Bulk Density of Forested Mineral Soils

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Relationships between bulk density and organic matter (OM) content, textural properties and depth are described for forested mineral soils from central and northern Finland. Core samples were taken of the 0–5, 30–35 and 60–65 cm layers at 75 plots. Three measures of bulk density were calculated: the bulk density of the < 20 mm fraction (BD_{20}), the bulk density of the < 2 mm fraction (BD_2), and laboratory bulk density (BD_l). BD_l was determined from the mass of a fixed volume of < 2 mm soil taken in the laboratory. All three measures of bulk density were strongly correlated with organic matter content ($r \geq -0.63$). Depth and gravel (2–20 mm) content (in the case of BD_2) were also important variables. BD_l was sensitive to clay contents > 7% but did significantly improve the prediction of both BD_2 and BD_{20} in coarse soils (clay contents ≤ 7%). The following predictive models were derived for coarse soils: $BD_2 = 0.7668 - 0.08523 \cdot \sqrt{OM} - 0.01217 \cdot Gravel + 0.1852 \cdot Depth + 0.4318 \cdot BD_l$, $R^2 = 0.86$ and $BD_{20} = 0.4718 - 0.01598 \cdot OM + 0.3125 \cdot Depth^2 + 0.5962 \cdot BD_l$, $R^2 = 0.86$ (BD_2, BD_{20} and BD_l in kg/dm^3, OM content as % of < 2 mm oven-dry soil and Gravel content as % < 20 mm air-dry soil, and Depth in m).

Keywords bulk density, organic matter, soil physical properties, regression analysis.
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1 Introduction

Bulk density is an important soil physical property. It is needed in order to convert soil chemical data, routinely expressed as mass concentrations, into amounts per unit area or unit volume (e.g. Viro 1951, Mälkönen 1974, Westman et al. 1985, Derome et al. 1986, Tamminen 1991). Because it is an index of soil compaction, bulk density is an important soil property affecting site productivity directly. Thus, bulk density has been found to correlate with root density (Strong and La Roi 1985, Gale and Grigal 1987) and tree growth (Hamilton and Krause 1985, Froelich et al. 1986). Bulk density has often been found to be strongly correlated to soil organic matter content and soil texture (Alexander 1980, Harrison and Bocock 1981, Rawls 1983, Alexander 1989, Grigal et al. 1989, Huntington et al. 1989, Manrique and Jones 1991).

The determination of bulk density necessitates the taking of volumetric soil samples. However, it is often difficult and time consuming to take representative volumetric samples of mineral soil, particularly when stony. Forest soils in Finland are typically stony and reported bulk density values are sparse (Westman et al. 1985, Niska 1986).

Our aim in this paper is to present bulk density values and various regression models based on routinely determined soil properties–organic matter and soil textural variables. These models can be used to estimate bulk density.

2 Material and Methods

During 1987–1989, volumetric mineral soil samples were taken from 75 sample plots located throughout central and northern Finland (Fig. 1). Chemical soil properties of some of the plots have been described by Tamminen and Starr (1990) and acidity (pH) of all of the plots by Starr and Tamminen (1992). All the sample plots are part of a network of permanent plots belonging to the 8th National Forest Inventory and are regularly monitored for forest condition and needle chemistry (Salemaa et al. 1991).

A volumetric sample of the 0–5 and 30–35 cm layers was taken from 2–3 soil pits dug around each plot (300 m^2, r = 9.77 m) and the samples composited by layer. One of the pits was deepened and a volumetric sample of the 60–65 cm layer taken (plots sampled in 1988 and 1989 only). The samples were taken using a sharpened steel cylinder (d = 72 mm, h = 50 mm). The cylinder was fitted with a protective metal cap and pushed into the soil – using a hammer, if necessary. The soil-filled cylinder was then carefully dug free and soil extending beyond the open end of the cylinder was trimmed flush. The metal cap was then removed and soil core pushed into a plastic bag. Stones (> 20 mm) and large roots were avoided.

