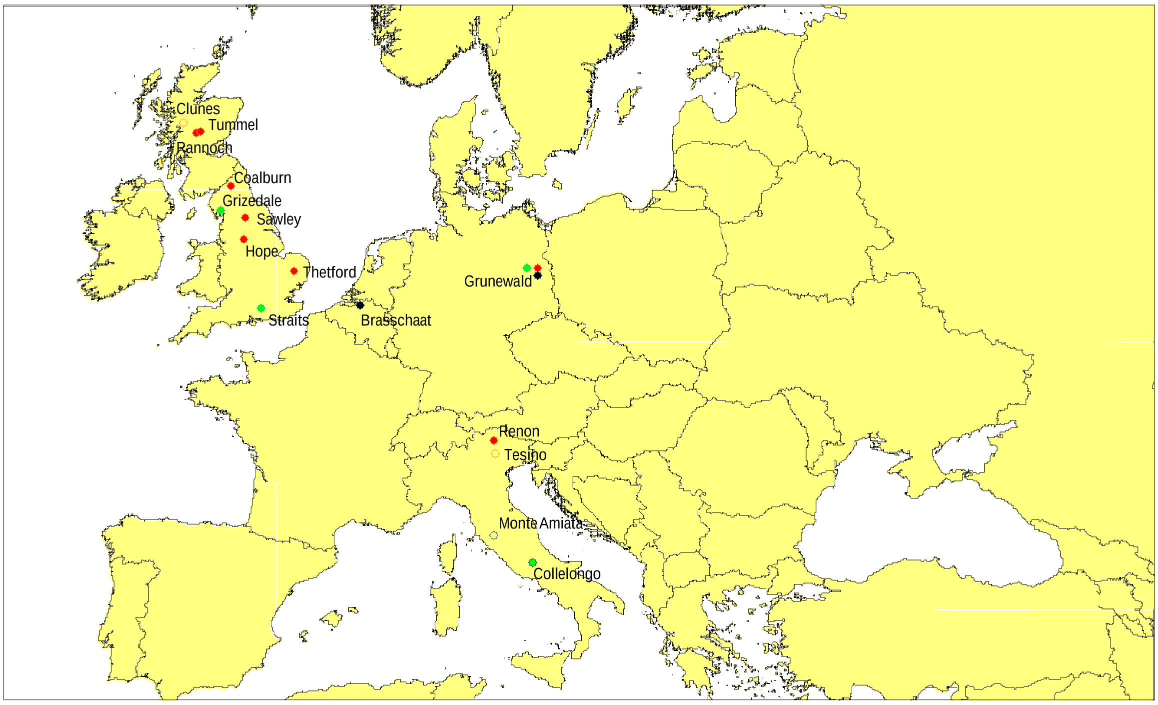
APPENDICES

Table of Contents

Appendix 1-A. List of Principal MEFYQUE Scientists**.**

Participant	Role	Principal Scientist	Address	Telephone	Telefax	E-mail
P1	Co-ordinator & Full Partner	S.P. Evans	Forestry Commission Research Agency Alice Holt Lodge Wrecclesham, Farnham Surrey GU10 4LH, UK	+44-(0)1420-526207	+44-(0)1420-23450	Sam.Evans@forestry.gsi.gov.uk
P2	Full Partner	R. Ceulemans	Department of Biology, University of Antwerpen (UIA) Universiteitsplein 1, B-2610 Wilrijk, BELGIUM	+32-(0)3-820.2256	+32-(0)3-820.2271	rceulem@uia.ua.ac.be
P3	Full Partner	~~J. Liski,~~ M. Lindner	European Forest Institute Torikatu 34, FIN-80100 Joensuu FINLAND	+358-(0)13-252.0240	+358-(0)13-124.393	Marcus.Lindner@efi.fi
P4	Full Partner	D. Overdieck	Landschaftsoekologie/Oekologie der Gehoelze, FB 7, Technical University of Berlin, Koenigin-Luise-Strasse 22, D-14195 Berlin, GERMANY	+49-(0)30-314-71270	+49-(0)30-314-71429	over1433@mailszrz.zrz.Tu-Berlin.De
P5	Full Partner	G. E. Scarascia-Mugnozza	Dipartimento di Scienze dell'Ambiente Forestale e delle sue Risorse Università degli Studi della Tuscia Via San Camillo de Lellis I-01100 Viterbo, ITALY	+39-0761-357395	+39-0761-357389	gscaras@unitus.it
AP6	Associated Partner	J. van Acker	Universiteit Gent` Faculteit van de Landbouwkundige en Toegepaste Biologische Wetenschappen Vakgroep Bos- en Waterbeheer Coupure links 653 9000 Gent, BELGIUM	+32 9 264 61 20	+32 9 264 62 33	Joris.vanacker@rug.ac.be
P7	Full Partner	K. Maun	Building Research Establishment, Centre for Timber Technology and Construction Garston, Watford, WD2 7JR UK	+44 1923 66 4812	+44 1923 66 4785	Maunk@bre.co.uk

Appendix 1-B*. Location map of MEFYQUE primary sites*



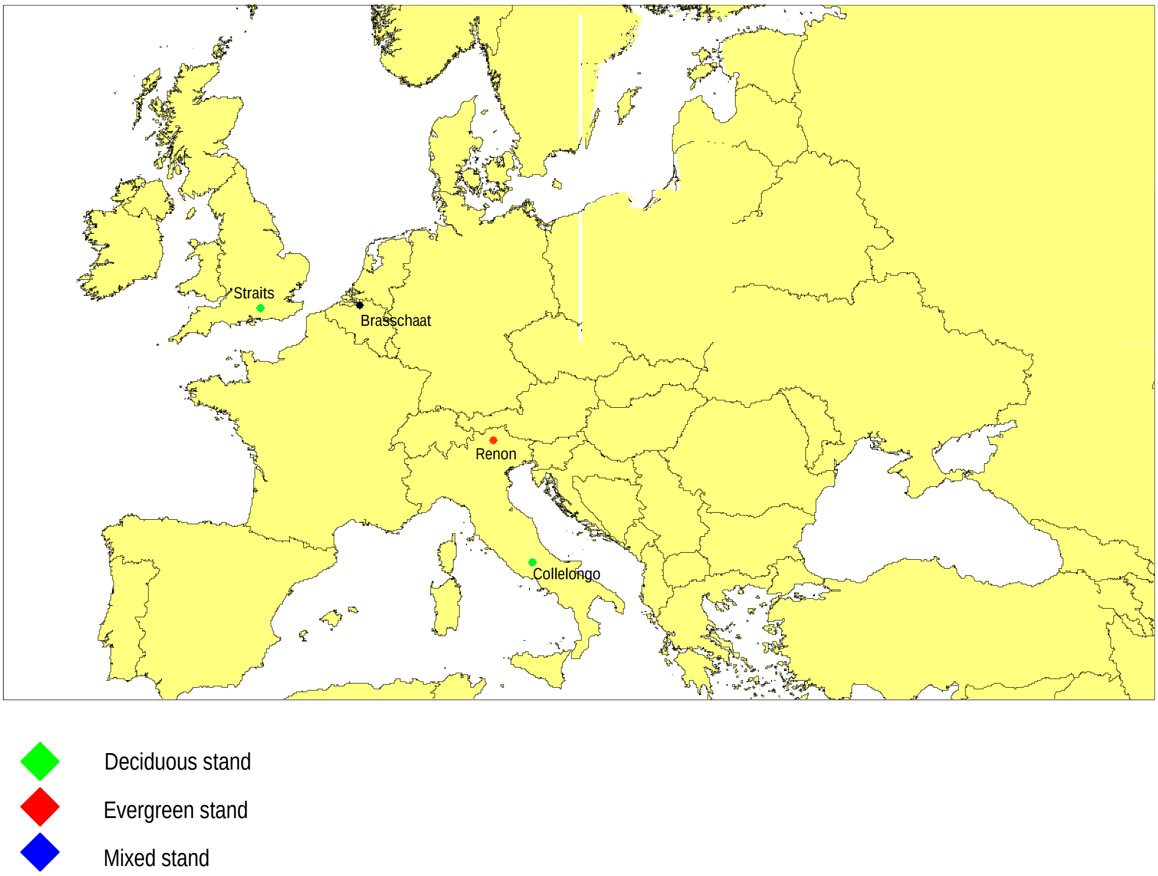
Deciduous plot

Evergreen plot

Mixed plot

Plot not yet established

Appendix 1-C. *Location map of MEFYQUE secondary sites.*



Appendix 1-D. *Sampling protocol.*

Forest Research
An agency of the Forestry Commission

MEFYQUE PROJECT

SAMPLE PLOT PROTOCOL

Final version

30 January 2002

TABLE OF CONTENTS

0. INTRODUCTION

1. Sample plots are used to gather data on tree growth, tree form, site factors and biomass samples from the primary and secondary sites in the MEFYQUE project.

2. <u>Pre-establishment information</u>. As much information as possible about potential plot sites should be obtained prior to starting any fieldwork and should be recorded on a suitable database.

3. <u>Sources of information</u>. The sources of the required data will depend on the location and ownership details of each site. The types of information required are categorised into information about the trees to be measured, and information concerning the site upon which the trees are standing.

4. <u>Sample plot numbers</u>. Plots will be numbered according to the following system:

		Site	Project Number	Level 2 number
FR	Forest Research	Straits Enclosure	01	512
		Coalburn	02	919
		Tummel	03	920
		Rannoch	04	717
		Grizedale	05	517
		Thetford	06	715
		Clunes	07	
		Sawley	08	
		Hope (Sherwood)	09	
		Headley Nursery (OTC)	18	
UIA	University of Antwerpen	Brasschaat	10	
		Antwerpen (OTC)	23	
TUB	University of Berlin	Grünewald	11	1101
		Grünewald	12	1102
		Grünewald	13	
		Berlin (CTC)	19	
		Berlin (phytotrons)	20	
UNITUS	University of Tuscia	Collelongo	14	
		Monte Amiata	15	
		Tesino	16	
		Renon	17	
		Montalto di Castro	21	
		Viterbo – Popface	22	

Where a plot is a Level II site, the Level II plot number is also to be recorded.

1. PLOT DATA

A. SELECTION OF PLOTS

5. <u>Plot selection</u>. Where new plots are being established, a visual inspection of the stand should be made prior to establishment. Ideally, plots should be:

a. even-aged;

b. fully stocked;

c. with as little growth variation as possible (i.e. not two-storied);

d. not from coppice.

6. Some previously thinned plots may be acceptable but attempts should be made to locate any existing records of thinning volumes removed.

7. History of crop. Provide as full a description as possible obtained from on-site inspection and knowledge of local foresters, owners or agents. Include current (e.g. stocking density) and any evidence of past forestry operations (such as brashing, stocking, previous thinning, etc.) and existing damage, with an indication of damaging agents (e.g. wind damage, grazing etc.).

8. Location. The following location information is required:

   a. Region.
   b. Name of owner and/or agent.
   c. Estate name.
   d. Forest name, if known.
   e. Latitude, longitude and map number (including publisher, series, edition and publication date).
   f. Contact name and telephone number if different from b. above

9. Directions for locating plot. A photocopied 1:50,000 map of the respective locality is to be placed in the relevant file. Indication of how to reach the plot with a description in relation to nearby public roads, towns, villages etc. should also be provided.

10. Species. The main species should be recorded followed by its code number as listed in Appendix 1.

11. Origin. From planted stock or natural regeneration.

12. Planting year or age. If known for certain, this should be recorded. In plots of older trees where past records are not available, this may only be an estimate, so should be treated with caution. Very often, the age of older trees can only be estimated within broad ranges.

13. Local Yield Class. This should only be recorded if known.

14. Area of plot. Plot sides should be measured to the nearest 0.1 metre. A scaled plan will be drawn showing the north point, horizontal lengths of each side, the included angles and the scale used. The area should then be calculated, correct to 1 m^2 (0.0001 ha).

15. Previous measurement records. For non-Level II sites previous records are unlikely to be available unless the area of concern was previously a sample plot or species provenance trial. Local owners/managers should be able to indicate whether such data are likely to exist.

16. Other information. This involves providing a general description of other features of the stand not previously covered. Such details will be collated from field observation and discussions with local staff. Examples could include, for example, an estimate of stocking rates, stem distribution and a tree health survey.

B. DESCRIPTION OF PLOT

17. For each plot, a Description on Establishment form (MEFYQUE Form No. 1) is to be completed. This form records specific information relevant to the plot, much of which would have been collected as part of the pre-establishment information.

18. Topography.

   a. *Altitude*. This can be obtained directly from 1:10,000 or 1:50,000 map of the area. They should be recorded to the nearest 5 metres above sea level.
   b. *Aspect*. In compass degrees.

c. *Slope*. The angle of slope should be measured with a clinometer or hypsometer or other suitable instrument and recorded to the nearest degree. If the slope is irregular, note the limits of slope angle.

d. *Surface form*. Record as slightly or strongly convex or concave, or level, and as even or irregular.

e. *Other features*. Any topographical features within the plot, such as streams, gullies, rock outcrops etc., will be recorded here.

19. Major soil group. This is to be obtained by reference to FAO soils maps. Where a local soil survey has been carried out, details are to be provided, including reference to any published source.

20. Climate data.

a. Meteorological station or other source from which records was obtained and the period to which they refer.

b. The distance and direction of the plot site from the station from which records were obtained.

c. Mean annual rainfall in millimetres.

d. Other meteorological information that may be available, e.g. maximum and minimum temperatures etc., stating the source if it is different from a. above.

C. LAYOUT OF PLOTS

21. Size and shape of plots. Plots will normally be rectangular in shape and usually 0.1-0.2 ha in area. Both shape and area may vary according to local site conditions. Plots must not be < 0.1 ha in area.

22. Surround. The surround should preferably extend at least 10 metres outward from the perimeter of the assessment plot. Surrounds less than 10 metres may be acceptable only if the width is sufficient to avoid any edge effects from surrounding tree crops and/or open space. In no circumstances will it be less than 5 metres wide. Where the thinning in the plot differs markedly from adjoining crops, the width of the surround should be increased. This may also be desirable to make the edge of the surround coincide with the compartment/sub-compartment boundary.

23. Demarcation of plots. Where new plots are established, treated posts will mark the corners of the plot as necessary. The outer limits of the surround for each plot will be clearly marked by white crosses (+), painted on two sides of dominant trees so that the whole treatment area is easily seen when approached and avoided when work is being carried out in the remainder of the stand.

24. Survey of plot. Where planting rows can be distinguished, two sides of the plot will be parallel to and halfway between adjacent rows of trees. Where planting rows cannot be distinguished, corner posts should be put in, as near as possible to a square (40x40 or 40x30 metres) and then measured using a Criterion laser, artillery director or similar, as available.

25. Measurement. The sides of the plot will be measured to the nearest 0.1 metre. The angles between the sides will be measured to the nearest half degree by artillery director or, if one is not available, by prismatic compass or box sextant. To ensure accuracy of measurement, the plot will be surveyed both in a clockwise and an anticlockwise direction. If the two traverses vary by more than half a degree in angle, or 0.1 m in length, the plot should be resurveyed.

26. Slope. If a plot is on a slope, which exceeds 5º, measure the angle of slope on those sides affected. The horizontal distance is calculated from the product of the measured distance and the cosine of the angle of slope.

27. Plan. A plan of the plot will be drawn and the north point will be indicated. The horizontal lengths of sides, the included angles and the scale used (normally 1 cm to 5 metres) will be recorded on the plan. The area of the plot, correct to one (1) m^2 (0.0001 ha) will be calculated on the reverse side of the plan and the result transferred to the front.

28. Banding of trees. At establishment, every tree will have a band marked 1.3 metres above ground level. To ensure measurements are taken at right angles to the stem, an additional band will be drawn on the opposite side. The protocol for banding trees on sloping ground leaning trees with swellings at 1.3 metres and forked trees is as follows:

a. Sloping ground – draw band on upper side of the tree.

b. Leaning trees – band at 1.3 metres on the side of the tree with the smallest angle to the horizontal, measured parallel to the stem.

c. Swellings – draw bands equal distances above and below 1.3 metres. Measure both and determine the arithmetic mean.

d. Forked trees – below 1.3 m, treat as separate trees; at 1.3 m, band below the swelling.

2. TREE DATA

A. MEASUREMENT OF PLOT TREES

29. Tree numbering. As sites will only be visited once during the course of this project, trees do not require to be individually numbered. ***However it is strongly recommended that some form of temporary numbering be used, as it is possible that sites may necessarily have to be re-visited for additional sampling.***

30. Periodicity. Trees are to measured and sampled once only for each site. Where possible non-destructive tree measurement are to be taken during winter months in the absence of foliage. Destructive samples are to be taken during the growing season, once leaf development is complete.

B. MEASUREMENT PROCEDURES

31. Measurements required are:

a. *Diameter at breast height* (1.3 metres above ground level) of all trees.

b. *Top height* (the total height of the 100 largest standing diameter trees per ha).

c. The following parameters on 10 standing trees at existing Pan-European Monitoring Programme sites and 30 standing trees at new sites, selected across the dbh distribution, starting from the smallest:

(1) *Total height*, defined as the vertical height from ground level to the top of the tree i.e. the leader.

(2) *Upper crown height*, the height from ground of the lowest complete live whorl for conifers, and for broadleaves the point at which the crown is complete in all directions and unimpeded.

(3) *Lower crown height*, in both conifers and broadleaves, the height from ground of the lowest branch (not whorl) on the tree with live foliage, in other words, the lowest living branch.

(4) *Crown width*, the average width of the crown at the point where the crown is complete in all directions and unimpeded.

(5) *Stem form*, an estimation of stem quality on all plot trees.

32. Orientation. The North and the West sides of the tree are to be clearly marked on the trunk prior to felling.

33. In each plot the dead number of trees is to be recorded.

(1) DIAMETER MEASUREMENT

34. Each tree will be measured at breast height using a standard Mensuration girthing tape calibrated to 0.1 cm. At the same time, they will be assigned a dominance class from the following codes:

a. *Class 1.* *Dominant tree.* These are the tallest and most vigorous trees in the crop and usually have a large proportion of their crowns free. Whips may be included because of exceptional height growth. Wolf trees are often in this category.

b. *Class 2.* *Co-dominant trees.* These are trees in the upper canopy that help to complete the canopy but are below the crown level of the dominants. Some of the better stems will be used to fill up gaps in the canopy.

c. *Class 3.* *Sub-dominant trees.* These trees are not in the upper canopy but their leaders still have access to light which has not filtered through the foliage of adjacent trees.

d. *Class 4.* *Suppressed trees.* These are trees whose leaders have no direct access to light and stand beneath the crowns of adjacent trees.

e. *Class 5.* *Dead trees.*

Diameters will be measured to the nearest 0.1 cm and recorded on the General Register (MEFYQUE Form No 2).

