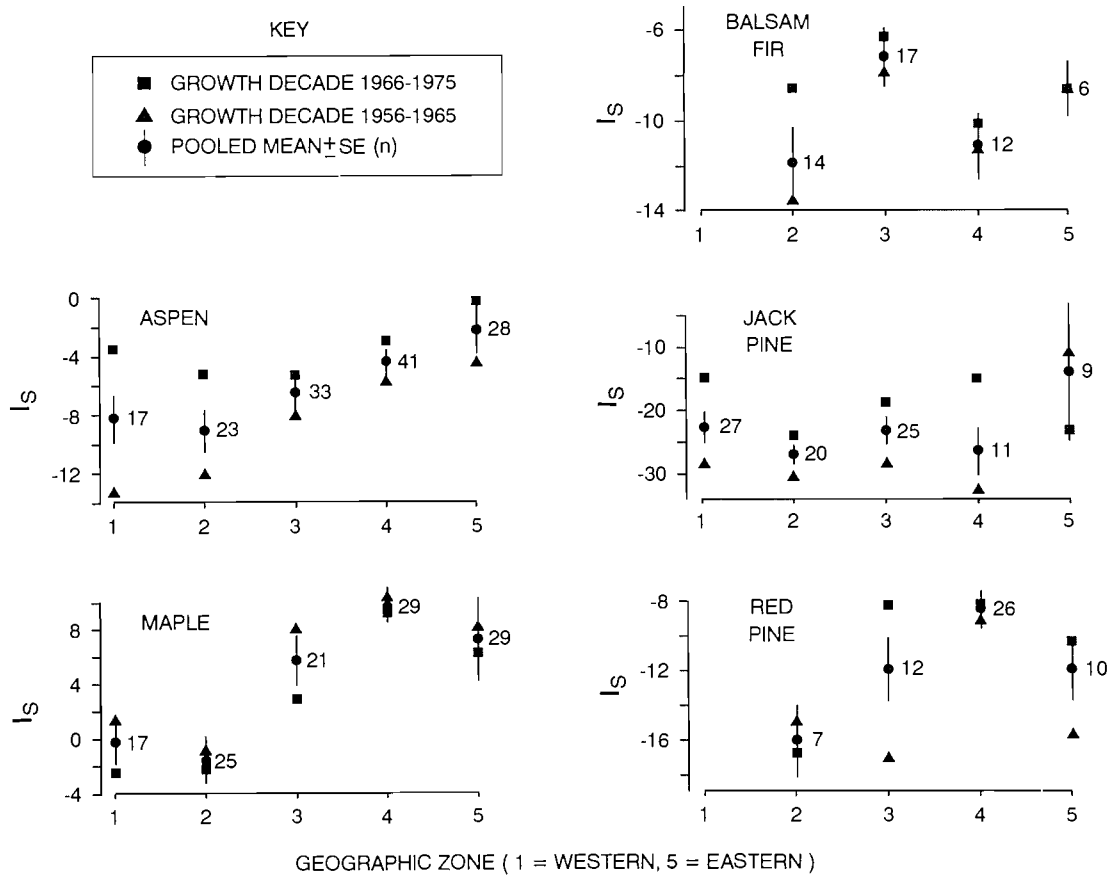

FIG. 2. Mean DRIS sulfur indices (I_s; which have been multiplied by 0.1) by species and geographic zone. Shown are the means of each of two growth decades, and the pooled means with standard errors and sample sizes. The standard errors were calculated separately for each zone and species.

TABLE 2. Analysis of variance of the DRIS sulfur index in relation to geographic zone by species (the analysis includes all samples for the growth decades 1956–1965 and 1966–1975)

Species and source	df	Mean square	*F*-ratio	*p*-value
Aspen				
Zone	4	0.000 200	4.44	0.002
Error	137	0.000 045		
Maple				
Zone	4	0.000 572	7.33	<0.001
Error	107	0.000 078		
Balsam fir				
Zone	3	0.000 065	2.55	0.068
Error	45	0.000 026		
Jack pine				
Zone	4	0.000 299	1.50	0.210
Error	87	0.000 200		
Red pine				
Zone	3	0.000 119	2.30	0.088
Error	51	0.000 052		

NOTE: The error is for among samples within a geographic zone.