The samples were air-dried (40–50°C) and weighed. They were then passed through a 2 mm sieve and the mass of the 2–20 mm (gravel) and < 2 mm (fine-earth) fractions recorded. The moisture content of the air-dried soil (> 6h drying at 105°C) and loss-on-ignition of the oven-dried soil (3h at 550°C) were determined from a subsample of the fine-earth fraction. Particle size analysis was determined using pipetting and sieving procedures (Elonen 1971, Heiskanen and Tamminen 1992). The fines (< 63m) fraction, expressed as a percentage of < 20 mm air-dry mass of soil, and sorting index of the < 20 mm air-dry soil ($SI = \sqrt{d75 / d25}$, where *d75* and *d25* are the particle sizes at the 75th and 25th quartiles) were calculated from the resulting particle size distributions. The organic matter contents and textural properties are described in Table 1.

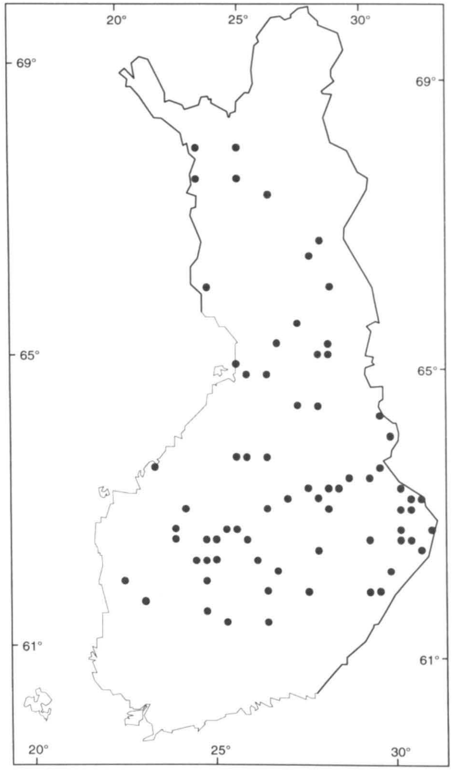

Fig. 1. Location of the sampling sites.

Three different measures of bulk density were calculated: 1) the ratio of the soil sample (< 20 mm) mass to the sample volume at time of sampling (BD_{20}), 2) the ratio of the sample's fine-earth fraction mass to the sample volume at time of sampling (BD_2), and 3) the mass:volume ratio of 15 ml of fine-earth soil (BD_l). BD_l (laboratory bulk density) was determined by filling a calibrated 15 ml scoop with air-dried < 2 mm soil, tapping it ten times, and removing any excess. If necessary, the scoop was topped-up with more soil, tapped twice and the excess removed. The mass of this 15 ml of soil was then recorded. Laboratory bulk density is commonly determined for agricultural soils (Erviö 1970). All three measures of bulk density are reported on an oven-dry mass basis.

Table 1. Mean, range and coefficient of variation (%) values for clay, gravel and organic matter (OM) contents and sorting index ($SI = \sqrt{d75 / d25}$) by sampling layer.

Soil layer	Property	x̄	Range	cv	n
0–5 cm	Clay, %	5.3	0.6–51.1	169	75
	Gravel, %	5.6	0.0–26.0	98	
	SI	3.2	1.5–12.8	57	
	OM, %	5.2	0.5–20.5	76	
30–35 cm	Clay, %	4.4	0.2–48.4	192	60
	Gravel, %	9.9	0.0–37.7	92	
	SI	3.3	1.4–7.2	48	
	OM, %	1.8	0.4–7.4	66	
60–65 cm	Clay, %	2.2	0.2–7.5	92	23
	Gravel, %	10.0	0.0–44.4	120	
	SI	3.2	1.4–10.4	65	
	OM, %	0.9	0.2–3.2	79	

3 Results

The magnitude of bulk density decreased in the order: $BD_l > BD_{20} > BD_2$ (Table 2). Variability was least for BD_{20} and highest for BD_2 and decreased with depth. The three measures of bulk density were well correlated with each other and with organic contents and, to some extent, also with textural variables (Table 3). BD_2 was correlated, as could also be expected, with gravel content (gravel fraction expressed as % of < 20 mm mass of air-dry soil) and sorting index. BD_l was positively correlated with median particle size but negatively correlated with clay, fine-earth and organic matter contents.

The relationship between bulk density and sampling depth is illustrated in Fig. 2. Bulk density rapidly increased with depth in the surface but remained uniform at depths > 20 cm. This pattern reflects the distribution of organic matter and the increase in soil compaction with depth.