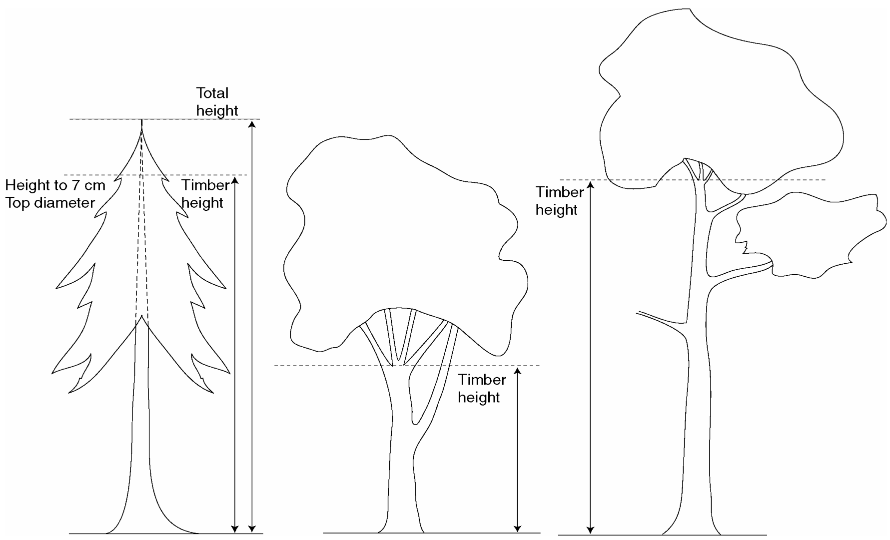
A girthing sheet should also be prepared, listing diameters in ascending order by 0.5 cm class onto a MEFYQUE Form No. 3. Each tree number is then listed against the appropriate diameter class.

35. The protocols for measuring the diameter of leaning trees, forked trees and those with swellings at 1.3 m are detailed at Appendix 2.

36. Recording on Hand-Held Computer. Every attempt should be made to use hand-held data capture equipment for the recording of measurements, as this will significantly ease subsequent data handling. If such equipment is available for data collection, the data will be entered as prompted by the computer program.

(2) HEIGHT MEASUREMENT

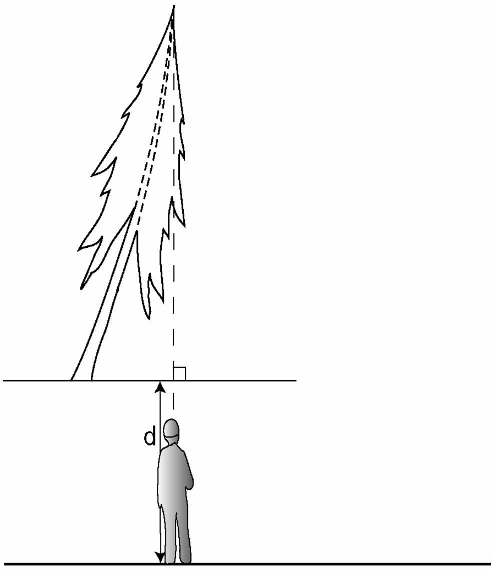
37. All heights will be measured using a hypsometer or clinometer (e.g. Vertex, Blume Leiss, Suunto). Total height is the vertical distance from the base of the tree to its tip, recorded to the nearest 0.1 metre. All height measurements on standing trees in sample plots will be recorded on MEFYQUE Form No. 4 irrespective of how the measurements were taken (see Tree and Crown Height Measurement Protocol).



38. The datum line for all heights will be the breast height diameter point, to which 1.3 metres is added (a Vertex adds 1.3 metres on for you). This is to prevent measurement errors due to ground vegetation, leaf litter, etc. obscuring the base of the tree, or shrinkage of ground, e.g. plough furrows in peat.

39. Two height measurements should be taken from opposite sides of the tree. The total height is the arithmetic mean of these two readings.

40. Leaning trees should be measured in exactly the same way as above, except the two measurements must be taken at 90º to the direction of the lean.



Stand at right-angle to direction of lean

41. Selecting top height sample trees. The number of top height sample trees to be measured in each plot can be found by multiplying the plot area (in hectares) by 100, e.g. plot area 0.1 ha x 100 = 10 trees. A minimum of 10 sample trees is required.

42. Selecting total height sample trees – a systematic sample for total height trees is obtained from the Girthing Sheet.

43. The sampling fraction is found by dividing the number of trees on the girthing sheet of 7 cms + diameter by the number of samples required, e.g. 30. The result determines the interval at which samples are taken from the girthing sheet. The first tree measured is determined by dividing the above result by 2, adding 0.5 and rounding to the nearest whole number. Subsequent trees are selected at intervals of the above.

Example: Plot area = 0.1 ha

Number of plot trees (7 cm + dbh) = 83

(i) Girthing fraction = $\frac{83}{30}$ = 2.8

i. First tree = $\frac{2.8}{2}$ + 0.5 = 1.9 => 2

ii. Start on the 2nd smallest tree and measure every 2.8th

44. <u>Measuring timber height</u>. Timber height is the vertical height of the tree from ground level (using 1.3 metres as the datum line) to seven (7) cm overbark, or, where a main stem is indistinguishable, the ‘spring of the crown’. It is determined by either physically climbing the tree, the use of a dendrometer or on felled stems, during thinning or clear-felling operations.

a. By tree climbing. Suitably trained and qualified individuals should only undertake this. The process requires a minimum 2 person team with one physically climbing the tree while his/her colleague remains on the ground as an anchorman.

b. With dendrometers. The Barr and Stroud standing tree dendrometer is used for sample plot measurements. Its primary function is to determine the volume of standing trees but in order to do this, the determination of timber height is required.

c. Felled trees. The measurement of timber height on felled trees is a straightforward procedure. The 7 centimetre overbark point is found, by trial and error, and the horizontal distance to the dbh band measured. 1.3 m is then added to this measurement to obtain the distance to ground level.

(3) VOLUME MEASUREMENT

45. The trees measured as volume sample trees will be those selected for total height measurement. A new sample of trees should be selected if a second volume measurement is undertaken.

46. The volume of individual trees can be determined by using a Barr and Stroud dendrometer, Spiegel Relascope, tree climbing or measuring felled trees.

a. By dendrometer. This method should be used whenever possible.

b. By climbing. When climbing trees for volume calculation, the following measurements should be taken.

(1) Timber height. Distance from the breast height band, or the mid point between double bands, to 7 cm diameter overbark, or to the point above which no main stem can be distinguished, whichever comes first, with the addition of 1.3 m to give the height from ground level.

(2) The overbark diameters at the mid-points of 3 metres sections up to timber height. The length of the last section below timber point will be between 1.0 and 3.9 metres. Where there is a ‘stop’ (a sudden change in diameter), it will be assumed to mark the end of the section. Branch-wood is not measured, nor is bark thickness.

c. Felled measure. As for climbed trees with the addition of length to the tip of the tree, or to the tip of the longest fork.

N.B. Forks are also measured, and the entry for timber height is the sum of section lengths.

(4) CROWN MEASUREMENT

47. Crown measurements are to be taken on those trees selected for total height measurement.

a. Lower crown. This is the height of the lowest live branch on the main stem (excluding epicormics and forks) recorded to the nearest 0.1 cm. In broadleaf trees, this is the lowest level of fine branching.

b. Upper crown. This is the height on the main stem where the lowest complete whorl of live branches occurs, recorded to the nearest 0.1 m. If no complete live whorl exists, the upper crown measurement is taken to be the total height less the length of the previous year’s growth. In broadleaves, this point will coincide with the point where the uppermost live branch joins the main stem of the tree.

c. Crown diameter. This provides an indication of the spread of the crown. It is the horizontal distance from crown edge to crown edge and is recorded to the nearest 0.1 m. The points to and from which measurements are taken are judged by eye. Normally, two diameters at 90º to each other will provide an adequate estimation of the average crown diameter, but more measurements may be required if the crowns are irregular.

d. Instrumentation. All heights will be measured with a suitable hypsometer or clinometer (e.g. Vertex, Blume Leiss or Suunto), using the *dbh* band as the datum line and adding 1.3 m (a Vertex will add the 1.3 m on for you).

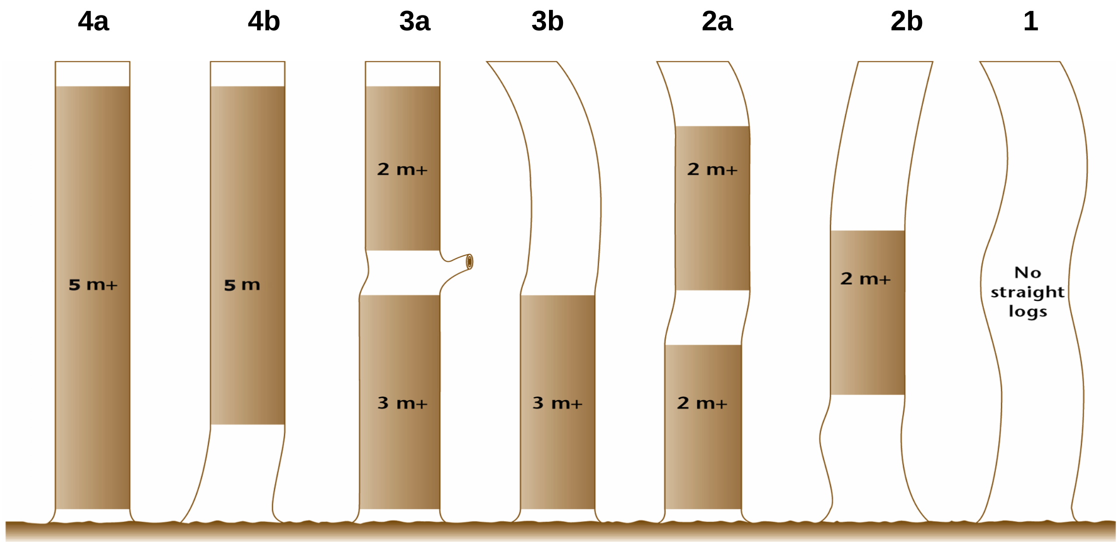
(5) STEM FORM

48. Stem straightness. An assessment on stem straightness will be made on all trees. This will be a subjective visual assessment, made according to previously developed protocols.

49. The assessment will take into account characteristics such as straightness, knots, incidence of forking, damage and any other factor which may affect stem quality. Each plot tree will be assigned a stem quality class based on the following table.

a. *Broadleaves*. For broadleaves a system with 4 classes will be adopted at tree level:

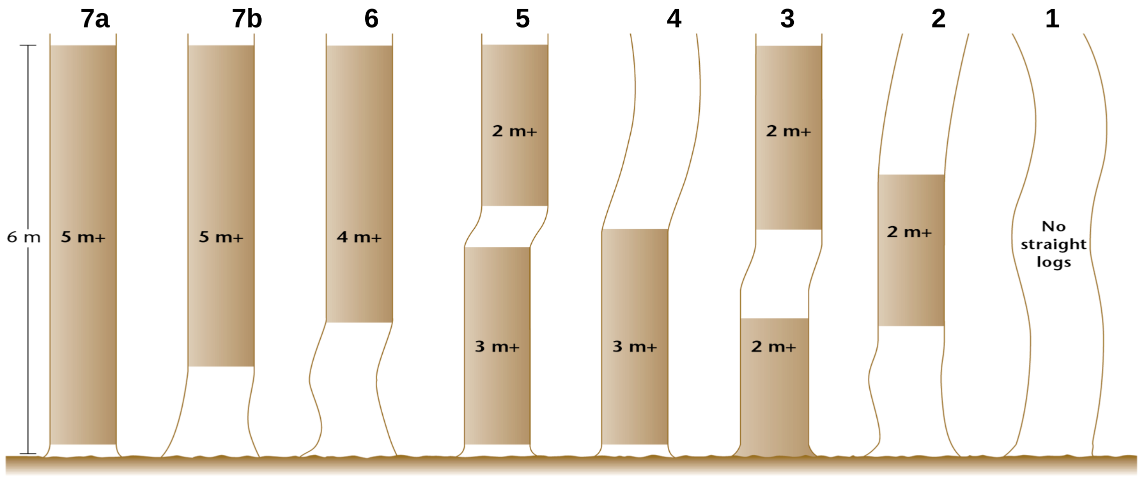
Class	Quality	Description
4	Good stem	A stem which is mainly straight and free from obvious defects. The stem has, or will have, the potential to produce a sawlog of millable quality with a minimum length of 5 m. Such a tree may also contain other short sawlog lengths in the stem or main limbs.
3	Slightly defective	The majority of the stem is, or will be, of good millable quality but slight defects prevent the production of a log with a minimum length of 5 m. However most of the stem will produce sawlogs with a minimum length of 2 m. Further logs may also be obtained from the major limbs.
2	Defective	Most of the stem is of poor quality but there is, or will be, the potential for producing 1 millable quality log with a minimum length of 2 m from within the stem or the major limbs.
1	Poor	Stem contains no millable quality wood and will never develop into a tree which will produce a millable log with a minimum length of 2 m.



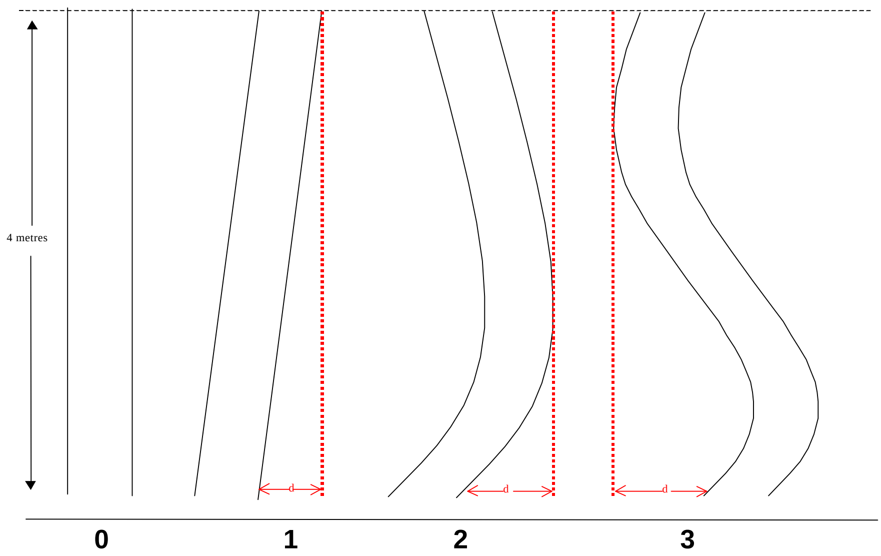
b. *Conifers*. For conifers a system with 7 classes will be adopted at tree level.

Class	Quality	Description
7	Very good stem	A stem which is mainly straight and free from obvious defects. The stem has, or will have, the potential to produce a sawlog of millable quality with a minimum length of 5 m. Such a tree may also contain other short sawlog lengths in the stem or main limbs.
6	Good stem	A stem which is mainly straight and free from obvious defects. The stem has, or will have, the potential to produce a sawlog of millable quality with a minimum length of 4 m. Such a tree may also contain other short sawlog lengths in the stem or main limbs.
5	Slightly defective	The majority of the stem is, or will be, of good millable quality but slight defects prevent the production of a log with a minimum length of 5 m; most of the stem will produce > 1 sawlog with a minimum length of 3 m. Further logs may also be obtained from the major limbs.
4	Defective	The majority of the stem is, or will be, of good millable quality however most of the stem will produce only 1 sawlog with a minimum length of 3 m. Further logs may also be obtained from the major limbs.
3	Moderately	The majority of the stem is, or will be, of good millable quality however most of the

Class	Quality	Description
	Defective	stem will produce > 1 sawlog with a minimum length of 2 m. Further logs may also be obtained from the major limbs.
2	Very Defective	Most of the stem is of poor quality but there is, or will be, the potential for producing 1 millable quality log with a minimum length of 2 m from within the stem or the major limbs.
1	Poor	Stem contains no millable quality wood and will never develop into a tree which will produce a millable log with a minimum length of 2 m.



c. Stem lean. Measure the angle to the vertical of the tree stem at the point of the maximum deviation in the first 4 metres of the stem.



(1) d = maximum deviation from vertical, measured in metres.

(2) % deviation, D, in first 4m of stem = (d/4) x 100.

(3) STEM FORM CLASS 1: D • 0.9%.

(4) STEM FORM CLASS 2: D = 1% - 2% inclusive.

(5) STEM FORM CLASS 3: D > 2%.

3. BIOMASS SAMPLING

A. WOOD MATERIAL

50. Primary and Secondary Sites. Nine (9) trees from each plot at the primary and secondary sites are to be felled for detailed biomass and mechanical studies.

a. Selection. Three (3) dominant/co-dominant, three (3) sub-dominant and three (3) suppressed individuals as defined at paragraph 34 and representative of the mean of the diameter class are to be selected for felling, irrespective of the stem form. The three (3) individuals are to be selected as follows:

(1) Sort the diameters at breast height (DBH) for trees in each class in ascending order retaining the tree number as the identified e.g.:

Tree number (dominant)	Diameter at breast height (DBH – cms)
….	
12	25.3
13	26.1
14	27.5
15	28.9
….	

(2) Divide the total number of trees in each class by 3: e.g. if there are 90 trees in the sample, then you will have 3 groups of 30 trees each, with trees 1-30 in group 1, trees 31-60 in group 2 and trees 61-90 in group 3. [Obviously tree numbers will not be as simple as in this example, as numbers will not necessarily be sequential).

(3) Calculate the arithmetic mean of the DBH for each group and select the individual whose DBH is closest to the arithmetic mean.

b. Each tree should be photographed (using a digital camera where possible) from two sides at 90^{o} for stem form analysis.

c. Assessment of felled tree. The following are to be measured to the nearest one (1) centimetre.

(1) Total tree length.

(2) Timber height at seven (7) centimetres over bark.

(3) For deciduous species, height of first live branch.

(4) For coniferous species, height of first live whorl defined as the lowest whorl where 75% of branches have some green needles.