TABLE 3. Analysis of covariance of the DRIS sulfur index in relation to estimated sulfate deposition levels for the growth decades 1956–1965 and 1966–1975

(A) Analysis of covariance

Source	df	Mean square	*F*-ratio	*p*-value
Species	4	0.009 279	107.75	<0.001
Sulfate deposition	1	0.002 258	26.23	<0.001
Error	444	0.000 086		

(B) Estimated sulfate deposition by geographic zone*

Zone	Sulfate deposition ($kg \cdot ha^{-1} \cdot year^{-1}$)
1	7.5
2	10.0
3	11.8
4	16.3
5	18.3

*From Ohmann and Grigal (1990).

for the decades 1956–1965 and 1966–1975 are at least four standard errors different from zero (standard errors are not shown), except for the Cu indices in aspen. Significant differences are expected because of the way the DRIS indices are defined, but the apparent trends can be interpreted qualitatively. For most elements, there is a consistent effect of wood age on DRIS index; the absolute value of the index increases for older wood. DRIS indices are not independent of sample position within trees.

The DRIS indices for the 1956–1965 decade indicate the relative tendencies for elements to appear depleted or enriched in older wood in comparison to younger wood. A qualitative interpretation of these data indicates that the older wood of most species appears to be relatively depleted of N, P, K, S, Fe, Cu, and Al, as indicated by a negative mean DRIS index for those elements. In at least one of the five species, however, K, S, Cu, or Al appears to be relatively enriched (indicated by a positive mean DRIS index) in older wood. The older wood of all species appears to be relatively enriched in Ca, Mg, Mn, B, and Zn.

The apparent differences in Fig. 1 may reflect either (or both) the translocation of mobile elements from older tissue to more metabolically active, younger tissue (McClenahen et al. 1989) or the decreased availability and uptake of cations during the most recent decade (Bondietti et al. 1989). The underlying reason cannot be decided based on DRIS indices alone because they do not indicate differences in the absolute concentrations of the elements in wood of different ages.

Examining concentrations, not ratios of individual elements from these same wood samples, Ohmann and Grigal (1991) found an increase in concentration of certain elements (Ca, Mg, and Mn) and a decrease in others (P), from the outer (most recent) decade of growth tissue to the oldest inner decade of tissue. The same pattern has also been reported for red pine by Tendel and Wolf (1988), who described a group of elements that decreased in concentration from older to younger wood (Ca, Mg, Mn, Zn, Al, Pb, and Cd) and a second group that increased in concentration (K, P, S, Fe, Cu, and N). These observations suggest that translocation of mobile elements within woody tissue is the reason for the observed differences in element ratios (see also Kohno et al. 1988; Lovestam et al. 1990).

DRIS S indices vary with geographic zones (Fig. 2). The significance of differences (*p*-values) in the pooled mean values for both growth decades among geographic zones is 0.002 for aspen, <0.001 for sugar maple, 0.068 for balsam fir, 0.210 for jack pine, and 0.088 for red pine (Table 2). The linear regression coefficient for the DRIS S index in relation to estimated sulfate deposition, adjusted for species, was significant ($p < 0.001$) and had a positive sign (Table 3). The trend of an increasing DRIS S index from west to east in the geographic zones studied is consistent with an earlier report (Ohmann and Grigal 1990) of increased S concentration in trees associated with increased sulfate deposition. The DRIS interpretation of this trend is that S becomes less depleted in older wood, relative to its balance with other elements in younger wood, from west to east across the deposition gradient. We can speculate that less S was translocated to meet the needs of actively growing tissue in areas where more S was available from the external environment. In any case, the observed trend strengthens the circumstantial evidence that sulfate deposition has an effect on elemental cycling in these trees.

Conclusion

We have demonstrated the application of DRIS to elemental analyses of tree increment cores and suggested ways that DRIS indices could be constructed and interpreted as part of regional forest monitoring. We hope our work will stimulate further research and applications of methods such as DRIS for constructing and interpreting multivariate indices based on forest monitoring data. DRIS is not a panacea, but it contributes unique information that is not available by other

methods. For example, Ohmann and Grigal (1990) showed that the S:N molar ratio increased with age of wood for the same data used in the present study. The DRIS interpretation emphasizes that this outcome is the net result of differing changes in both S and N relative to many other elements. Neither DRIS indices nor molar ratios alone can be used to infer changes in absolute concentrations of elements, but both are pieces of the total puzzle that must be solved by scientists when explaining forest status and trends.