The relationship between bulk density and organic matter content is shown in Fig. 3. The relationship is more linear than reported in other studies (Alexander 1989, Grigal et al. 1989). This is probably because of the narrower range in organic matter contents in our material (Table 1). Correlation coefficients between bulk density and various transformations of organic matter content are given in Table 4. The highest coefficient was obtained using the square root transformation of the organic matter content. Erviö (1970) and Alexander (1980) have also used the

Table 2. Mean (kg/dm^3), range and coefficient of variation (%) values for the < 20 mm (BD_{20}), fine-earth (BD_2), and laboratory (BD_l) bulk densities by sampling layer.

Bulk density measure	0–5 cm (n=75) x̄	Range	cv	30–35 cm (n=60) x̄	Range	cv	60–65 cm (n=23) x̄	Range	cv
BD_{20}	1.10	0.52–1.48	17	1.43	1.07–1.86	9	1.57	1.43–1.97	8
BD_2	1.04	0.48–1.33	18	1.29	0.87–1.84	14	1.40	0.98–1.67	11
BD_l	1.19	0.65–1.60	17	1.51	0.79–1.77	11	1.62	1.29–1.81	9

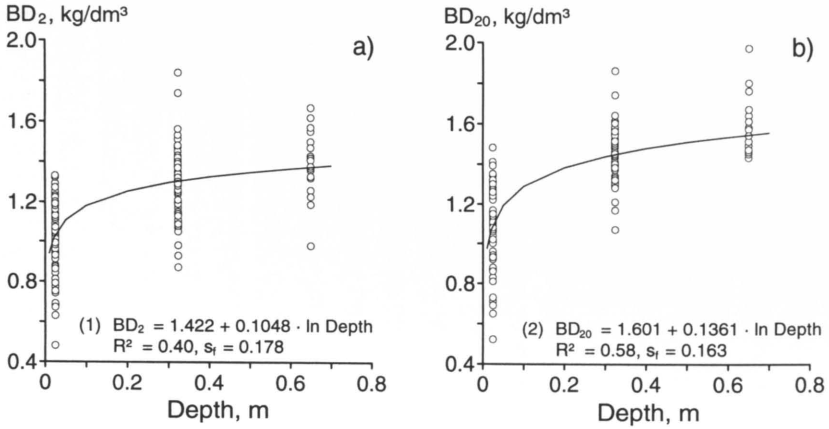

Fig. 2. Bulk densities BD_2 (a) and BD_{20} (b) as a function of sampling depth according to original observations and to regression models (1) and (2).

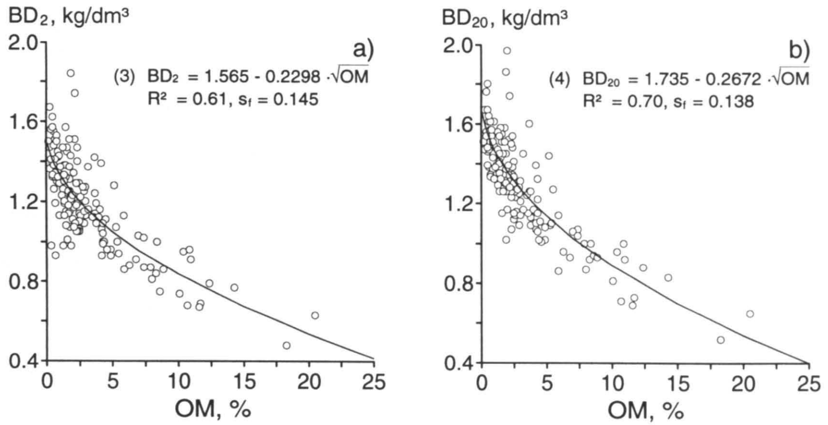

Fig. 3. Bulk densities BD_2 (a) and BD_{20} (b) as a function of organic matter content according to original observations and to regression models (3) and (4).

square root transformation of organic matter or carbon content to explain mineral soil bulk density. Additional transformation of bulk density, however, did not statistically improve the correlation between bulk density and organic matter content (cf. Erviö 1970, Huntington et al. 1989).