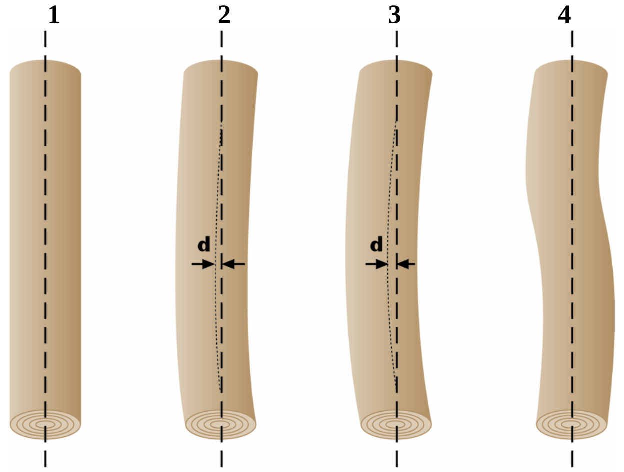
(5) Height of first whole dead branch.

(6) Taper. Measure diameter at one (1) metre intervals up the stem, recording the height at which the diameter is measured from the butt upwards.

(7) Tree quality. Felled stems are to be visually assessed using the scoring system for assessing log quality, and provided below.

d. Logs. Logs are to be produced of 2.5 metres in length, starting at fifteen (15) centimetres from the soil.

e. Log Quality. Logs are to be visually assessed for quality using the scoring system below.



(1) Logs 1 and 2 qualify as straight logs; logs 3 and 4 are not straight.

(2) Maximum deviation (d) on log 2 does not exceed one (1) centimetre over one (1) metre length.

(3) Maximum deviation (d) on log 3 exceeds one (1) centimetre over one (1) metre length.

(4) Log 4 shows bow in more than 1 direction.

b. Sample Numbering. L1 upwards, numbered from the butt of the tree; e.g. the sample FR-02-12-L03 will be the 3rd log cut from sample tree 12 in site 2 managed by Forest Research.

c. Marking. Each log is to be clearly marked as shown in the figure below, with the arrow indicating both the top of the tree and the position of magnetic north.

d. Transportation. Logs are to be sent to BRE.

e. Costs. The sender will cover costs.

51. Discs from Primary and Secondary Sites. Discs are to be taken from trees felled at the primary and secondary sites. Discs are to include all annual rings and bark. It is accepted this will affect the results of the 3-dimensional scanning.

a. Sampling. Five (5) cm high discs are to be taken in the field as parallel cut cross-sections, with an arrow indicating both the top and the position of magnetic north.

b. Position. The exact position of discs along the stem is to be recorded on the form provided.

c. Number of Samples. 5 samples for stem as shown in the figure on page 18, with samples at 100 mm from the ground and at 2.5 metre intervals.

d. Sample Numbering. D(height up the tree, measured from the bottom of the disc, in metres); e.g. disc cut at 2.50 metres will be D2.50; thus, the sample FR-02-12-D2.50 will be the disc cut at 2.50 metres height from sample tree 12 in site 2 managed by Forest Research.

e. Sample preparation. Samples are to be cold stored to avoid the formation of saprophytes and packed in pierced high-density polythene bags. Store in a dry place.

f. Wood sample for the Technical University of Berlin. The lower of the two discs taken at the base of the three wood samples are to be taken as follows:

(1) Mature trees. In mature trees the following wood blocks are to be taken:

(a) 10 cm^3 of wood the youngest sapwood,

(b) 10 cm^3 of younger heartwood (not from the transition zone)

(c) 10 cm^3 of older heartwood.

(2) Juvenile trees. 10 cm^3 of wood of the youngest wood.

(3) Recording. Growth rings are to be counted from the centre and recording the area, using ring counts, where the samples were taken. Where no heartwood/sapwood border exists, samples are to be taken from the youngest wood and from middle and old aged wood.

(4) Contamination. To reduce the risk of contamination of the wood, a clean band saw in laboratory conditions

g. Transportation.

(1) Four (4) complete discs are to be sent to Gent University. Discs will subsequently also be scanned for compression wood evaluation by the COMPRESSION WOOD project (co-ordinator: Barry Gardiner – Forest Research telephone: +44-(0)131-445 2176 extension 6950). Gent University is requested to liase with Dr Gardiner to discuss phasing of analyses. The cost of scanning for compression wood is free to the MEFYQUE consortium.

(2) The wood blocks are to be sent to Technical University of Berlin.

h. Costs. The sender will cover costs.

52. Tertiary sites. The same sampling protocol outlined above for the primary and secondary sites applies for tertiary sites with the following exceptions:

a. Sampling. >5 centimetres high discs are to be taken in as parallel cut cross-sections, with an arrow indicating both the top and the position of magnetic north.

b. Number of samples. 10 cross-sections, as a minimum.

c. Sample Numbering. D(height up the tree, measured from the bottom of the disc, in metres); e.g. disc cut at 2.50 metres will be D2.50; e.g. the sample FR-02-12-D2.50 will be the disc cut at 2.50 metres height from sample tree 12 in site 2 managed by Forest Research.

d. Sample preparation. Each sample is to be placed in a pierced high-density polythene bag. Samples are to be frozen.

e. Transportation. Discs are to be sent to Gent University.

f. Costs. The sender will cover costs.

B. BIOMASS SAMPLES FOR CHEMICAL ANALYSIS

53. General. Samples for chemical analyses are to be taken from primary, secondary and tertiary sites.

54. Primary and Secondary Sites. At the primary and secondary sites the average individual within the diameter distribution range of each competition class (dominant/co-dominant (where present). sub-dominant and suppressed) is to be selected for biomass sampling; therefore a total of three (3) trees will be selected for biomass sampling.

a. Components. Fresh samples are to be taken for leaves/needles, branches, stems, coarse roots and fine roots.

b. Sample Numbering.

(1) Above ground components. B(sample number) will indicate the 1st biomass sample; e.g. the sample FR-02-12-B01 will be the 1st biomass sample from sample tree 12 in site 2 managed by Forest Research. Records are to be maintained to indicate the position of each sample within the tree.

(2) Below ground components. Samples are to be numbered from the top as follows: site/tree/core/length e.g. Sample FR-02-T1-C5-L3 corresponds to tree 1, core 5, depth interval 20-30 centimetres taken at site 2 managed by Forest Research. Records are to be maintained to indicate the position of each core around the tree.

f. Labelling of samples. Great care must be taken to mark each sample clearly in the field before sending it to the laboratory for analysis. These identifications must be given on the outer side of the bag (directly on the bag by indelible ink, or by clasping a label on the bag). It is recommended to repeat these identifications on the inner side of the bag on a paper label written with indelible ink. The label should be folded in order to avoid contamination of samples by contact with the ink.

c. Sampling procedure for above ground components. For each felled tree the tree crown is to be separated into 3 parts of equal size, labelled lower, middle and upper crown.

(1) Total canopy biomass. The fresh weight of the canopy is to be measured to the nearest one hundred (100) grams as follows:

(a) Separate each crown component (lower, middle and upper crown) into 1 metre sections, with dead branches to be weighed together with the live ones;

(b) Bundle and weight each one (1) metre section;

(c) Measure the length of all branches in each the central one (1) metre section of each crown component (lower, middle and upper crown).

(d) To avoid contamination of the plant material to be used for laboratory analyses from steel and aluminium cutters, tungsten carbide drill burrs are to be used.

(2) Leaves/needles. Select a small number of branches, determine the fresh weight and:

(a) *for broadleaves*: from the upper third of the live crown and from branches in full sunlight detach 100 matured leaves from the twigs (avoiding the small leaves on the axis of certain species) and store in pierced high-density polythene bags. This quantity is roughly equal enough leaves to fully cover 2 A4 sheet of paper. The foliage must be mature and samples should avoid material from secondary flushing; all cardinal directions should be sampled. It is not necessary to cut the petiole of the leaves. **Please ensure all samples are kept flat as the leaves are required for leaf-area analysis.**

(b) *for conifers*: from the upper third of the live crown (approximately 5th whorl from the top of each tree) and from branches in full sunlight detach 30 grams of material for each needle class. This is equal to enough needles to fully cover an A4 sheet of paper, or about 5 shoots of between 15 (spruce) - 20 (pine) cms in length. Store in pierced high-density polythene bags. It is not necessary to detach the needles from small twigs.

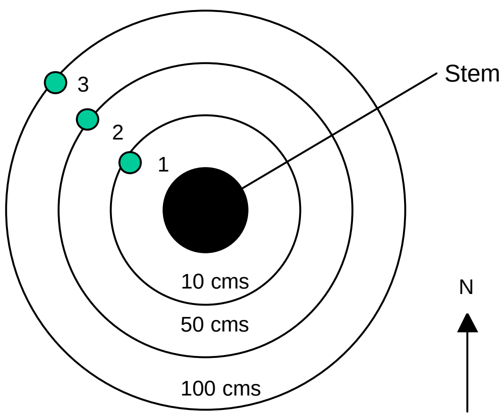
(c) Sampling should be done as hygienically as possible and contamination from pruners, secateurs, industrial gloves or hands should be avoided. Excess water should be shaken from the foliar sample if wet, and before placing in bags.

(3) Branches. For each crown component of the felled tree (lower, middle and upper crown) take one (1) sample >10 cm^3. Place each sample in a pierced high-density polythene bag.

(4) Stem. For each felled tree one (1) sample >10 cm^3. Place each sample in a pierced high-density polythene bag.

(5) Determination of initial fresh weight. All biomass samples measured in laboratory conditions are to be weighed fresh (i.e. not after storage but after washing where appropriate) to an accuracy of 0.1 grams. Water adhering to washed samples is to be carefully removed using blotting paper (or other appropriate medium) prior to weighing.

d. Sampling procedure for below ground components. Root sampling is to be carried out on each felled tree using a chamber auger (either manual or mechanical, depending on the local circumstances). Three (3) cores per tree are to be taken, as shown the figure below.



(1) Core extraction. Extracted cores are to be placed in PVC piping of the appropriate length (cut in half) and placed in an appropriately labelled black plastic bag, to avoid formation of moulds and retain humidity. The PVC pipe is to be taped together before placing into the bag so as to prevent damage to the core.

(2) Coring depth. Cores are to be taken to a depth of 1 metre. Where roots are visible at 1 m depth, a further core is to be taken until roots are no longer visible at the base of the core.

(3) Core description. Following core sample extraction and prior to soil-root sampling, the following description of each core is to be taken:

(a) Measurement of total core length.

(b) Measurement and brief description of visible horizons, e.g. depth at which a horizon starts and ends. A horizon is described as a major transition where visible differences in texture, sediment composition and Munsell colour are identified.

(c) Any other visible characteristics within each horizon e.g. stoniness.

(4) Field Sampling. For the biochemical analyses to be carried out at the Technical University of Berlin, 10 cm^3 coarse roots (>5 mm diameter) are to be extracted from Core 1 (see figure above) immediately and the sample stored immediately in a cool box. After determination of fresh weight as described below samples must be stored frozen at -20°C'; where possible the samples should be stored in liquid nitrogen. Samples are then to be oven dried (para 54h), powdered, stored in sealed containers and sent to the Technical University of Berlin. Where grinding equipment is not held, frozen samples are to be sent to Gent University for grinding and powdered samples will then be forwarded to Berlin.

e. Sample Storage. The remaining fraction of the samples is to be stored in a cool and dry environment.

f. Sample preparation.

(1) Leaf and wood samples. It is not necessary to systematically wash leaf and wood the samples, but where necessary samples will be washed in water without additions.

(2) Root samples. Where possible roots are to be extracted immediately from the soil medium.

(3) Soil-Root sampling. In the laboratory, the core is to be separated into soil horizons. Within each horizon sub-samples are to be taken of ten (10) centimetre soil-root intervals and stored in appropriate labelled sealed plastic bags. If the last sample is less than ten (10) centimetres in length, the length is to be recorded.

(4) Sample preparation. Additional water is to be added to the soil-root-water mixture and this is to be stirred by hand (not using a mechanical aid e.g. a stick) until a homogeneous suspension is achieved. When the soil-root-water mixture is fully dispersed, the stirring will be interrupted for a few seconds to allow settling of the soil particles. The soil-root-water suspension is to be poured into stacked sieves of diameter ranging between 2 cm à 0.2 mm^2 mesh size and washed by hand using a jet or spray of water aided by hand manipulation. If soil remains on the container, the process of suspension-decanting-sieving described above is to be repeated until all the sediment has been sieved. Where necessary, roots are to be removed individually.

(5) Sample storage after washing. Where cleaned samples cannot be processed to determine root parameters, root samples are to be placed in bottles containing a water-alcohol solution, with alcohol at 25-35% and stored, where possible, at an air temperature of 10 degrees C.

(6) Determination of initial weight. The fresh soil-root sample is to be weighed to an accuracy of 0.1 grams.

(7) Storage before washing. Depending on the clay content of the soil, the soil sample containing roots is to be suspended in water for 1-3 days at a temperature of 15-25 degrees C. The storage period must not exceed 5 days as root decay will start. If samples require storage for a longer period, ethanol or another alcohol is to be added to the soil-root-water suspension at an alcohol concentration of 25-35% and stored at an air temperature of 15-20 degrees C.

(8) Root diameter. Before starting, roots are to be placed for some hours in water as many roots can be at different stages of drying. Individual root diameters are to be measured under a stereoscopic microscope and are to be assigned to one of the following tapers:

Root diameter (mm)	Class
<5	Small, Fine/Very fine
>5	Medium/ Large and very large

Roots are to be separated into samples of diameter class and placed into a pierced high-density polythene bag and stored appropriately.

g. Determination of root fresh weight. On completion of the biometric measurements, water adhering to washed and cleaned root samples is to be carefully removed using blotting paper (or other appropriate medium) and weighed to an accuracy of 0.1 grams.

h. Determination of oven-dry weight. The method for the determination of oven-dry weight of biomass samples is as follows. Place a weighed sample in a labelled tin tray, dry in an oven for at least 24 hours at no more than 80ºC, and then reweigh to an accuracy of 0.01 grams.

Initial weight – Final weight = Change in weight

g. Grinding. Where possible, all samples are to be oven dried and powdered to obtain a fine powder as homogenous as possible. Optimally, 5 grams dry matter is to be prepared and stored in sealed containers. Depending on the species, some fibres may be present in the ground sample; this is not a major inconvenience if they are small and if the powder is carefully mixed prior to analysis. Where grinding equipment is not held, sample preparation will be carried out at Gent University.

h. Contamination. To avoid contamination it is advised that the use of powdered plastic gloves is avoided. It will also be necessary to ensure the grinder does not contaminate the samples.

i. Transportation

(1) Oven-dry samples are to be sent to Gent University.

(2) Powdered samples are to be sent to Berlin University.

j. Costs. The sender will cover costs.

55. Tertiary Sites. At tertiary sites three (3) individuals are to be selected for biomass sampling from each experimental block.

a. Transportation of samples.

(1) Oven-dry samples are to be sent to Gent University.

(2) Powdered samples are to be sent to Berlin University.

b. Costs. The sender will cover costs.

4. TIMETABLE OF ACTIVITY

56. Felling programme.

a. Softwoods. Winter 2001/02.

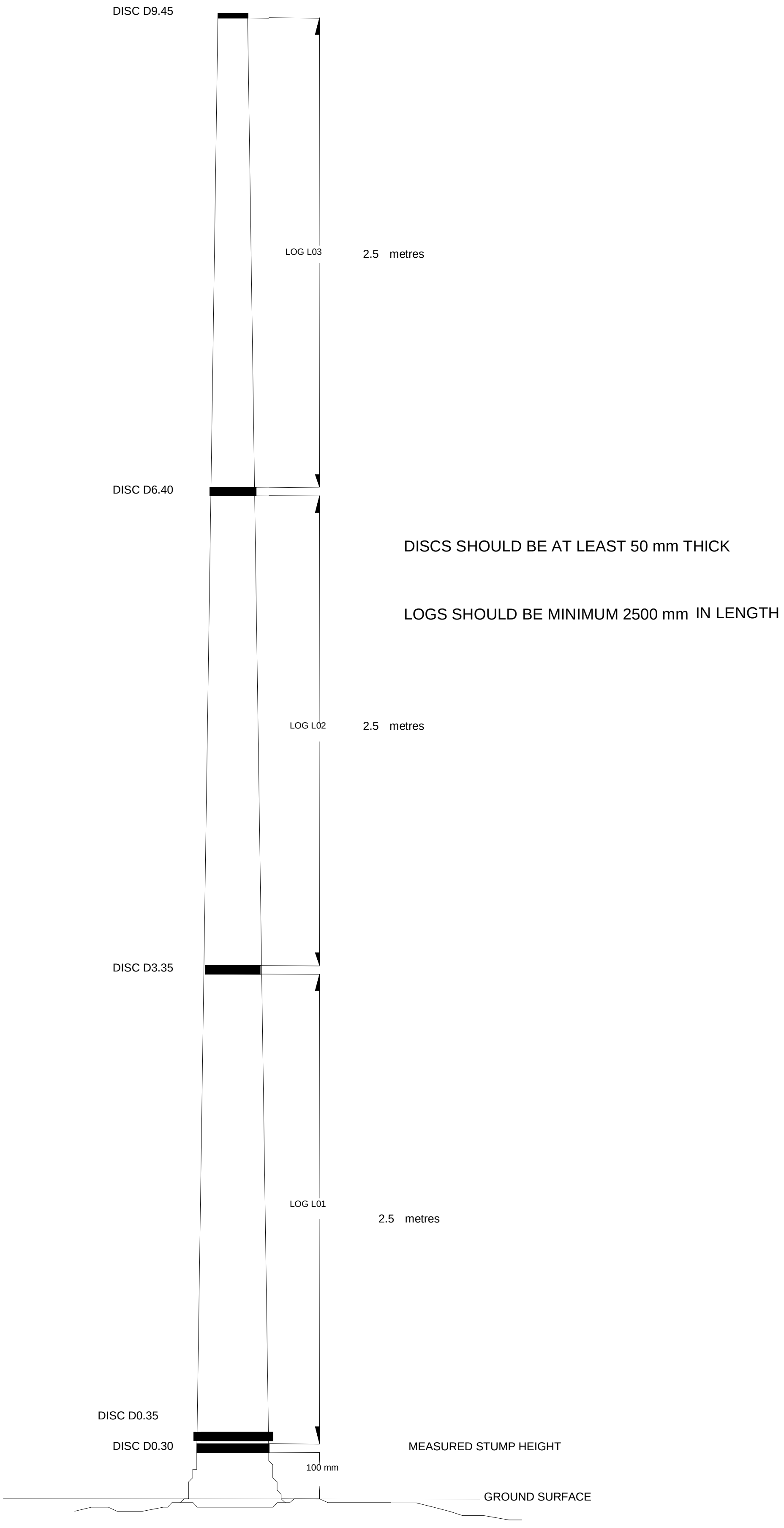
b. Hardwoods. Summer 2002.