Acknowledgments

Funding was provided by the United States Environmental Protection Agency Environmental Monitoring and Assessment Program, the USDA Forest Service National Vegetation Survey, and the Minnesota Agriculture Experiment Station under project 25-054. Although the research described in this article has been funded in part by the United States Environmental Protection Agency through contracts 68-02-4444 and 68-D0-0106 to ManTech Environmental Technology, Inc., it has not been subjected to Agency review and therefore does not necessarily reflect the views of the Agency, and no official endorsement should be inferred. Mention of trade names or commercial products does not constitute endorsement or recommendation for use.

BAES, C.F., III, and MCLAUGHLIN, S.B. 1984. Trace elements in tree rings: evidence of recent and historical air pollution. Science, **2**: 494–496.

BAES, C.F., III, and RAGSDALE, H.L. 1981. Age-specific lead distribution in xylem rings of three tree genera in Atlanta, Georgia. Environ. Pollut. **2**: 21–35.

BEAUFILS, E.R. 1973. Diagnosis and recommendation integrated system (DRIS). Department of Soil Science and Agro-Meteorology, University of Natal, Pietermaritzburg, South Africa. Soil Sci. Bull. No. 1.

BEAUFILS, E.R., and SUMNER, M.E. 1976. Application of the DRIS approach for calibrating soil and plant factors in their effects on yield of sugarcane. Proc. Annu. Congr. S. Afr. Sugar Technol. Assoc. **50**: 118–124.

BEVERLY, R.B. 1987. Modified DRIS method for simplified nutrient diagnosis of 'Valencia' oranges. J. Plant Nutr. **10**: 1401–1408.

BONDIETTI, E.A., BAES, C.F., III, and MCLAUGHLIN, S.B. 1989. Radial trends in cation ratios in tree rings as indicators of atmospheric deposition on forests. Can. J. For. Res. **19**: 586–594.

DAVID, M.B., GRIGAL, D.F., OHMANN, L.F., and GERTNER, G.Z. 1988. Sulfur, carbon, and nitrogen relationships in forest soils across the northern Great Lakes States as affected by atmospheric deposition and vegetation. Can. J. For. Res. **18**: 1386–1391.

DOMAN, A.P., ENNIS, R., and WEIGEL, D. 1981. North Central resources evaluation field instructions. USDA Forest Service, North Central Forest Experiment Station, St. Paul, MN.

EVANYLO, G.K., SUMNER, M.E., and LETZSCH, W.S. 1987. Preliminary development and testing of DRIS soil norms for soybean production. Commun. Soil Sci. Plant Anal. **18**: 1355–1377.

GRIGAL, D.F., and OHMANN, L.F. 1989. Spatial patterns in elemental concentrations of the forest floor across the north central United States. J. Environ. Qual. **18**: 368–373.

HALLMARK, W.B., ADAMS, J.F., and MORRIS, H.F. 1985. Detection of zinc deficiency in soybeans by the diagnosis and recommendation integrated system using seeds. J. Fert. Issues, **2**: 11–16.

HOCKMAN, J.N., and ALLEN, H.L. 1990. Nutritional diagnoses in loblolly pine stands using a DRIS approach. *In* Sustained Productivity of Forest Soils. Proceedings of the 7th North American Forest Soils Conference, 1988, Vancouver, B.C. *Edited by* S.P. Gessel, D.S. Lacote, G.F. Weetman, and R.F. Powers. University of British Columbia, Faculty of Forestry, Vancouver. pp. 500–514.

HOCKMAN, J.N., BURGER, J.A., and SMITH, D.W. 1989. A DRIS application to Fraser fir Christmas trees. Commun. Soil Sci. Plant Anal. **20**: 305–318.

KIM, Y.T., and LEECH, R.H. 1986. The potential use of DRIS in fertilizing hybrid poplar. Commun. Soil Sci. Plant Anal. **17**: 429–438.

KOHNO, M., KOISUMI, Y., OKUMURA, K., and MITO, I. 1988. Distribution of environmental cesium-137 in tree rings. J. Environ. Radioact. **8**: 15–19.