The correlation coefficients between BD_{20} and BD_2 and soil texture variables were rather weak (Table 3). The importance of textural properties was examined in more detail by grouping the bulk density values according to degree of sorting and median particle size. An analysis of covariance, using depth and organic matter content as covariates, revealed that BD_2 was significantly (p< 0.001) affected by both sorting and median particle size but BD_{20} and BD_l were only significantly affected by median particle size. Covariate-adjusted mean bulk density values are presented in Table 5. BD_2 tended to decrease with increasing particle size while BD_l, in contrast, tended to increase with particle size. The highest BD_{20} values were associated with both the finest and coarsest particle size classes.

Table 3. Simple and partial correlation coefficients between < 20 mm (BD_{20}), fine-earth (BD_2), and laboratory (BD_l) bulk densities and other soil physical properties.

Variable	BD_{20}	BD_2	BD_l
	Simple correlations		
BD_{20}	–		
BD_2	+0.85	–	
BD_l	+0.79	+0.66	–
ln Depth	+0.76	+0.64	+0.69
	Partial correlations (Depth)		
Clay	–0.14	–0.04	–0.68
Fines	–0.24	–0.10	–0.67
Gravel	+0.15	–0.55	+0.16
ln d_{50}†	+0.23	–0.07	+0.65
SI	–0.08	–0.42	–0.29
Dry matter	+0.61	+0.57	+0.72
OM	–0.72	–0.63	–0.76

Critical correlation coefficients: $|r_{0.05}| = 0.16$, $|r_{0.01}| = 0.21$, $|r_{0.001}| = 0.26$.
† natural log transformation of the median particle size

Table 4. Correlation coefficients between bulk density measures and various transformations of organic matter (OM) content.

Bulk density measure	OM	OM^2	$\sqrt{OM}$	ln OM
BD_{20}	–0.81	–0.66	–0.84	–0.83
BD_2	–0.76	–0.63	–0.78	–0.77
BD_l	–0.84	–0.67	–0.88	–0.89

Table 5. Covariate (sampling depth and organic matter content) adjusted mean bulk density values (kg/dm³) as a function of sorting index and median particle size.

Bulk density measure	Degree of sorting	Median particle size, m <20	–63	–200	–632	>632
BD_{20}	Sorted	1.51	1.23	1.26	1.30	1.24
BD_2	(SI < 3)	1.49	1.22	1.22	1.22	0.99
BD_l		1.16	1.22	1.40	1.41	1.32
	n	2	7	41	35	4
BD_{20}	Non-sorted	1.38	1.36	1.28	1.38	1.43
BD_2	(SI ≥ 3)	1.34	1.23	1.15	1.05	0.69
BD_l		1.08	1.39	1.39	1.44	1.38
	n	8	6	41	13	1

BD_l was significantly correlated with both BD_{20} and BD_2 (Table 3), as has been found in other studies (Erviö 1970, van Lierop 1981). The relationship between BD_l and BD_{20} and BD_2 is shown in Fig. 4. A closer study revealed that soils containing > 7% clay clearly had higher BD_{20} and BD_2 values than their corresponding BD_l values (Fig. 5). These finer textured soils evidently were not packed in the laboratory as tightly as in the natural state.

Stepwise multiple regression analysis was used to develop models for predicting BD_2 (Models 7–10; Table 6) and BD_{20} (Models 11–14; Table 7) using sampling depth, soil texture, organic matter content and BD_l variables as predictors. Intercorrelation between the independent variables was kept low by using a value of 0.25 for the parameter tolerance (Dixon and Jennrich 1985). Models based on the whole material and making all predictor variables available (Models 7 and 11) had an explaining power of 83%. Models 8 and 12 were derived excluding the depth variables. Organic matter content was clearly the most important variable, but gravel and clay contents and the depth variable were also highly significant variables.

When models were derived for coarse (clay < 7%) and fine (clay ≥ 7%) soils separately, BD_l was brought into the models for coarse soils (Models 9 and 13). The models for the fine soils are of limited value because of the small sample size, but the models for the coarse soils are of practical value; they are also the most precise models.