57. Biomass Samples for Chemical Analysis.

a. Primary and Secondary Sites. When felling is convenient/appropriate.

b. Tertiary Sites. Start in Autumn 2001, with priority on existing plant material where held.

Sample Tree


DISC D9.45
LOG L03
2.5 metres
DISC D6.40
DISCS SHOULD BE AT LEAST 50 mm THICK
LOGS SHOULD BE MINIMUM 2500 mm IN LENGTH
LOG L02
2.5 metres
DISC D3.35
LOG L01
2.5 metres
DISC D0.35
DISC D0.30
MEASURED STUMP HEIGHT
100 mm
GROUND SURFACE

CHECK LIST

On completion of sample plot establishment, refer to the following list to check that all establishment and measurement procedures have been carried out.

1. *Establishment form completed*

Plot number; location; compartment number; grid reference, ownership details; general details; crop history; climate and soil type. Area of plot (m^2). Slope (degrees). Aspect (degrees). Altitude (m). Plot shape (or form). Surface rock type.

2. *Diameter measurements*

All tree diameters recorded.

Dead trees classified 5.

3. *Girthing sheet*

Diameter distribution completed.

Total height sample trees and top height sample trees selected.

4. *Height measurement*

All tree height and crown measurements for total height sample trees recorded.

All tree heights for top height sample trees recorded.

5. *Felled samples*

All total heights, timber heights, branch measurements and diameters recorded, including taper.

All log and disc samples taken and recorded

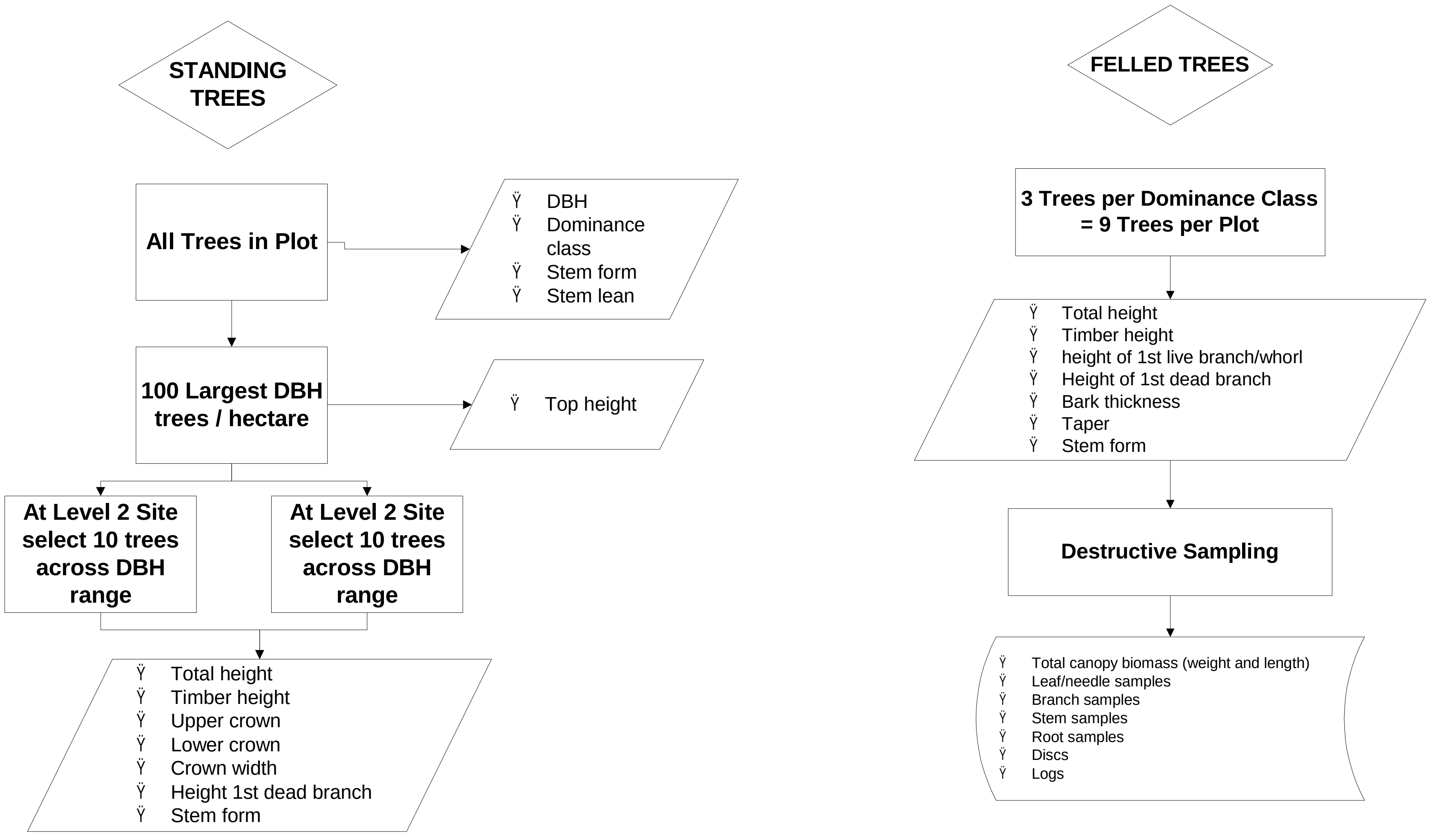
6. *Photographs*

Sample trees prior to felling.

7. *Biomass samples*

Samples bagged and correctly labelled.

Checklist flow diagrams

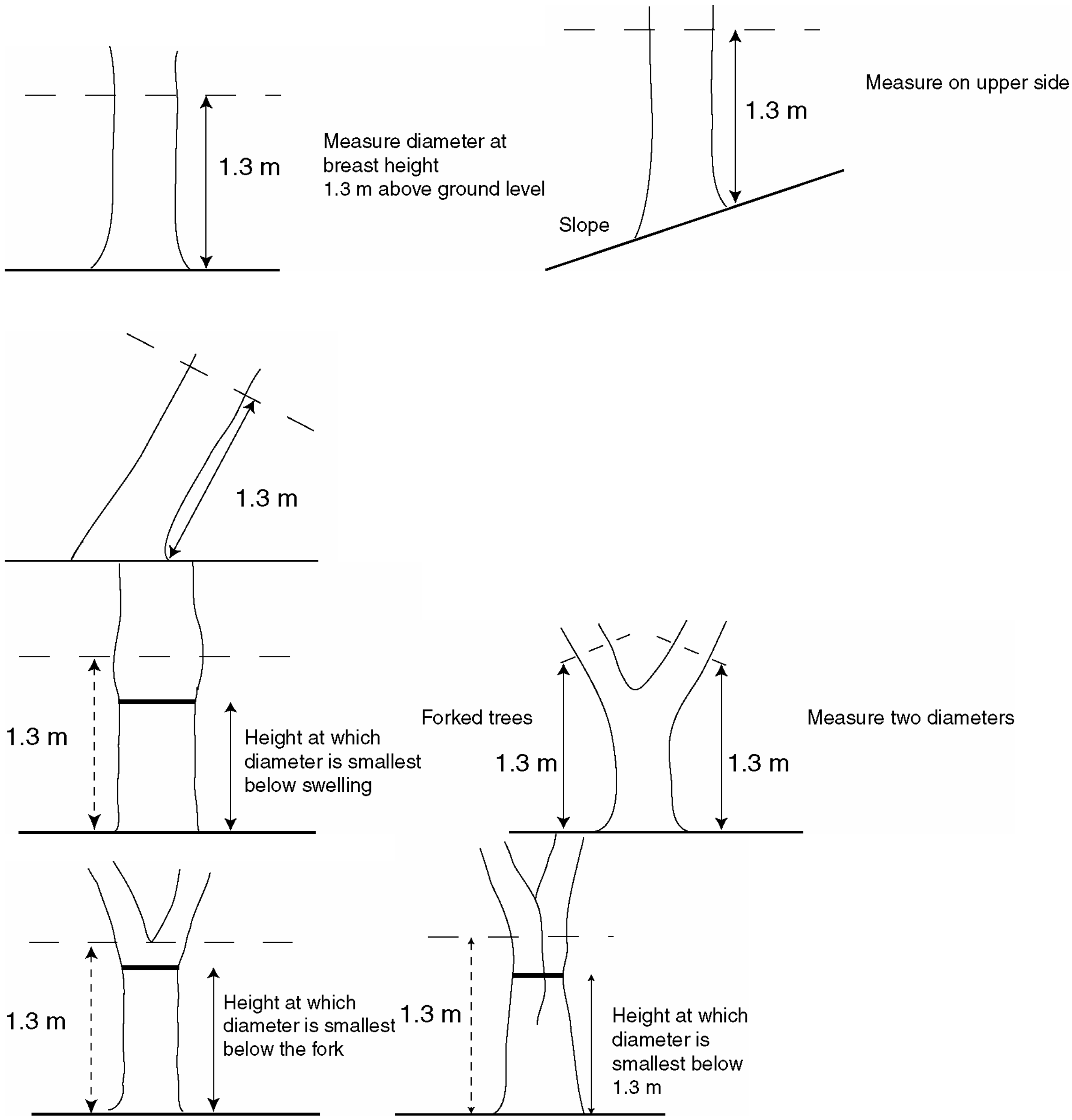


APPENDIX 1. Species Code Numbers.

1	*Pinus sylvestris*	Scots pine
2	*Pinus nigra* var *maritima*	Corsican pine
3	*Pinus contorta*	
4		
5	*Larix decidua*	European larch
6	*Larix kaempferi*	Japanese larch
7	*Larix x eurolepis*	Hybrid larch
8	*Pseudotsuga menziesii*	Douglas fir
9	*Picea abies*	Norway spruce
10	*Picea sitchensis*	Sitka spruce
11		
12	*Abies grandis*	Grand fir
13	*Abies procera*	Noble fir
14		
15	*Tsuga heterophylla*	Western hemlock
16	*Thuja plicata*	Western red cedar
17	*Chamaecyparis lawsoniana*	Lawson cypress
18	*Sequoia sempervirens*	Coastal redwood
19	*Taxus baccata*	Yew
20	*Chamaecyparis nootkatensis*	Nootka cypress
21	*Sequoiadendron giganteum*	Wellingtonia/Sierra redwood
22	*Quercus robur* and *petraea*	Oak
23	*Quercus borealis*	Red oak
24	*Quercus cerris*	Turkey oak
25	*Fagus sylvatica*	Beech
26	*Fraxinus excelsior*	Ash
27	*Betula* spp.	Birch
28	*Catanea sativa*	Spanish chestnut
29	*Populus* spp.	Poplar
30	*Alnus* spp.	Alder
31	*Tilia* spp.	Lime
32	*Acer pseudoplatanus*	Sycamore
33	*Ulmus* spp.	Elm
34	*Cedrus deodara*	Deodar
35	*Betula papyrifora*	Paper birch
36	*Pinus muricata*	Bishop pine
37	*Picea engelmanii*	Engelmann spruce
38	*Carpinus betulus*	Hornbeam
39	*Fraxinus americana*	White ash
40	*Pinus strobus*	Weymouth pine
41	*Pinus rigida*	Northern pitch pine
42	*Pinus banksiana*	Jack pine
43	*Pinus radiata*	Monterey pine
44	*Pinus resinosa*	Red pine
45	*Pinus peuce*	Macedonia pine
46	*Pinus ponderosa*	Western yellow pine
48	*Abies concolor*	Colorado white fir
49	*Cedrus atlantica*	Atlas cedar/Atlantic cedar
50	*Cryptomeria japonica*	Japanese cedar
51	*Cupressus macrocarpa*	Monterey cypress
52	*Picea omorika*	Serbian spruce
53		
54	*Quercus coccinea*	Scarlet oak
55	*Quercus canariensis*	Algerian oak
56	*Nothofagus obliqua*	Roble beech (Southern beech)
57	*Nothofagus procera*	Raoul or Rauli beech (Southern beech)
58	*Acer platanoides*	Norway maple

59	*Quercus palustris*	Pin oak
60	*Liriodendron tulipifera*	Tulip tree
61	*Picea orientalis*	Oriental spruce
62	*X Cupressocyparis leylandii*	Leyland cypress
63	*Abies veitchii*	Veitch's silver fir
64	*Picea rubens*	Red spruce
65	*Picea glauca*	White spruce
66	*Araucaria araucana*	Monkey puzzle/Chile pine
67	*Pinus mugo*	Mountain pine
68	*Pinus monticola*	Western white pine
69	*Betula ermanii*	Erman's birch
70	*Abies cephalonica*	Grecian fir
71	*Prunus serotina*	
72	*Sorbus aucuparia*	Rowan

APPENDIX 2. Protocols for measuring the diameters of leaning trees, forked trees and those with swellings at 1.3 m.



Form MEFYQUE 1

APPENDIX 3. Field Forms

Sample plot number | | | | | | | | |

LOCATION

Name of forest or estate ____________________

Compartment Number (UK only) | | | | Grid Reference | | | | | | | | | ____________

OWNER:

____

Directions for locating plot ____________________

General Details

Species name ____________ Code | | | GYC (UK only) | | | LYC (UK only) | | |

Plot area (sq metres) | | | | | P Yr | | | | | Date established | | | • | |

OBJECT OF SAMPLE PLOT AND TREATMENT PROPOSED

____

HISTORY OF CROP

Vegetation prior to planting, ploughing, seed identification no., provenance, planting method, spacing and type of plants, beating-up, fertilising, brashing, pruning, thinning, and damage, remarks.

____

TOPOGRAPHY

Altitude - meters | | | | |

Aspect - degrees | | | |

Slope - degrees | | |

Surface Form ____________

Other features (streams, gullies, rock outcrops etc)

___

___

___

Major soil group ___

CLIMATE

Meteorological station ___ Period ___

Direction of plot from Met' station ___ Distance ___ km

Mean annual rainfall

				mm

Other meteorological data e.g. max/min temperature, solar radiation, wind speed, relative humidity etc.

Source ___

___

___

___

Form MEFYQUE 2

GENERAL REGISTER

Sample Plot No. . . . .

Date of measurement	Initials
1	. . . . . .
2	. . . . . .
3	. . . . . .
4	. . . . . .
5	. . . . . .

Tree No.	**Tree Species**	**Tree Class**					**Diameter (cm)**					**Remarks**				
		1	**2**	**3**	**4**	**5**	**1**	**2**	**3**	**4**	**5**	**1**	**2**	**3**	**4**	**5**

GIRTHING SHEET

Form MEFYQUE 3

Plot No. . . . . Area . . . . hectares Location . . . .

Species 1 . . . . Initials . . . . Date . . . .

Checked . . . .

Summary

Group	**No. of trees**	**Total basal area**	**Average basal area**	**Average diam.**	**Average height**	**Average volume m^3**	**Total volume m^3**	**Form height**
Total and means of 100 largest trees per ha								
Totals and means of trees of 7 cm upwards								
Totals and means of trees of 6.5 cm and under								
Totals and means of plot after thinning								
Totals and means of thinnings 7 cm upwards								
Totals and means of thinnings 6.5 cm and under								
Totals and means of thinnings								

1 This form is to be repeated for each of the species present in the plot

Diameter class (cm)	No. of trees	Main crop		Thinnings		Main crop
		No. of trees	Basal area m^2	No. of trees	Basal area m^2	Height (m)
	Totals:					

Form MEFYQUE 4

HEIGHT MEASUREMENT OF STANDING TREES*/THINNINGS*
(* delete as appropriate)

Initials: ....

Checked by: ....

Project Plot No: .... **Species:** .... **Date:** ....

**** For thinnings only, enter 0. If missing trees included refer to programme specifications**

THINNING CODE ** 1	ALL TREES					ALL STANDING SAMPLE TREES * / FELLED TREES *					DENDROMETER MEASUREMENTS*: Height to Zero m	Butt Section: Mid-Diameter cm	Butt Section: Length	First Read	Second Read	Sine	
											CLIMBED/FELLED TREES*						Remarks
Tree Number	Stem form	Stem lean	Diameter at 1.3 m cm	Total Height m	Timber Height 7 cms over bark m	Height first dead branch m	Lower Crown * / Height of First Live Branch * M	Upper Crown * / Height of First Live Whorl * m	Crown Width m	NUMBER OF MEASUREMENTS	Section diameters at 1 m intervals m	Log Length m	Log Mid-Section Diameter cm	Log Quality	Bark Thickness mm		

THINNING CODE ** 1	ALL TREES						ALL STANDING SAMPLE TREES * / FELLED TREES *				DENDROMETER MEASUREMENTS*						
											Height to Zero m	Butt Section Mid-Diameter cm	Butt Section Length	First Read	Second Read	Sine	
											CLIMBED/FELLED TREES*						Remarks
Tree Number	Stem form	Stem lean	Diameter at 1.3 m cm	Total Height m	Timber Height 7 cms over bark m	Height first dead branch m	Lower Crown * / Height of First Live Branch * M	Upper Crown * / Height of First Live Whorl * m	Crown Width m	NUMBER OF MEASUREMENTS	Section diameters at 1 m intervals m	Log Length m	Log Mid-Section Diameter cm	Log Quality	Bark Thickness mm		

Form MEFYQUE 5

Plot No. ………………. **Date** / / **Initials** ……….. **Page of**

Tree Number ……………….