LEECH, R.H., and KIM, Y.T. 1979. Assessment of nutrient requirements of poplars. *In* Poplar Research, Management and Utilization in Canada. Proceedings of the North American Poplar Council Annual Meeting, 1977, Brockville, Ont. *Edited by* D.C.F. Fayle, L. Zsuffa, and H.W. Anderson. Ontario Ministry of Natural Resources, Toronto. For. Res. Inf. Pap. No. 102. pp. 15-1–15-16.

———— 1981. Foliar analysis and DRIS as a guide to fertilizer amendments in poplar plantations. For. Chron. **57**: 17–21.

LOVESTAM, G., JOHANSSON, E.M., JOHANSSON, S., and PALLON, J. 1990. Elemental micro patterns in tree rings—a feasibility study using scanning proton microprobe analysis. Ambio, **19**: 87–93.

LOZANO, F.C., and HUYNH, K.D. 1989. Foliar diagnosis of sugar maple decline by DRIS. Commun. Soil Sci. Plant Anal. **20**: 1895–1914.

MCCLENAHEN, J.R., BIMMERSTEDT, J.P., and SCHERZER, A.J. 1989. Elemental concentrations in tree rings by PIXE: statistical variability, mobility, and effects of altered soil chemistry. Can. J. For. Res. **19**: 880–888.

NEEDHAM, T.D., BURGER, J.A., and ODERWALD, R.G. 1990. Relationship between Diagnosis and Recommendation Integrated System (DRIS) optima and foliar nutrient critical levels. Soil Sci. Soc. Am. J. **54**: 883–886.

OHMANN, L.F., and GRIGAL, D.F. 1990. Spatial and temporal patterns of sulfur and nitrogen in wood of trees across the north central United States. Can. J. For. Res. **20**: 508–513.

———— 1991. Properties of soils and tree wood tissue across a Lake States sulfate deposition gradient. USDA For. Serv. North Central For. Exp. Stn. For. Resour. Bull. NC-130.

ROBITAILLE, G. 1981. Heavy-metal accumulation in the annual rings of balsam fir *Abies balsamea* (L.) Mill. Environ. Pollut. **2**: 193–202.

SCHAFFER, B., LARSON, K.D., SNYDER, G.H., and SANCHEZ, C.A. 1988. Identification of mineral deficiencies associated with mango decline by DRIS. HortScience, **23**: 617–619.

SCHUTZ, C.J., and DE VILLIERS, J.M. 1987. Foliar diagnosis and fertiliser prescription in forestry—the DRIS system and its potential. S. Afr. For. J. **141**: 6–12.

———— 1988. Foliar diagnosis and fertilizer prescription in forestry: the DRIS system and its potential. *In* Forest site evaluation and long-term productivity. *Edited by* D.W. Cole and S.P. Gessel. University of Washington Press, Seattle. pp. 34–43.

SVENSON, G.A., and KIMBERLEY, M.O. 1988. Can DRIS improve diagnosis of nutrient deficiency in *Pinus radiata*? N.Z. J. For. Sci. **18**: 33–42.

TENDEL, J., and WOLF, K. 1988. Distribution of nutrients and trace elements in annual rings of pine trees (*Pinus sylvestris*) as in indicator of environmental changes. Experientia, **44**: 975–980.

TRUMAN, R., and LAMBERT, M.J. 1980. The use of DRIS indices to determine the balance between nitrogen, phosphorus and sulphur in *Pinus radiata* foliage. *In* Managing nitrogen economies of natural and man-made forest ecosystems. *Edited by* R.A. Rummery and F.J. Hingston. Commonwealth Scientific and Industrial Research Organization, Division of Land and Resource Management, Mandurah, West Australia. pp. 369–377.

WALWORTH, J.L., and SUMNER, M.E. 1987. The Diagnosis and Recommendation Integrated System (DRIS). Adv. Soil Sci. **6**: 149–188.

WARD, S.C., PICKERSGILL, G.E., MICHAELSON, D.V., and BELL, D.T. 1985. Responses to factorial combinations of nitrogen, phosphorus, and potassium fertilizers by saplings of *Eucalyptus saligna* Sm., and the prediction of the responses by DRIS indices. Aust. For. Res. **15**: 27–32.