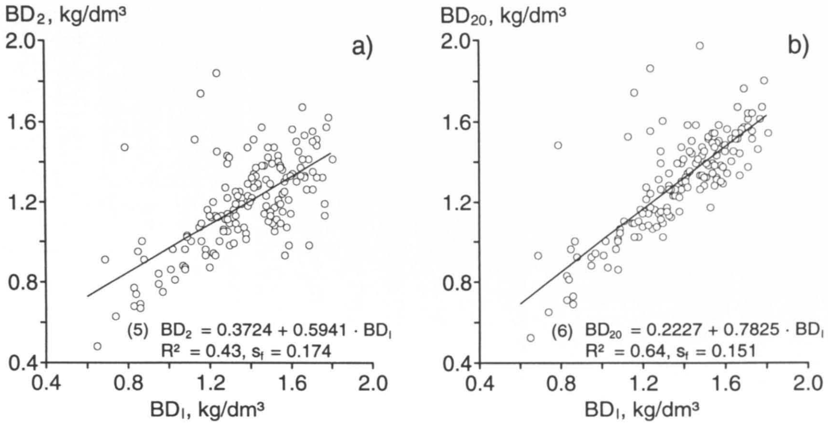

Fig. 4. Bulk densities BD_2 (a) and BD_{20} (b) as a function of laboratory bulk density (BD_l) according to original observations and to regression models (5) and (6).

4 Discussion

Because of the need to complete other tasks, it was only possible to spend a limited amount of time on the taking of volumetric samples. The more easily sampled sites and layers (i.e., those with fewer stones and pebbles) have therefore been favoured. The sample population is thus somewhat subjective and biased, and does not cover the whole country evenly. Nevertheless, it is the most comprehensive set of data available.

Bulk density was strongly related to the organic matter content, as has been found in numerous other studies (e.g. Harrison and Bocock 1981, Rawls 1983, Westman et al. 1985, Alexander 1989, Grigal et al. 1989, Huntington et al. 1989, Manrique and Jones 1991). However, depth and gravel content (in the case of BD_2) were also important factors. Laboratory density (BD_l) was sensitive to clay contents but did significantly improve the prediction of BD_2 and BD_{20} in coarser textured soils. BD_l is easily and cheaply determined in the laboratory.

BD_{20} is needed in studies concerned with soil moisture-release and micromorphological characteristics while BD_2 is needed to convert soil organic matter and chemical mass concentration data into amounts per unit area or unit volume

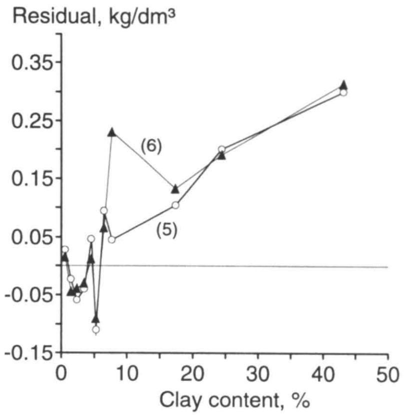

Fig. 5. Residuals from regression models (5) and (6) as a function of clay content.

since most chemical analysis is made on the fine-earth fraction. Clearly, the difference between BD_2 and BD_{20} is determined by the size of the coarse fraction (Erviö 1970).

It is also necessary to correct areal or volumetrically expressed soil chemical data for stone (d > 20 mm) content. In Finland, Viro's (1952)

Table 6. Fine-earth bulk density (BD_2, kg/dm³) models 7–10.

Variable	Coefficient	t value†	s_f, kg/dm³	R^2
Model 7: Whole material, n=158				
Constant	+1.667		0.097	0.83
$\sqrt{OM}$, %	–0.2221	–14.2***		
Gravel, %	–0.00107	–11.0***		
ln Depth , m	+0.04827	+6.30***		
ln (Clay+1), %	+0.06046	+4.83***		
Model 8: Whole material, Depth variables excluded, n=158				
Constant	+1.625		0.108	0.78
$\sqrt{OM}$, %	–0.2870	–21.7***		
Gravel, %	–0.00905	–8.65***		
ln (Clay+1), %	+0.08265	+6.15***		
Model 9: Coarse soils (clay < 7%), n=140				
Constant	+0.7668		0.079	0.86
$\sqrt{OM}$, %	–0.08523	–3.71***		
Gravel, %	–0.01217	–13.9***		
Depth, m	+0.1852	+4.39***		
BD_l, kg/dm³	+0.4318	+5.25***		
Model 10: Fine soils (clay ≥ 7%), n=18				
Constant	+1.457		0.110	0.93
ln (OM+1), %	–0.2855	–2.57**		
Gravel, %	–0.01627	–4.46***		
$\sqrt{Depth}$, m	+0.8466	+2.44**		

†Significance levels: *** = p < 0.001; ** = p < 0.01

Table 7. < 20 mm bulk density (BD_{20}, kg/dm³) models 11–14.