Crown component **L / M / U*** (*delete) Component length ……..…**m**

1st live branch to live crown	Length ..…… m	wt whorl 1 ………… kg	wt whorl 2 ………… kg	wt whorl 3 ……….. kg

1st section length m				Mid section 1m																		Top section length m			
Wt / whorl kg				L/D	Branch length (m)				Wt / whorl (kg)				L/D	Branch length (m)				Wt / whorl (kg)				Wt / whorl (kg)			

Appendix 1-E. *Location map of MEFYQUE tertiary sites.*

Appendix 1-F. *Wood anatomy sampling protocol.*

MEFYQUE PROJECT

WOOD ANATOMY AND BIOCHEMICAL PROTOCOL

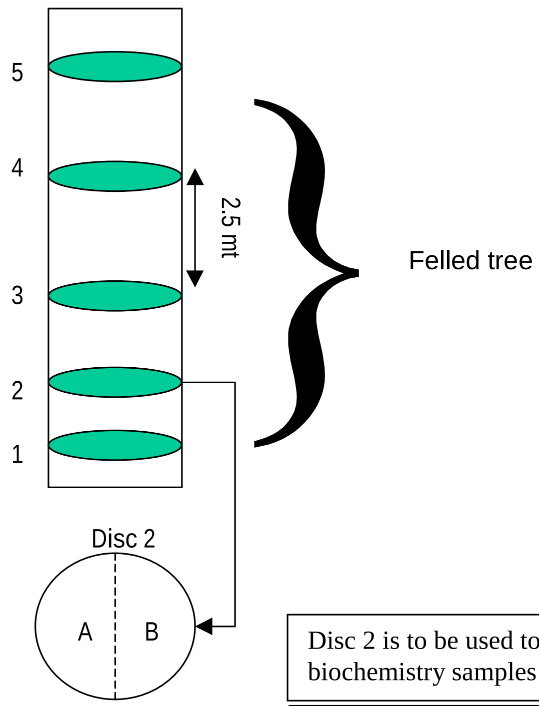
Dieter Overdieck and Daniel Ziche

Final version

May 2002

FIELD SAMPLING

1. <u>Sampling</u>. At each primary, secondary and tertiary site a disc is to be taken in the field as a cross section from each tree selected for destructive sampling and a disc sampled as described in the sampling protocol, as shown in Figure 1. The disc is to be >5cm thick is to be taken, with an arrow indicating both the top and the position of the magnetic north.



Disc 2 is to be used to extract wood anatomy and wood biochemistry samples

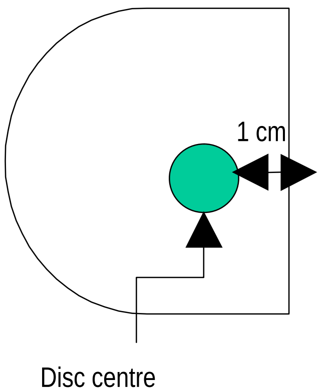
Segment A is for anatomical studies
Segment B is for biochemical studies

- The disk must be divided into two halves along the North-South axis. The western half-disk (marked as *A* in Figure 1) is for anatomical analyses. It must include all annual rings and the bark.

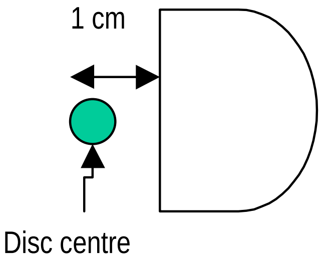
Either the whole disc or the two sub-samples are to be stored immediately in the field at 4 degrees Celsius (using cool box) and sent to TU-Berlin as quickly as possible. Rapid storage is required in particular for the biochemical studies sub-sample, as exposure to ambient conditions will rapidly degrade the sample. In the absence of a cool box, store in a dry and cool place and place the samples in a refrigerator at the earliest opportunity.

- For transportation and to minimise bulk, the discs can be cut into radial pieces (from the bark to the centre, like cutting a cake).

2. <u>Characteristics of sub-sample for wood anatomy studies</u>. The *A* portion of the disc is to include the youngest tree ring (the external one), with a 1 cm margin from the centre of the tree and the edge of the disc (see Figure 2).



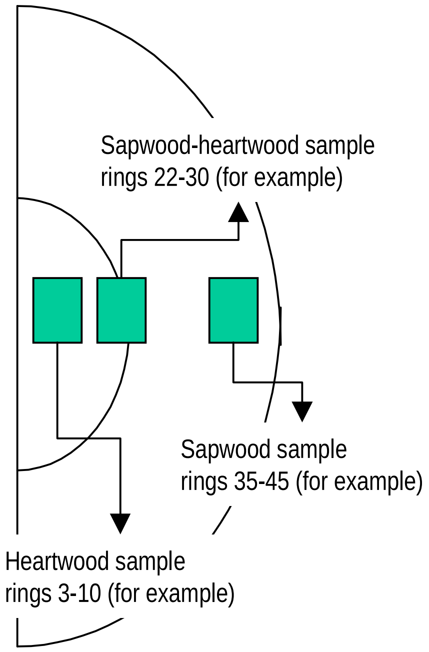
3. Characteristics of sub-sample for biochemical studies. The *B* portion of the disc is the balance of the disc left over after the sampling for wood anatomy material. (see Figure 3). The portion of the disc is to be cut 1 cm away from the centre of the disc, so that the youngest tree ring is available for the anatomical studies



4. Sub-sampling for biochemical studies. Portion B is to be oven dried according to the procedure in the Sample plot protocol. In accordance with the protocol and using a tungsten saw, sub-samples are to be taken from three portions of the disc (see figure 3):

- Sapwood
- Sapwood-heartwood transition
- Heartwood

It is essential to count the total number of rings and determine from which rings sub-samples have been taken. It is recommended that photographs be taken to document the position of samples. Individual sub-samples are to be powdered. Where powdering is not locally possible, then the oven dry portion B is to be sent intact to the University of Gent for milling.



LABORATORY PROTOCOL

1. <u>Measurements</u>. The following anatomical parameters will be measured on each disc.

<u>Parameter</u>	***Transversal Section***	***Radial Section***
Bark width	ó	
Ring width	ó	
Area of the lumina and diameter of conductive tissue in early and late wood 2	ó	
Cell wall thickness of early and late wood	ó	ó
Vessel/fibre length of early and late wood	ó	
Density profile and early/latewood ratio	ó	
Ratio between tissue types	ó	

[<u>Note</u>. The degree of lignification as a measured parameter is missing: it is only practicable to detect non-matured cells in the maturing zone behind the cambial zone and is only of interest if several wood samples are taken over the vegetation period to calculate, for example, cell maturation rate.]

With the exception of ring width, also measured using the density profile and earlywood : latewood ratio, measurements are conducted by light-microscopy.

2. Sample preparation

- <u>Storage</u>. Samples are stored in a dry and cool place.
- <u>Cutting</u>. Sections of 15µm thickness are obtained using a sliding microtome. Care is taken to ensure growth rings do not get out of sequence.
- <u>Staining</u>. Staining is carried out using Phloroglucin + HCL or Safranin + Astrablue (for contrasting tissue types)

3. Measurement Equipment

- Bark and ring width measured using standard dendrometer 3.
- Digital pictures taken separately of earlywood and latewood at different magnifications (x40, x20 and x10). Digital pictures of 2-3 successive growth rings in cross and radial sections; determine the scale of each picture.
- Two repetitions per growth ring, one along the north radii and one along the south radii.
- Measurements are done with a digital image analysing system using a TU-Buses Qwin500, Leica.

4. <u>Measurement priority</u>. Initially, measurement priority has been assigned to primary sites that are also Level II sites and for the most recently developed 10 growth rings.

2 Distinction between early- and latewood is made only in conifers or in ring-porous angiosperms.
3 Dendrometer supplied by the Dendrochronological Laboratory of the German Archaeological Institute.

Appendix 1-G. *Wood technology sampling protocol.*

MEFYQUE PROJECT

WOOD TECHNOLOGY PROTOCOL

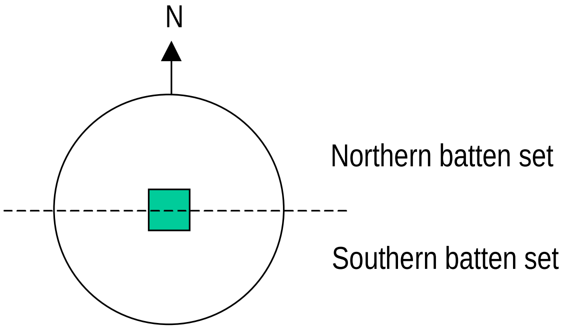
Joris van Acker and Keith Maun

July 2001

PRIMARY AND SECONDARY SITES

1. <u>Sampling of Softwoods</u>. After 3D scanning of logs from primary and secondary sites, these will be milled at the sawmill and battens (47x100 mm and 47x200 mm) will be produced from each 2.5 m log, racked and transported to BRE. 2.5 m battens will then be divided into a 'northern' and a 'southern' set (see diagram) according to their position in the log. Separate tests will be carried out on each set of battens (see table below)

NOTE. BRE is to clarify sampling and tests on box pith.



2. <u>Tests on Softwood Battens</u>. The following tests are to be carried out on softwood battens from primary and secondary sites and for each set.

SET	Test(s)	Responsible PI	Remarks/Action
A. Northern	1. Machine grading	BRE	• Battens to dry
	2. Drying distortion	BRE	• Twist, spring and bow at 15-18% and 10% m.c.
	3. Performance measures	BRE	• At 15% m.c.
	4. Growth characteristics	BRE	•
	5. 4-point structural tests	RUG	• Tests to be carried out on 50 large battens from each site. • Samples are to be representative of the age of the tree, through the height of the tree and for each of the 3 dominance classes. • Transport arrangements and costs of movement of battens are the responsibility of BRE.
B. Southern	1. Small clear tests (See slide 9 for details)	RUG	• Small clears (150x20x20 mm) are to be produced by BRE from the N axis of the log from each of the 9 logs sampled at each primary site. • Samples to be taken from heartwood, heartwood-sapwood transition and sapwood. Samples are to be representative of the age of the tree, through the height of the tree and for each of the 3 dominance classes. • Transport arrangements and costs of movement of battens are the responsibility of BRE. • RUG to confirm whether can carry out tests on small clears (density, MOR, MOE at 12% moisture content) and 3-point flexure tests.
C. Tip of tree	2. Small clear tests (See slide 9 for details)	RUG	• Small clears are to be produced by BRE. • Transport arrangements and costs of movement of battens are the responsibility of BRE.

PRIMARY AND SECONDARY SITES

3. <u>Sampling of Hardwoods</u>. After 3D scanning of logs from primary and secondary sites at BRE, these will be milled and battens (47x100 mm) will be produced from the central portion of each 2.5 m log and racked. Separate tests will be carried out on each set of battens (see table below).

NOTE. BRE is to clarify sampling and tests on box pith.

4. <u>Tests on Hardwood Battens</u>. The following tests are to be carried out on hardwood battens from primary and secondary sites.

SET	Test(s)	Responsible PI	Action /Remarks
A. 1 m batten	1. Machine grading	BRE	Battens to dry
	2. Drying distortion	BRE	Twist, spring and bow at 15-18% and 10% m.c.
	3. Performance measures	BRE	At 15% m.c.
	4. Growth characteristics	BRE	
	5. 4-point structural tests	RUG	Tests to be carried out on 50 large battens from each site. Samples are to be representative of the age of the tree, through the height of the tree and for each of the 3 dominance classes. Transport arrangements and costs of movement of battens are the responsibility of BRE.
	6. Small clear tests (See slide 9 for details)	RUG	Small clears (150x20x20 mm) are to be produced by BRE from the N axis of the log from each of the 9 logs sampled at each primary site. Samples to be taken from heartwood, heartwood-sapwood transition and sapwood. Samples are to be representative of the age of the tree, through the height of the tree and for each of the 3 dominance classes. Transport arrangements and costs of movement of battens are the responsibility of BRE. RUG to confirm whether can carry out tests on small clears (density, MOR, MOE at 12% m.c.) and 3-point flexure tests.
B. Tip of tree	Small clear tests (See slide 9 for details)	RUG	Small clears are to be produced by BRE. Transport arrangements and costs of movement of battens are the responsibility of BRE. Tests detailed at point A6 of current table

TERTIARY SITES

5. <u>Sampling of Tertiary Site Wood Material</u>. After 3D scanning of material from tertiary sites at BRE, small clear are to be produced from the juvenile wood, here defined as wood from complete rings age 1-3 years.

6. <u>Tests on Small Blears</u>. The following tests are to be carried out on small clears produced from wood sampled at tertiary sites.

Wood technology test number	Partner	Definition of test	Remarks
1	BRE	3-D scanning of wood material	
2	BRE	Wood density	
3	BRE	Tension tests	
4	RUG	Compression tests	BRE responsible for arrangement and transport costs of material to RUG

Appendix 1-H. Weather generator report.

Forest Research
An agency of the Forestry Commission

A SYNTHETIC WEATHER GENERATOR FOR SIMULATING DAILY METEOROLOGICAL DATA AT THE DAILY TIMESTEP IN THE UK

by

Samuel P. Evans, Tim Randle, Paul Henshall and Paul Taylor

August 2002

Report Number:

2002 EU Annual Report

Title:

A synthetic weather generator for simulating daily meteorological data at the daily timestep in the UK

Authors:

S.P. Evans, T. Randle, P. Henshall and P. Taylor

Address:
Mensuration Branch
Forest Research, an executive Agency of the Forestry Commission
Alice Holt Lodge
Wrecclesham, Farnham
Surrey GU10 4LH
UNITED KINGDOM

TABLE OF CONTENTS

A SYNTHETIC WEATHER GENERATOR FOR SIMULATING DAILY METEOROLOGICAL DATA AT THE DAILY TIMESTEP IN THE UK

A. INTRODUCTION

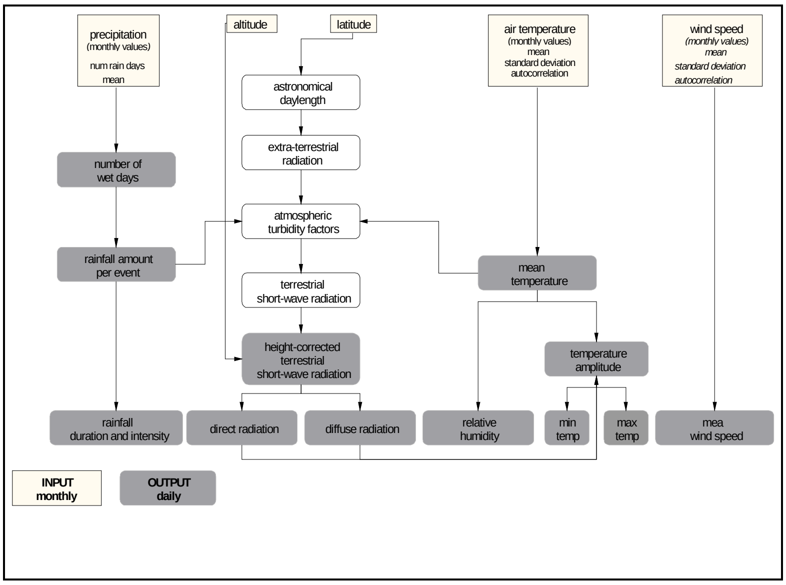
1. The Weather Generator. This report outlines the development and validation of a weather generator, a simulation tool that allows widely available monthly summaries of climatological parameters to be downscaled to the daily timestep, while maintaining the same properties of the original climate input.
A weather generator does not output weather that is directly comparable to that observed in a particular year; rather the model produces a random timeseries constrained by the distribution of its input values so that the random timeseries has similar statistical properties (mean and standard deviation) as the observed input. As each model run is random, so the outputs will be unique, and will therefore display some differences to the properties of the observed distribution.

Weather generator models based on a stochastic approach have received considerable attention in the climate change impacts community, as these are conceptually simple solutions well suited to ecological and environmental applications. Such models strike a balance between complexity and goodness-of-fit (Hutchinson, 1987), coupled to an ability to provide good approximations of the large, and apparently random, variability of daily weather patterns. Based on the structure outlined by Richardson (1981) a number of models simulating a varying range of climate parameters have been developed for different applications at different spatial scales. Models range from site-specific (e.g. Larsen and Pense, 1982; Richardson and Wright, 1984; Williams et al., 1985; Geng et al., 1988; Wilks, 1992; Posch, 1994; Semenov and Barrow 1997; van der Voet et al., 1996) to spatial models that encompass the variability of climate phenomena through correlation to atmospheric circulation patterns (e.g. Bardossy and Plate 1991; Hutchinson, 1991; Hutchinson 1995; Wilks 1992; Semenov and Barrow 1997; van der Voet 1996; Wilby 1994).

B. WEATHER GENERATOR MODEL STRUCTURE

1. Overview of the Weather Generator. The structure here proposed defines a stochastic-deterministic, site-scale model. Instrumental precipitation data are inputted into a first-order two-state Markov chain to generate daily scale estimates of precipitation on a rain day; a constrained random distribution around the observed mean. In turn this is coupled to an auto-correlation intensity factor, is used to generate daily scale estimates of mean, maximum and minimum temperature, wind speed and relative humidity. Total, direct and diffuse solar radiation are approximated using spherical geometry, corrected for latitude. Inter-dependence between variables is outlined to adjust terrestrial solar radiation for cloudiness; terrestrial radiation is used to develop temperature amplitude. The outline structure of the model is shown at Figure 1. In its current version the model uses the Climatic Research Unit - University of East Anglia 1961-90 monthly time step climatology available for GB at a 10 km resolution, as its principal inputs. An option for user-defined inputs is also available.

Figure 1. Model structure.



2. Key Properties.

(a) Solar radiation. Following the approach proposed by Lui and Jordan (1960, 1963) and Klein (1977), solar radiation (in MJ) is approximated from spherical geometry. This approach uses the position of the earth in relation to the sun, to provide an approximation of the solar radiation at a given latitude on a horizontal surface outside the atmosphere reaching the top of the earth's atmosphere. A further correction is introduced to account for leap years. On entering the atmosphere the solar beam impacts with molecules of the atmosphere's constituent gases (CO_2, O_3 and H_2O), as well as with dust particles (Iqbal 1983), resulting in particle absorption and scattering; the solar beam is further attenuated and scattered by cloud cover. Solar beam atmospheric attenuation is approximated using a set of atmospheric turbidity factors (Iqbal 1983; Palz & Grief 1996) coupled to a cloudiness generator approximating cloud cover (in tenths) for each dry and wet day (Nikolov and Zeller, 1992); wet day cloudiness is a function of rainfall amount. A range of values for atmospheric turbidity or Ångström (Ångström 1924) factors are available in the literature (e.g. Rietveld 1978; Iqbal 1983; Nikolov and Zeller 1992; Gueymard 1993; Burman and Pochop 1994) and a standard set are built into the model or can be user-defined. As the model does not account for cloud type, that will in turn affect terrestrial radiation, an UK-wide correction factor has been introduced to improve the model's predictive accuracy. The solution approximates total radiation received on a horizontal plane at the earth's surface, which in turn is be for altitude, aspect and slope (e,g, Iqbal 1983; Nikolov and Zeller 1992; Duffie and Beckman 1991); slope can affect the fraction of sky which can be viewed from the surface, affecting the diffusive component of incoming solar radiation (Paltridge and Platt, 1976). No consensus has formed around a value for the solar 'constant'. Most authors report 1367 W m^{-2} s^{-1} as the most accurate measurement, but the following values are also given in the literature: 1.934 cal/min/cm^2 or 2.00±2% cal/min/cm^2 (Smithsonian Institute, in Lide, 1990); 1353 W/m^2 or 1.940 cal/min/cm^2 (NASA, 1970). A number of physiological processes are sensitive to the direct:diffuse radiation ratio, e.g. photosynthesis (e.g. Gueymard 1989). Terrestrial radiation is therefore separated into the direct and diffuse components to allow for suitable slope factor correction, with a further separation into the photosynthetically active elements (Bristow and Campbell 1985). No orbital tilt factor is introduced in the current version of the model, but may easily be added following the approach in Klein (1977) and Keith and Kreider (1978).