Variable	Coefficient	t value†	s_f, kg/dm³	R^2
Model 11: Whole material, n=158				
Constant	+1.6811		0.104	0.83
$\sqrt{OM}$, %	–0.2400	–14.2***		
Gravel, %	+0.00462	+4.42***		
ln Depth, m	+0.05048	+6.10***		
ln (Clay+1), %	+0.06779	+5.02***		
Model 12: Whole material, Depth variables excluded, n=158				
Constant	+1.637		0.116	0.79
$\sqrt{OM}$, %	–0.3078	–21.7***		
Gravel, %	+0.00631	+6.32***		
ln (Clay+1), %	+0.0910	+5.62***		
Model 13: Coarse soils (clay < 7%), n=140				
Constant	+0.4718		0.085	0.86
OM, %	–0.01598	–3.23**		
$Depth^2$, m	+0.3125	+5.00***		
BD_l, kg/dm³	+0.5962	+8.34***		
Model 14: Fine soils (clay ≥ 7%), n=18				
Constant	+0.9098		0.107	0.94
OM, %	–0.02323	–2.64**		
$\sqrt{Depth}$, m	+1.320	+6.85***		

†Significance levels: *** = p < 0.001; ** = p < 0.01

stoniness method is used to measure soil stone content. According to this method, a steel rod (d = 10 mm, h = 900 mm) is pushed vertically into the soil and the depth of penetration (maximum = 30 cm) into the mineral soil is recorded. Such measurements are carried out at 15–30 systematically chosen points, and the mean penetration depth in cm calculated. The volumetric stone content of the 0–30 cm layer can then be calculated according to the equation: $y = 83 - 2.75 \cdot x$, where y = volumetric stone content (m³/m³, %) and x = average depth of rod penetration (cm). This equation is the average of the two equations presented by Viro (1952, p. 5).

If bulk density has not been determined, the regression models we present may be of use. However, the goodness of the models was not validated against other material and therefore they should be applied with some caution. Nevertheless, their use is to be preferred to that of the direct use of BD_l values (cf. Tamminen 1991).

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Information presented in tabular form in the text itself should be of single column width (68 mm) and no more than 10 printed lines in height. Anything larger than this should be presented in the form of a table with an appropriate title.

Headings

Words in the headings should have an initial capital. Headings are numbered as follows: 1, 1.1, 1.1.1 etc. Of the first level headings, "References" is not numbered.

Italics

If italics have not been set in the text processing software, they should be indicated on the printout by underlining.

Equations

Equations will be printed over a single column width. Equations should be numbered consecutively in parenthesis on the right margin of the page. Symbols used should be explained in the List of Symbols.

Citing References in the Text

When citing references in the text, the "name and date system" should be used:

(Allen 1984)
Allen (1985a, b)
(Allen et al. 1986)
(Allen and Jones 1980)
(Allen 1978, Smith 1981, Jones 1984)*
(Smith 1977, 1980, Allen 1978, Jones 1979)*
(Handbook of forest... 1981)**
"Allen (1985, p. 12) on the other hand has shown that...".

* If in the same connection reference is made to the work of several authors, the references should be given in chronological order. If however, each author has several works referred to, the references should be given in chronological order of the oldest publications of each author.

** Where a publication has no known author or editor, the first 2–3 words of the title are quoted (followed by three dots), together with the year of publication. The term "Anonymous" must not be used in references.

References to Figures and Tables

References to all figures and tables should be made in the text. References are written with an initial capital letter: Fig. 3, Figs. 3–5, Table 2.

Footnotes

Footnotes should not be used in the body text. They can be used in tables.

Tables

The title of the table should be written above the table. A horizontal line should be drawn above and under the column headings, and at the bottom of the table. In tables neither upper case letters nor vertical lines are normally used. The tables are numbered consecutively.