(b) Precipitation. After Richardson (1981) and Ross (1983) precipitation (in millimetres), is approximated using a stationary, irreducible, continuous first-order, two-state Markov process to determine the occurrence of a rain day. Transitional probabilities determine the occurrence of each model state (dry/wet), or the probability that a wet day is followed either by a wet ([P(W/W)] or a dry ([P(W/D)] day (Hutchinson 1991). Values for transitional probabilities are estimated for each (Julian) day across a number of years (long method) and, in order to encompass the seasonality of rainfall, for each month separately across a number of years (short method). The probability is then compared against a random uniform deviate (*u*) of interval [0,1]; if *u* is less than or equal to P(W/D) or P(W/W), then that day is classified as a dry or a wet day, whichever is appropriate. On a rain day the model assumes a single rainfall event of uniform intensity. When precipitation occurs at air temperatures between +2 and –2 degrees Celsius, this is assumed to be in the form of sleet; when < -2 degrees Celsius, this is assumed to be in the form of snow. The accuracy of the transitional probabilities is underpinned by an assumption of rainfall homogeneity within the time-step and across the number of years of available instrumental data (Richardson and Wright, 1984). A two-parameter gamma probability distribution function (pdf), allocating the probability of occurrence to a given event, characterises the amount of rainfall occurring on a rain day. Following standard notation, the two parameters are designated α and β, where (α x β) is the mean and (α x β^2) is the variance of the distribution; the value of α influences the proportion of small amounts of rainfall and β the proportion of large amounts of (heavy) rainfall.

(c) Air temperature. The model proposes an auto-correlation intensity process to the continuous time (Hutchinson, 1991), coupled with a uniformly random generated distribution around the observed mean and constrained within the observed standard deviation, to generate daily time-step synthetic data for up to three temperature variables namely, mean, minimum and maximum air temperature. Air temperature amplitude can also approximated from generated terrestrial solar radiation data (Bristow and Campbell 1985) and when associated with the mean, amplitude approximates maximum and minimum air temperature; this last approach is the one used for the present version of the model. The auto-correlation intensity process to the continuous time approach is applied to input data at the monthly time-step, derived separately for each month across a number of years.

(d) Wind speed and relative humidity. Wind speed and relative humidity are estimated using a modelling solution analogous to mean air temperature.

(e) Other values. Values for saturated vapour pressure, air humidity and atmospheric pressure are approximated using widely accepted solutions with one or more of the simulated parameters described above as input.

3. Model Input Parameters. The model requires a range of input parameters, as outlined in table 1.

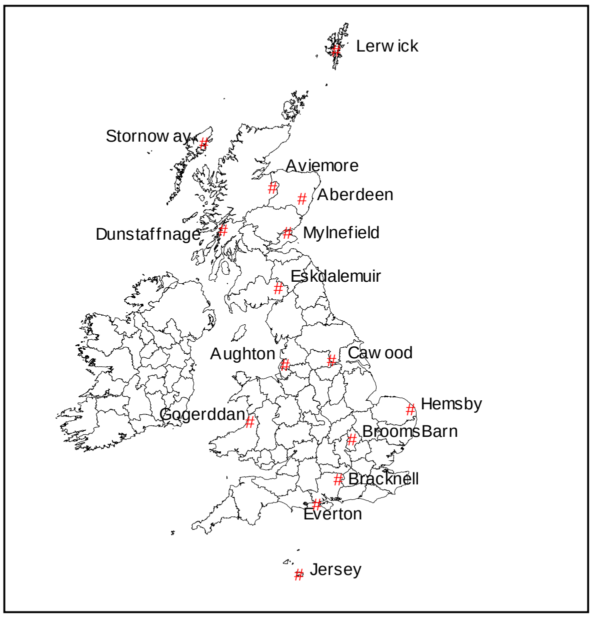
Variable	Variables	Timestep
Solar radiation	Latitude, longitude, elevation, slope and aspect	
Precipitation	rain days per month total precipitation per month	Monthly
Mean air temperature	average, standard deviation [first-order auto-correlation default value = 0.65]	Monthly
Mean wind speed	average, standard deviation [first-order auto-correlation default value = 0.65]	Monthly

1. Minimum Input Requirements. No minimum requirements concerning the length of observed instrumental time series used as input are defined. As a guideline, the time series should be of sufficient length to encompass the underlying climatic pattern of a given period. This is usually assumed to be a decade or more in duration (Leemans and Cramer, 1991), given that climate changes on different time scales (Jones et al., 1986) and there is no particular 'average' weather to which climate will return (Gribbin and Lamb, 1978).

C. MODEL VALIDATION

1. Validation Sites. Model validation has been carried out at the *national scale* in GB using 15 sites broadly representative of the range of climatic conditions, (Figure 2). Sites have been selected from the BADC database and for which at least 10 years of daily instrumental data were available for all meteorological variables simulated by the model. Daily instrumental data were summarised to provide monthly values in turn used as inputs to the model. Model outputs (mean and standard deviation) were then compared with the inputs at the same resolution to assess the model's overall predictive ability. The distribution of generated values has also been compared against the observed values to further assess the model's performance.

Figure 2. Location of validation sites.



2. Discussion. The overall predictive ability of the model is assessed using the coefficient of determination (R^2) of a constrained regression comparing the simulated mean and standard deviation against the observed values at the monthly timestep.

At the *national scale*, as can be seen from figures 3-7, where the monthly means for observed *vs* simulated values are compared, the model has a high predictive ability for mean solar radiation, air temperature and precipitation ($R^2 > 0.95$); the model performs poorly for relative humidity. While the model is less able to accurately represent the standard deviation of the observed data, it is necessary to take into account that the model develops a unique random timeseries within the constraints of the observed distribution, resulting in some departure from the observed values. In Appendix A, tables 1-15 provide the monthly observed and simulated values for each site; the *F*-test (99% and 95% confidence) has been performed for each pair of monthly values to assess the difference between simulated against observed.

Figure 3. Model validation: solar radiation.

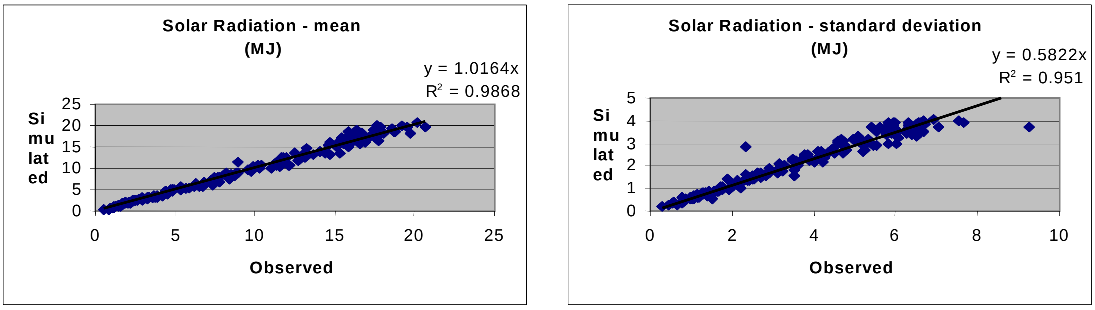


Figure 4. Model validation: temperature.

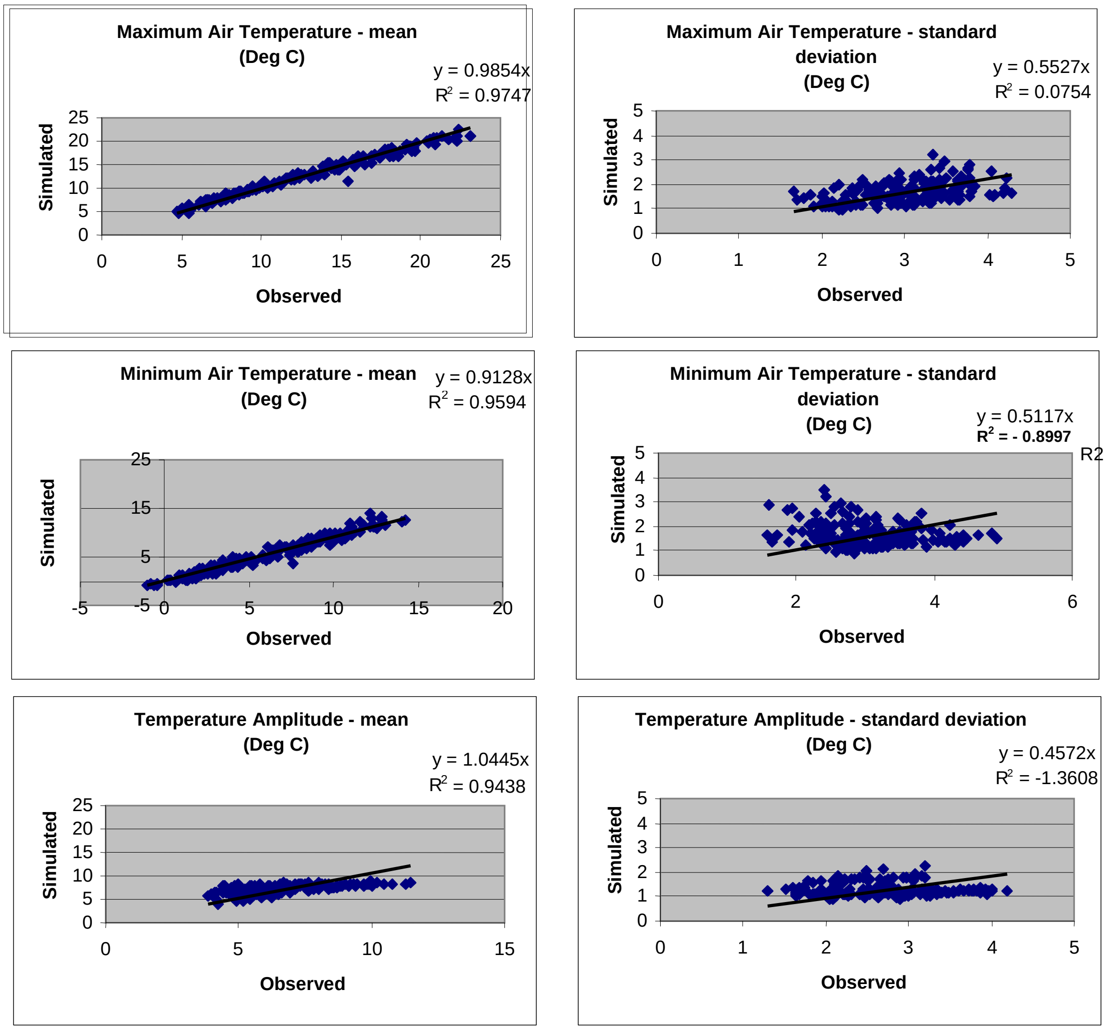


Figure 5. Model validation: windspeed.

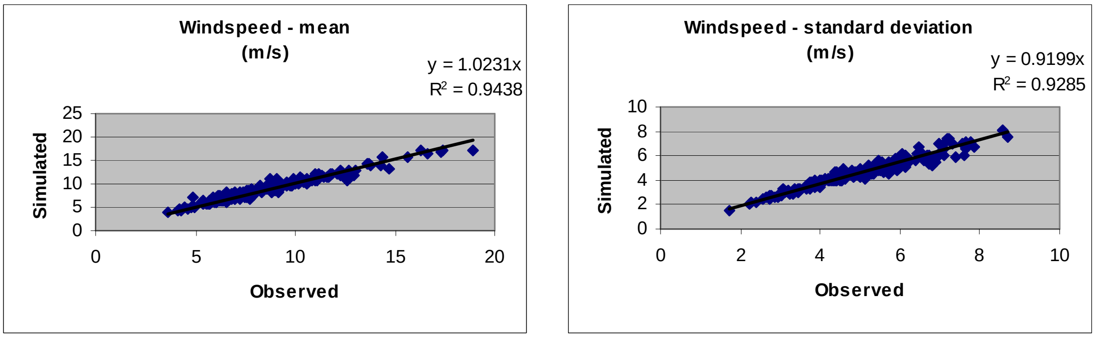


Figure 6. Model validation: precipitation.

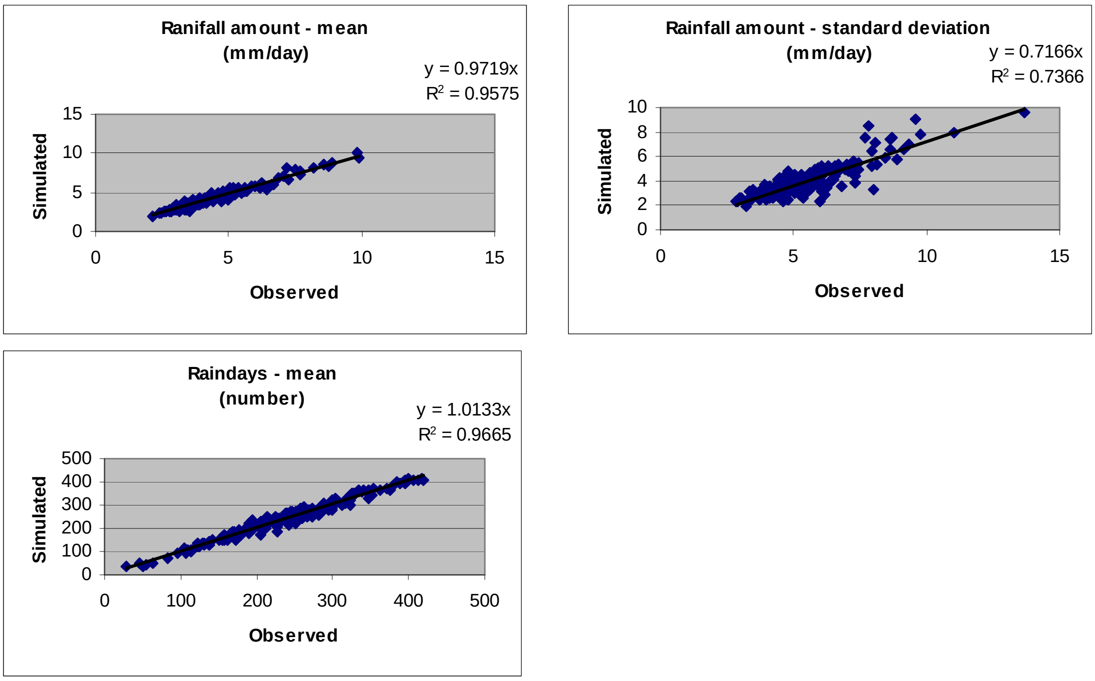
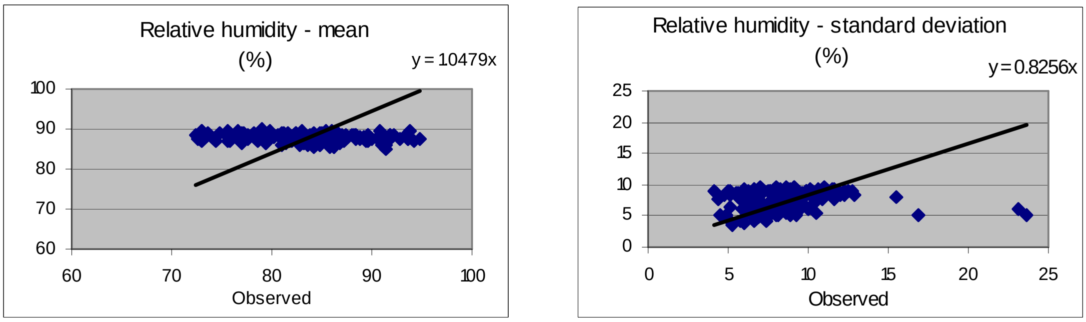


Figure 7. Model validation: relative humidity



To assess the model's predictive ability at the *local scale*, a random selection of data from 4 sites has been selected to explore the properties of the model at the *site scale*. The following considerations can be made at the local scale.

(a) Solar radiation. The model is robust in predicting total solar radiation (R^2: mean > 0.98; st. dev > 0.95) and is good for both wet (R^2 > 0.84) and dry days (R^2 > 0.70). When comparing the occurrences of mean simulated daily values to the observed values over a 10-year period the relationship appears robust, with R^2 for total radiation > 0.76 (up to 0.96), particularly for wet day radiation (R^2 > 0.84) and less so for dry day radiation (R^2 > 0.46). The model under-estimates the number of dry days with very

high solar radiation (>25 MJ/day), where the optical properties of the atmosphere favour extremely high levels of radiation.

(b) Temperature. The model is robust in estimating minimum (R^2 mean > 0.98) and maximum (R^2 mean > 0.99) air temperature at the monthly timestep. At the same timestep the variability of the simulated data is less good when compared with observed. For minimum air temperature a north-south gradient appears to be present with the England sites presenting an R^2 for the standard deviation > 0.98, while the Scottish sites present a very low coefficient of determination. The relationship is very poor overall for describing the variability of maximum air temperature. When comparing the occurrences of mean simulated daily values to the observed values over a 10-year period the relationship is good for both minimum (R^2 > 0.75) and for maximum air temperature (R^2 > 0.85). The model appears to present a systematic bias in estimating minimum and maximum air temperature in the range between 0-4 degrees C; the number of simulated days with air temperatures approximating zero are significantly over-estimated. The simulation approach adopted is the same as that used for windspeed; it is interesting to note that the relationship appears stable for windspeed, indicating that the numerical solution adopted may be breaking down at values around 0. Additionally, the simulation approach used does not entirely span the range of the observed temperatures, with a truncation around –2 degrees C at the lower end of the distribution and +28 degrees C at the upper end. In the observed values, there appears to be a tendency towards a bimodal distribution, possibly reflecting a seasonal behaviour; as the model currently assumes the same relationship throughout the year, the observed patters is not encompassed in its entirety by model outputs.