Figures

Line drawings should be submitted on a A4 sheet. Most figures will be printed either one column (68 mm) or two columns (140 mm) wide. For letters and numerals appearing on graphs, transfers, stencils or high quality computer graphics systems should be employed. When preparing graphs, bear in mind the effect of reduction on text size and line weight. Characters should have a height of 1.5–2 mm when printed. Aim at clarity and simplicity, avoid unnecessary effects, like depth and shadows on column graphs. Where a figure is made up of several parts, the parts should be numbered (e.g. 5a, 5b, ...).

Monochrome prints should preferably be on glossy paper of size approx. 13 x 18 cm (5 x 7 in.). There should be a good range of tones. Colour prints or transparencies (slides) are less suitable as originals. Any desired cropping of the print should be clearly marked.

The costs of colour pictures are normally paid by the author. The best original in this case is a colour transparency with good colour saturation.

All figures should be marked with the number of the figure. The figures should be numbered consecutively irrespective of the type of figure.

Legends to figures should be printed on a separate sheet. The legends should be self-explanatory and independent, so that the reader need not refer to the text.

Where the copyright to a figure is held by someone other than the author, the copyright holder's name should be published with the figure. In matters of copyright, strict adherence to the law must be observed.

Title and Abstract

A good title is one that is brief and informative. Empty words and constructions like "A study of...", "Observations on..." and the like conveying very little to the reader are not used.

An abstract is a concise, independent résumé of the paper. Its purpose is to assist the reader in deciding whether it is worth reading the entire paper, to provide sufficient information for a reader who is not an expert on the topic involved, and to assist the communication of information. Its length should not exceed 20 typewritten lines. Use of the first person singular and references or quotes must be avoided.

The abstract is preceded by bibliographic information necessary for identifying the paper, and followed by 3–7 keywords describing the topics dealt with as fully as possible.

List of References

Reference should be made only to published, available material. For sources of low circulation or extreme rarity, the author should indicate where they are available from. Reference should not be made to second-hand sources.

Personal communications are not included in the list of references.

For the order, structure and form of the references, consult the examples below. In addition, note the following:

- Where the same author has more than one publication, the author's name should not be repeated, but replaced by a dash. Where there are several authors, only the name of the first author is replaced by a dash.
- Where a publication has no obvious author or editor, the publication should be listed in alphabetical order of its own title.
- The titles of journals should always be written in full, not abbreviated.
- The standard number, ISBN in books, or STRN in reports, should be given for sources of low circulation. The number is placed at the end of the reference.
- No italics are used in the reference list.

Examples:

Order of references

Smith, C. 1977. Aspen. Timber 77(4): 369–384.
— 1978. Silver birch. Timber 78(1): 17–23.

— & Harris, B. 1976a. Scots pine. Forest Management 15(1): 5–9.
— & Harris, B. 1976b. Norway spruce. Forest Management 15(2): 135–143.
— , Harris, B. & Allen, A. 1969. Sawn goods. Timber 69(2): 131–140.

Article in a journal

Repo, T. 1988. Physical and physiological aspects of impedance measurements in plants. Silva Fennica 22(3): 181–193.

Article in a book

Jarvis, P. G., Edwards, W.E. & Talbot, H. 1981. Models of plant and crop water use. In: Rose, D.A. & Charles-Edwards, D.A. (eds.). Mathematics and plant physiology. Academic Press, London. p. 151–194.

Monograph

Cochran, W. G. 1977. Sampling techniques. 3rd edition. John Wiley & Sons, New York. 428 p.

Congress proceedings

Cooper, R. W. 1971. Current use and place of prescribed burning. Proc. Prescribed Burning Symposium, Charleston, South Carolina, April 14–16, 1971. USDA Forest Service, Southeastern Forest Experiment Station, Asheville, N. C. p. 21–27.

Scientific Names

Scientific names should be according to authoritative contemporary sources. Scientific names should be in italics, except in the list of references. Authors of scientific names should be added only the first time a name is given.

Correcting the Proofs

Corrections should be clearly marked, preferably in red ink. The positions of figures and tables should be checked. Proof reading is an important task and at least two people should check each proof. Alterations to the original text may not normally be made. Corrected proofs should be returned to the editors within one week from receipt.

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