(c) Precipitation. The model is well able to simulate the total number of wet days (R^2 > 0.93) and, by definition, the number of dry days. When comparing the occurrences of dry/wet days compared to the observed values over a 10-year period the relationship appears robust, with R^2 > 0.93; for wet days only the relationship is good (R^2 > 0.70). The number of rain days with events >2 mm is well simulated; the model is less able to simulate the number of days with rainfall between 0-1 mm where the number is under-estimated; overall the model follows the observed magnitude of rainfall events. The loss of accuracy in simulating low rainfall events is a consequence of the modelling solution adopted, representing a trade-off between modelling simplicity and over-parameterisation. Given the purpose of the overall ETp model, simulation of low rainfall events will only become crucial when the soil water content is approximating saturated conditions (field capacity).

(d) Windspeed. Overall, the model is good at simulating wind-speed (R^2 of mean values > 0.57 and up to 0.91), and to large extent captures both the mean and the range observed in the data (R^2 st. dev. > 0.84).

(e) Relative humidity. In general the range of values simulated by the model is generally within that of the observed, however the distribution is much narrower, with an over-estimation of the monthly mean by approximately 15%, an a significant number of values approaching 100% humidity, not observed in the data.

D. CONCLUSIONS

A weather generator has been developed that downscales monthly timestep inputs to daily values. The model has been developed so that inputs can be obtained from widely available spatial databases (e.g. University of East Anglia Climate Research Unit climatologies). The model has been validated at 15 sites in the UK. The validation exercise has shown that, with the exception of relative humidity, the model is well able to replicate instrumental values. Analysis of a sub-set of data for single stations has indicated that, again with the exception of relative humidity, the model approximates the values of climate variables, and their distributions, to an acceptable standard.
In the context of the current project, the majority of model components are considered appropriate for use in the MEFYQUE project.

E. REFERENCES

BADC/UKMO. 2001. British Atmospheric Data Centre. http://www.badc.rl.ac.uk.

Bardossy A. and Plate E.J. (1991). Modeling daily rainfall using a semi-Markov representation of circulation pattern occurrence. *Journal of Hydrology* **122**: 33-47

Barrow, E.M., Hulme, M. and Semenov, M., 1996. Effect of using different methods in the construction of climate change scenarios: examples from Europe. *Climate Research* **7**: 195-211.

Bristow, K. L., and G. S. Campbell. 1985. An equation for separating daily solar irradiation into direct and diffuse components. *Agricultural and Forest Meteorology* **35**: 123-131.

Burman, R.D. and, Pochop, L.O., 1994. *Evaporation, Evapotranspiration & Climatic Data*. Elsevier, London, GB, 302 pp.

Duffie J.A. and Beckman W.A., 1991. *Solar engineering of Thermal Processes*. John Wiley & Sons, London, GB, 944 pp.

Evans S.P., Mayr T.R., Hollis J.M. and Brown C.D. (1999). SWBCM: A soil water balance capacity model of soil water balance for environmental applications in the UK. *Ecological Modelling* 121: 17-49.

Geng, S., Penning De Vries, F.W.T., and Supit, I., 1986. A simple method for generating daily rainfall data. *Agricultural and Forest Meteorology* **36**: 363-376.

Gribbin, J., and Lamb, H.H., 1978. Climatic change in historical times. In *Climatic Change*. ed. Gribbin J., CUP, Cambridge, UK.

Gueymard, C., 1989. An atmospheric transmittance model for the calculation of the clear sky beam, diffuse and global photosynthetically active radiation. *Agricultural and Forest Meteorology* **45**: 215-229.

Gueymard, C., 1993. Assessment of the accuracy and computing speed of simplified saturation vapor equations using a new reference data set. *Journal of Applied Meteorology* **32**: 1294-1300.

Hutchinson, M. F., 1995. Interpolating mean rainfall using thin plate smoothing splines. *Int. J. Geog. Inf. Sys*. **9**: 385-403.

Hutchinson, M.F., 1987. Methods of generation of weather sequences. In: Bunting A.H. (editor). *Agricultural Environments: Characterisation, Classification and Mapping*, pp. 149-157, CAB International, Wallingford, UK.

Hutchinson, M.F., 1991. Climatic analyses in data sparse regions. In: Muchow, R.C., and Bellamy, J.A., (editors). *Climatic Risk in Crop Productions*, CAB International, Wallingford, UK, pp. 55-71.

Iqbal, M., 1983. *An Introduction to Solar Radiation*. Academic Press, Toronto, Ontario, Canada, 390 pp.

Jones, P.D., Wigley, T.M.L., and Wright, P.B., 1986. Global temperature variations between 1981 and 1984. *Nature* **322**: 430-434.

Keith, F., and Kreider, J.F., 1978. *Principles of Solar Engineering*. Hemisphere Publishing Corporation, Washington D.C., USA, 778 pp.

Klein, S.A., 1977. Calculation of monthly average insolation on tilted surfaces. *Solar Energy* **19**: 325-329.

Larsen, G.A., and Pense, R.B., 1982. Stochastic generation of temperature and solar radiation data. *Journal of Hydrology* **48**: 1-17.

Leemans, R., and Cramer, W.P., 1991. *The IIASA database for mean monthly values of temperature, precipitation and cloudiness on a global terrestrial grid*. Report RR-91-18, International Institute of Applied Systems Analysis, Laxenburg, Austria, 62 pp.

Lide, D.R., editor 1990. *CRC Handbook of Chemistry and Physics*. 71st edition, CRC Press, Boca Raton, Florida, USA.

Lui, B.Y.H., and Jordan, R.C., 1960. The interrelationship and characteristic distribution of direct, diffuse and total radiation. *Solar Energy* **4**: 1-19.

Lui, B.Y.H., and Jordan, R.C., 1963. The long-term average performance of flat-plate solar engineering collectors. *Solar Energy* **7**: 53-74.

NASA, 1970. *The Solar Constant and the Solar Spectrum Measured from a Research Aircraft*. Thekaekara M.P. editor, Technical Report R-351, Goddard Space Flight Centre, Greenbelt, Maryland, USA,

Nikolov, N.T., and Zeller, K.F., 1992. A solar radiation algorithm for ecosystem dynamics models. *Ecological Modelling* **61**: 149-168.

Paltridge, E.W., and Platt C.M.R. 1976. *Radiative Processes in Meteorology and Climatology*. Elsevier, London, GB.

Palz W., Greif J and Commission of the European Communities (eds) (1996). *European Solar Radiation Atlas: solar radiation on horizontal and inclined surfaces*. Springer, London, GB, 333 pp.

Posch, M., 1994. *Development of a weather generator for Finland II*. Kanninen M., and Heikinheimo P., (editors), The Finnish research Programme on Climate Change. Second Progress Report. Publication of the academy of Finalnd 1/94, Helsinki, Finland, pp. 323-328.

Richardson, C.W., 1981. Stochastic simulation of daily precipitation, temperature and solar radiation. *Water Resources Research* **17**: 182-190.

Richardson, C.W., and Wright, D.A., 1984. *WGEN: A model for generating daily weather variables*. USDA-ARS, ARS-8, 83 pp.

Rietveld,M.R. 1978. A new method for estimating the regression coefficients in the formula relating solar radiation to sunshine *Agric. Meteorol*., **19**: 243-252.

Ross, S.M., 1983. Stochastic Processes. Academic Press, New York, New York State, USA.

Semenov, M. and Barrow, E.M., 1997. Use of a stochastic weather generator in the development of climate change scenarios. *Climate Change* **35**: 397-414.

van der Voet, P., Kramer, K., and van Diepen, C.A., 1996. Parameterisation of the Richardson weather generator within the European Union. Report 92, DLO Winand Staring Centre, Wageningen, The Netherlands, pp. 72.

Wilby, R.L. 1994. Stochastic weather type simulation for regional climate change impact assessment. *Water Resources Research* **30**: 3395–3403.

Ångström, A., 1924. Solar and terrestrial radiation. *Quarterly Journal of the Royal Meteorological Society* **50**: 121-124.

Wilks, D.S., 1992. Adapting stochastic weather generation algorithms for future climate change studies. *Climate Change* **22**: 67-84.

Williams, J.R., Nicks, A.D., and Arnold, J.G., 1985. Simulator of water resources in rural basins. *American Society for Civil Engineering Hydraulics Journal* **111**: 970-986.

APPENDIX I

Monthly observed and simulated values for each site; the *F*-test (99% and 95% confidence) has been performed for each pair of monthly values to assess the difference between simulated against observed

Month		Days With Data	Max Temp (C)	SD Max Temp.	Min Temp (C)	SD Min Temp	Temp Amplitude	SD Amplitude	RH %	SD RH	RAD MJ/day	SD RAD	Wind-speed (m/s)	SD Wind	Wet Days	Mean ppt mm/ day	SD ppt	Cloud	SD Cloud	Beam Rad MJ/day	Beam SD	Diff Rad MJ/ day	Diff SD	SVP mbar	SD Svp
1	O	236	6.87	2.68	1.69	2.79	5.18	2.25	93.42	4.45	1.48	0.78	9.93	7.66	120	4.05	6.01								
	S	236	8.20	2.30**	2.03	2.04**	6.15	1.17**	88.71**	5.08*	1.37	0.58**	11.12	6.52**	119	3.98	3.83**	0.62	0.28	0.19	0.21	1.18	0.39	8.26	0.50
2	O	267	7.30	3.30	1.68	3.11	5.63	2.25	91.79	6.21	3.74	1.99	9.21	7.38	128	3.74	6.06								
	S	267	8.72	2.69**	1.64	2.39**	6.95	1.11**	88.27**	5.38**	3.32	1.14**	9.87	5.93**	135	3.73	3.37**	0.64	0.27	0.64	0.58	2.68	0.66	8.28	0.64
3	O	301	8.64	3.20	2.55	2.73	6.09	2.69	91.49	5.80	7.29	3.28	7.84	6.99	157	2.83	4.08								
	S	301	9.34	2.60**	1.63	2.54	7.66	1.18**	85.19**	7.69**	7.16	2.00**	8.77	6.21*	171	2.62	2.54**	0.58	0.28	1.80	1.26	5.36	1.01	8.97	0.73
4	O	264	9.88	2.96	3.25	2.81	6.63	2.76	91.31	6.31	11.37	4.75	6.96	6.13	130	3.67	5.41								
	S	264	12.20*	3.05	4.15	2.78	7.77	1.23**	87.27**	7.76**	11.49	2.91**	8.01	5.98	130	3.70	3.33**	0.60	0.28	3.01	2.11	8.48	1.10	9.64	0.78
5	O	332	12.50	2.95	5.81	2.71	6.70	2.51	91.61	5.09	16.18	5.92	6.56	5.80	124	3.89	4.83								
	S	332	11.82	4.56**	3.67*	4.29**	8.17	1.23**	87.07**	9.12**	16.31	3.44**	7.56	4.96**	122	3.38	3.16**	0.53	0.29	4.83	2.79	11.49	0.96	11.35	0.80
6	O	278	15.18	2.94	8.64	2.26	6.54	2.50	91.71	5.52	16.71	5.99	5.92	5.45	110	4.18	5.66								
	S	278	15.57	5.90**	7.37	5.70**	8.13	1.31**	88.39**	8.76**	18.22	3.89**	6.47	4.83*	110	4.35	3.71**	0.55	0.30	5.36	3.26	12.86	0.81	13.50	1.31
7	O	238	17.75	2.86	11.03	2.18	6.71	2.82	92.76	4.97	15.88	5.79	5.44	5.14	96	3.15	3.92								
	S	238	20.23*	5.45**	11.58	5.16**	8.62	1.25**	87.50**	9.08**	18.51**	3.55**	6.10	4.07**	90	2.67	2.69**	0.43	0.31	6.19	3.02	12.32	0.83	15.88	1.78
8	O	299	17.87	2.74	10.74	2.37	7.13	2.51	93.80	4.15	13.13	4.57	5.90	5.52	141	3.61	4.17								
	S	299	16.92	5.95**	8.59*	5.81**	8.13	1.33**	89.26**	9.10**	13.51	3.07**	6.99	4.77**	151	3.63	3.36*	0.52	0.32	3.97	2.44	9.54	1.04	15.69	1.60
9	O	231	15.06	2.58	8.25	2.72	6.81	2.78	93.63	4.71	8.91	3.47	6.76	6.80	105	3.14	4.07								
	S	231	18.46**	4.20**	10.27*	3.99**	8.04	1.28**	87.70**	8.42**	8.99	2.33**	6.93	5.27**	116	2.95	2.84**	0.51	0.31	2.58	1.64	6.41	1.00	13.33	1.26
10	O	329	11.77	2.66	5.85	3.45	5.92	2.80	94.87	4.22	4.42	2.33	6.38	5.81	186	4.97	6.49								
	S	329	11.84	5.06**	4.66	4.96**	7.19	1.20**	87.53**	8.72**	4.31	1.45**	6.47	4.79**	197	4.13	4.12**	0.63	0.29	0.93	0.82	3.39	0.78	11.19	1.01
11	O	304	8.79	2.67	3.41	3.46	5.38	2.58	94.23	4.34	2.06	1.18	6.80	6.40	170	5.05	6.08								
	S	304	10.54	2.91	4.37	2.89**	6.21	1.16**	86.86**	7.68**	1.70	0.68**	7.86	5.65*	178	5.63	5.14*	0.67	0.29	0.24	0.28	1.46	0.46	9.27	0.74
12	O	302	6.92	2.94	1.42	3.57	5.50	2.29	93.57	4.82	1.06	0.52	7.01	6.94	138	4.19	5.53								
	S	302	8.45	1.96**	2.82	1.94**	5.60	1.12**	87.42**	5.08	0.85	0.32**	7.60	5.89**	131	4.31	4.30**	0.61	0.28	0.08	0.09	0.77	0.24	8.13	0.64

Table 1. Aberdeen site.

Month	Days With Data	Max Temp (C)	SD Max Temp.	Min Temp (C)	SD Min Temp	Temp Amplitude	SD Amplitude	RH %	SD RH	RAD MJ/day	SD RAD	Wind-speed (m/s)	SD Wind	Wet Days	Mean ppt mm/day	SD ppt	Cloud	SD Cloud	Beam Rad MJ/day	Beam SD	Diff Rad MJ/day	Diff SD	SVP mbar	SD Svp
1	O 454	6.05	3.01	0.73	3.25	5.32	2.30	86.15	8.90	1.60	1.01	6.48	6.14	299.0	3.83	5.06								
	S 454	6.71	2.24^{**}	0.58	2.17^{**}	6.05	1.13^{**}	88.49^{*}	5.08^{**}	1.44	0.60^{**}	6.98	5.04^{**}	276.0	3.89	3.69^{**}	0.66	0.27	0.19	0.22	1.25	0.41	7.76	0.54
2	O 444	6.60	3.11	1.24	3.15	5.36	2.22	83.69	9.26	3.66	2.14	7.26	6.55	250.0	2.82	4.02								
	S 444	7.92	2.24^{**}	0.68	2.08^{**}	7.25	1.12^{**}	87.83^{**}	5.00^{**}	3.70	1.20^{**}	8.00	6.05^{*}	244.0	2.57	2.58^{**}	0.58	0.28	0.82	0.65	2.89	0.66	8.04	0.55
3	O 489	8.75	2.84	2.33	2.68	6.42	2.42	79.49	10.32	7.32	3.55	6.95	5.64	301.0	3.00	6.03								
	S 489	9.64	2.83	2.11	2.72	7.43	1.18^{**}	86.52^{**}	7.20^{**}	7.02	2.04^{**}	7.72	5.09^{*}	318.0	3.37	3.10^{**}	0.63	0.28	1.65	1.28	5.37	1.00	8.95	0.62
4	O 493	10.95	3.16	3.85	2.74	7.10	2.78	75.78	12.23	11.55	5.11	6.69	5.03	257.0	3.37	6.11								
	S 493	12.70	3.55^{**}	4.64	3.41^{**}	7.75	1.22^{**}	87.10^{**}	8.28^{**}	11.59	2.86^{**}	7.62	4.72	254.0	3.55	3.14^{**}	0.60	0.29	3.04	2.12	8.55	1.07	10.33	0.85
5	O 494	13.94	2.96	6.30	2.67	7.64	2.77	72.56	11.66	15.72	6.23	6.61	4.53	242.0	3.01	3.94								
	S 494	14.68	4.54^{**}	6.41	4.39^{**}	8.40	1.28^{**}	87.49^{**}	9.04^{**}	17.00	3.51^{**}	6.51	4.25	212.0	2.81	2.78^{**}	0.48	0.31	5.44	2.97	11.56	0.89	12.08	1.03
6	O 479	16.86	3.02	8.87	2.39	7.98	2.68	73.04	10.96	17.41	6.68	6.08	4.34	238.0	3.92	5.58								
	S 479	17.82	5.93^{**}	9.56	5.66^{**}	8.12	1.35^{**}	89.32^{**}	8.89^{**}	18.24	4.01^{**}	6.76	4.04	262.0	3.71	3.61^{**}	0.54	0.32	5.43	3.42	12.81	0.78	14.29	1.32
7	O 308	19.52	2.54	11.12	2.33	8.40	2.73	75.63	11.64	16.85	5.94	6.11	4.27	150.0	3.29	6.17								
	S 308	16.39^{**}	9.19^{**}	8.15^{**}	8.60^{**}	8.28	1.32^{**}	87.87^{**}	9.38^{**}	17.64	3.77^{**}	7.51	4.04	153.0	3.34	2.94^{**}	0.50	0.32	5.48	3.16	12.15	0.92	16.65	1.74
8	O 486	19.01	2.73	10.76	2.52	8.25	2.66	76.66	10.6	13.24	4.72	5.74	4.27	244.0	3.71	5.17								
	S 486	16.84^{*}	6.71^{**}	8.76^{*}	6.43^{**}	8.09	1.33^{**}	88.85^{**}	9.40^{**}	13.61	3.12^{**}	5.78	4.14	271.0	3.50	3.20^{**}	0.53	0.32	4.00	2.51	9.61	1.02	16.34	1.81
9	O 474	15.83	2.36	8.35	2.88	7.48	2.88	78.96	10.65	8.90	3.90	6.05	5.31	254.0	3.87	5.60								
	S 474	16.52	6.51^{**}	8.65	6.24^{**}	7.87	1.29^{**}	89.87^{**}	8.54^{**}	8.93	2.35^{**}	6.25	4.48^{**}	269.0	3.52	3.31^{**}	0.55	0.32	2.47	1.67	6.47	1.00	13.65	1.31
10	O 485	12.50	2.68	5.80	3.46	6.70	2.63	83.71	9.01	4.79	2.49	5.71	5.27	289.0	4.13	5.67								
	S 485	12.32	4.68^{**}	4.97	4.48^{**}	7.15	1.17^{**}	86.93^{**}	8.88	4.47	1.53^{**}	6.50	4.65^{**}	305.0	4.06	3.57^{**}	0.64	0.28	0.96	0.85	3.51	0.82	11.37	1.00
11	O 445	8.62	2.91	2.75	3.67	5.87	2.48	85.78	8.41	2.22	1.33	4.84	5.16	250.0	3.68	5.45								
	S 445	9.26	3.33^{**}	2.63	3.22^{**}	6.42	1.10^{**}	85.85^{**}	7.46^{**}	1.89	0.71^{**}	7.20^{*}	4.71^{*}	253.0	3.66	3.40^{**}	0.64	0.28	0.29	0.30	1.60	0.46	9.09	0.76
12	O 488	6.93	3.14	1.47	3.29	5.46	2.12	86.76	8.58	1.12	0.63	5.35	5.51	300.0	3.42	4.94								
	S 488	7.98	2.57^{**}	2.28	2.56^{**}	5.68	1.13^{**}	87.55	5.50^{**}	0.96	0.36^{**}	6.43	4.78^{**}	284.0	3.57	3.46^{**}	0.62	0.29	0.10	0.11	0.86	0.25	8.16	0.65

Table 2. Mylnefield site.

Month	Days With Data	Max Temp (C)	SD Max Temp.	Min Temp (C)	SD Min Temp	Temp Amplitude	SD Amplitude	RH %	SD RH	RAD MJ/day	SD RAD	Wind-speed (m/s)	SD Wind	Wet Days	Mean ppt mm/day	SD ppt	Cloud	SD Cloud	Beam Rad MJ/day	Beam SD	Diff Rad MJ/day	Diff SD	SVP mbar	SD Svp
1	O 396	4.81	3.23	-1.06	4.47	5.87	2.96	86.04	5.95	1.60	0.86	9.73	5.75	304	5.40	7.09								
	S 396	5.38	1.24**	-0.29	1.25**	5.49	1.01**	89.26**	3.71**	1.11	0.49**	9.48	5.22*	306	5.25	4.82**	0.77	0.22	0.10	0.15	1.01	0.37	7.11	0.72
2	O 394	5.56	3.12	-0.64	4.31	6.20	2.93	83.22	5.70	3.84	1.75	9.60	5.04	282	4.59	6.07								
	S 394	6.57	1.56**	0.06	1.58**	6.69	1.04**	88.03**	4.26**	3.10	1.07**	9.69	4.65	256	4.36	4.37**	0.71	0.24	0.52	0.51	2.58	0.65	7.30	0.62
3	O 398	7.41	3.08	0.30	3.41	7.11	2.88	81.08	6.16	7.32	2.91	8.99	4.48	294	4.34	5.70								
	S 398	8.03	2.73**	0.96	2.60**	7.03	1.12**	85.88**	6.19	6.25	1.90**	8.71	4.03*	292	4.84	4.44**	0.72	0.25	1.22	1.12	5.03	1.00	7.99	0.69
4	O 400	10.74	4.19	2.03	3.37	8.71	3.94	77.10**	8.64	11.54	4.77	7.42	3.83	259	2.94	4.11								
	S 400	12.44	4.00	4.37*	3.86**	7.73	1.26**	86.40	7.77*	11.37	2.82**	7.81	3.77	258	2.99	2.61**	0.61	0.30	2.91	2.10	8.45	1.07	9.71	1.02
5	O 450	13.96	4.30	4.23	3.36	9.73	3.92	74.46	10.18	15.68	6.04	6.62	3.43	260	3.21	4.21								
	S 450	13.66	6.01**	5.64	5.78*	8.12	1.32**	87.12**	8.72**	16.13	3.60**	6.51	3.03**	242	3.01	2.90**	0.54	0.31	4.71	2.96	11.41	0.95	11.29	1.13
6	O 416	16.47	4.21	7.10	3.06	9.37	3.72	75.93	9.12	16.37	6.30	6.14	2.96	254	3.53	4.73								
	S 416	17.63	5.31**	9.54*	5.13**	7.93	1.32**	88.51**	9.76	17.60	3.91**	6.47	2.61**	269	3.53	3.44**	0.59	0.30	4.85	3.25	12.75	0.85	13.33	1.44
7	O 265	19.4	3.78	9.51	2.73	9.89	3.86	75.79	8.85	16.02	5.96	6.31	3.01	138	3.45	4.95								
	S 265	19.95	6.77**	11.67*	6.53**	8.22	1.37**	89.14**	8.42	17.34	3.94**	6.37	3.08	145	3.45	3.11**	0.51	0.33	5.26	3.23	12.08	1.00	15.87	1.76
8	O 460	18.11	3.85	8.68	3.11	9.43	3.79	79.16	7.65	12.48	4.59	6.04	3.07	285	3.06	3.87								
	S 460	17.51	6.37**	9.30	6.11**	8.12	1.31**	88.52**	9.05**	13.45	3.09**	6.22	3.23	299	2.79	2.71**	0.53	0.31	3.93	2.44	9.53	1.04	14.94	1.63
9	O 491	14.86	3.09	6.30	3.61	8.56	3.60	82.14	6.94	8.67	3.50	6.69	4.01	328	4.17	6.07								
	S 491	14.43	5.94**	6.97	5.74**	7.55	1.24**	88.63**	8.74**	8.25	2.26**	6.73	3.36**	348	3.61	3.53**	0.62	0.29	2.00	1.52	6.25	1.02	12.45	1.13
10	O 481	11.28	3.22	3.65	3.84	7.64	3.05	83.90	6.17	4.52	1.90	7.59	4.39	338	4.45	5.57								
	S 481	11.18	3.34	4.14	3.29**	6.89	1.15**	86.18*	7.74**	4.04	1.41**	7.79	4.03*	360	4.51	4.09**	0.69	0.27	0.76	0.74	3.28	0.82	10.17	0.90
11	O 471	7.52	3.39	1.04	4.39	6.48	2.96	85.88	6.87	2.00	1.06	7.60	4.81	325	3.99	5.38								
	S 471	8.17	2.27**	1.87	2.26**	6.21	1.15**	86.09	6.63	1.67	0.69**	8.26	4.73	348	3.72	3.55**	0.67	0.28	0.24	0.28	1.44	0.46	8.43	0.82
12	O 452	5.42	3.80	-0.83	4.90	6.25	3.04	87.04	7.35	1.11	0.55	8.01	5.02	322	4.10	5.67								
	S 452	5.42	1.30**	0.20	1.28**	5.21	1.10**	88.56	4.26**	0.73	0.31**	8.50	4.87	319	4.07	4.04**	0.70	0.26	0.06	0.08	0.67	0.23	7.16	0.78

<u>Table 3.</u> Aviemore site**.**

Month	Days With Data	Max Temp (C)	SD Max Temp.	Min Temp (C)	SD Min Temp	Temp Amplitude	SD Amplitude	RH %	SD RH	RAD MJ/day	SD RAD	Wind-speed (m/s)	SD Wind	Wet Days	Mean ppt mm/day	SD ppt	Cloud	SD Cloud	Beam Rad MJ/day	Beam SD	Diff Rad MJ/day	Diff SD	SVP mbar	SD Svp
1	O 486	6.95	2.34	2.15	2.80	4.80	1.87	84.26	6.74	1.27	0.83	14.69	7.09	389	5.96	6.67								
	S 486	8.38	2.12*	2.99	1.93	5.37	1.10**	87.72**	4.94**	0.95	0.46**	13.39	7.05	393	5.70	5.36**	0.76	0.24	0.08	0.13	0.87	0.35	8.45	0.57
2	O 410	7.06	2.24	1.88	3.07	5.18	2.07	83.37	7.24	3.27	1.71	13.76	6.67	312	5.11	5.56								
	S 410	8.26	2.14	1.86	1.99	6.57	1.08**	87.72**	5.67**	2.82	1.07**	13.99	6.01	299	4.68	4.18**	0.72	0.24	0.44	0.49	2.38	0.67	8.28	0.55
3	O 463	7.92	2.09	2.80	2.76	5.12	1.84	84.33	7.03	6.69	3.25	13.60	5.53	385	4.82	5.91								
	S 463	9.18	3.08**	2.29	2.89	6.85	1.07**	85.79	6.93	5.82	1.79**	14.22	5.45	402	5.16	4.75**	0.76	0.23	1.01	1.00	4.81	1.00	8.78	0.58
4	O 498	9.45	2.24	3.92	2.58	5.53	2.09	83.00	7.02	11.55	4.79	11.16	4.63	351	3.74	4.75								
	S 498	11.44*	2.91**	3.87	2.78	7.45	1.19**	86.69**	7.39	10.49	2.67**	12.08	4.59	345	3.80	3.43**	0.67	0.26	2.36	1.86	8.13	1.11	9.77	0.74
5	O 495	12.01	2.69	6.22	2.54	5.79	2.28	81.45	7.11	16.90	6.25	10.58	4.33	272	3.34	3.99								
	S 495	13.5	5.05**	5.40	4.84	8.13*	1.32**	86.98**	8.68**	15.97	3.58**	9.83	4.39	252	3.06	2.96**	0.54	0.31	4.59	2.89	11.38	1.00	11.33	0.95
6	O 487	13.85	2.36	8.39	2.25	5.46	2.06	83.24	6.66	16.27	6.59	9.87	3.88	306	3.29	3.78								
	S 487	13.75	5.59**	5.75**	5.36**	7.93*	1.33**	88.64**	9.20**	17.49	3.92**	9.60	3.47**	321	3.26	3.04**	0.58	0.30	4.73	3.22	12.76	0.88	12.86	1.18
7	O 310	16.42	2.40	10.80	1.94	5.62	2.08	84.98	6.21	15.32	5.88	9.13	3.64	193	3.89	4.77								
	S 310	16.68	6.26**	8.75*	5.95*	7.92*	1.33**	88.59**	8.84**	16.37	3.81**	9.74	3.54	196	3.63	3.19**	0.59	0.30	4.42	3.02	11.95	1.04	14.98	1.51
8	O 480	16.11	2.15	10.68	2.09	5.43	1.94	85.42	5.66	11.74	4.60	9.16	3.73	328	3.95	5.37								
	S 480	16.58	6.88**	8.92	6.58	7.74*	1.30**	89.63**	8.43**	12.43	3.06**	9.05	3.81	343	3.68	3.44**	0.61	0.30	3.16	2.31	9.27	1.09	14.81	1.51
9	O 508	14.01	1.87	8.67	2.60	5.34	2.04	85.58	6.10	8.36	3.53	10.53	5.19	380	4.92	6.73								
	S 508	14.78	5.54**	7.53	5.37	7.27	1.23**	88.87**	8.56**	7.52	2.15**	10.45	4.98	385	4.92	4.89**	0.68	0.27	1.60	1.37	5.92	1.05	12.98	1.11
10	O 513	11.59	2.07	6.38	2.75	5.21	1.81	85.44	5.59	4.24	2.10	11.65	5.70	420	5.43	6.58								
	S 513	13.20	3.82**	6.48	3.77	6.68	1.07**	86.95	8.64**	3.62	1.25**	11.37	5.47	410	5.40	5.26**	0.74	0.25	0.59	0.60	3.04	0.79	11.19	0.90
11	O 506	9.18	2.24	4.10	3.00	5.08	1.92	84.80	6.30	1.73	0.98	11.89	5.89	413	5.30	5.90								
	S 506	9.22	3.72**	3.41	3.69	5.87	1.10**	85.78	7.36**	1.37	0.61**	12.14	5.70	404	5.24	5.09**	0.73	0.25	0.16	0.22	1.21	0.43	9.79	0.77
12	O 511	7.81	2.47	2.67	3.11	5.14	1.99	85.18	6.19	0.84	0.45	13.02	6.07	416	5.58	5.77								
	S 511	7.81	2.57	3.10	2.53	4.67	1.09**	87.20*	6.17	0.51	0.25**	12.78	6.22	412	5.35	5.00**	0.75	0.24	0.03	0.05	0.48	0.20	8.78	0.61

Table 4. Stornoway site**.**

Month	Days With Data	Max Temp (C)	SD Max Temp.	Min Temp (C)	SD Min Temp	Temp Amplitude	SD Amplitude	RH %	SD RH	RAD MJ/day	SD RAD	Wind-speed (m/s)	SD Wind	Wet Days	Mean ppt mm/day	SD ppt	Cloud	SD Cloud	Beam Rad MJ/day	Beam SD	Diff Rad MJ/day	Diff SD	SVP mbar	SD Svp
1	O 336	7.66	3.32	1.98	4.40	5.68	2.87	85.95	9.42	2.26	1.33	6.22	5.94	226	4.28	4.83								
	S 336	8.88	2.24**	2.51	2.20**	6.46	1.08**	87.54	5.86**	2.36	0.81**	6.44	4.77**	188	4.02	3.58**	0.64	0.28	0.40	0.40	1.95	0.46	8.55	0.80
2	O 321	8.45	3.32	2.72	4.20	5.73	2.59	85.47	9.74	4.44	2.49	7.74	6.74	206	4.23	4.67								
	S 321	9.83	2.91*	2.83	2.86**	7.07	1.07**	88.62**	6.84**	4.55	1.39**	6.89	5.34**	168	4.32	4.35**	0.64	0.27	1.01	0.82	3.54	0.70	9.07	0.85
3	O 415	9.86	2.40	4.07	3.29	5.79	2.76	81.95	10.35	7.63	4.21	7.68	5.91	273	4.22	5.22								
	S 415	11.78	3.34**	4.41	3.23	7.32	1.10**	87.10**	7.66**	8.02	2.16**	8.28	5.33*	287	3.93	3.79**	0.67	0.26	1.93	1.48	6.09	0.96	9.85	0.77
4	O 399	12.04	3.25	4.52	3.56	7.52	3.48	77.65	11.98	12.84	6.01	6.84	4.73	228	4.62	7.32								
	S 399	11.70	4.31**	4.07	3.99**	7.57	1.18**	87.37**	8.18**	12.20	2.94**	7.35	4.56	227	4.71	4.38**	0.64	0.29	3.24	2.31	8.96	0.99	10.85	1.08
5	O 405	15.32	3.38	7.26	3.34	8.06	3.54	74.45	12.81	17.39	6.70	6.59	3.92	178	3.63	4.99								
	S 405	15.04	6.38**	6.80	6.03**	8.27	1.23**	87.99**	8.99**	17.49	3.53**	6.20	3.56*	168	3.48	3.41**	0.51	0.30	5.81	3.13	11.69	0.78	13.09	1.24
6	O 406	16.95	3.08	9.73	2.99	7.21	3.33	78.45	11.22	17.44	7.53	6.71	3.95	213	5.51	7.44								
	S 406	17.01	6.78**	9.15	6.53**	7.84	1.28**	88.25**	9.10**	17.94	3.99**	7.10	3.57*	229	5.11	4.88**	0.61	0.30	5.28	3.50	12.66	0.71	14.83	1.61
7	O 249	19.78	3.31	12.43	2.42	7.35	3.37	77.55	11.46	17.89	7.03	5.67	3.72	108	4.61	5.20								
	S 249	20.29	6.63**	12.07	6.34**	8.27	1.26**	88.59**	9.45**	18.36	3.74**	5.67	3.23*	94	4.52	3.84**	0.51	0.30	6.13	3.31	12.22	0.79	17.55	2.09
8	O 370	19.28	3.43	12.16	2.89	7.12	3.26	79.74	10.7	14.38	6.06	5.94	3.91	213	5.27	5.68								
	S 370	18.96	7.95**	11.37	7.79**	7.62	1.23**	89.55**	9.09**	13.50	3.21**	6.16	3.70	249	4.97	4.45**	0.64	0.29	3.67	2.61	9.83	0.96	17.19	2.08
9	O 360	16.91	2.42	9.56	3.40	7.34	3.30	81.04	9.13	10.26	4.52	5.38	4.53	193	4.86	5.84								
	S 360	16.41	6.24**	8.73	5.95**	7.74	1.26**	88.57**	9.55	9.90	2.55**	5.61	4.03*	206	4.33	4.07**	0.58	0.31	2.84	1.94	7.06	0.95	14.80	1.51
10	O 386	14.36	2.64	7.88	4.07	6.48	3.38	83.34	9.11	5.69	2.91	5.55	5.01	247	6.21	7.23								
	S 386	16.02	4.82**	8.94	4.63**	6.94	1.16**	88.33**	8.80	5.23	1.67**	5.78	4.26**	270	6.25	5.68**	0.70	0.28	1.11	1.02	4.12	0.83	13.01	1.30
11	O 385	10.70	2.69	4.39	4.32	6.31	2.99	85.78	9.33	2.95	1.66	5.26	4.94	258	5.62	6.96								
	S 385	12.11	2.97*	5.65	3.00**	6.37	1.06**	86.26	8.49*	2.64	0.87**	6.21	4.58	284	5.19	4.95**	0.70	0.27	0.42	0.45	2.21	0.50	10.41	1.04
12	O 427	8.94	2.87	3.13	4.41	5.81	2.93	86.63	8.90	1.64	0.98	6.54	6.07	295	5.59	6.98								
	S 427	8.80	2.82	2.85	2.91**	5.90	1.03**	88.57	6.82**	1.62	0.52**	8.06	5.57*	281	5.50	5.33**	0.71	0.25	0.20	0.23	1.42	0.31	9.30	0.81

Table 5. Gogerddan site.

Month	Days With Data	Max Temp (C)	SD Max Temp.	Min Temp (C)	SD Min Temp	Temp Amplitude	SD Amplitude	RH %	SD RH	RAD MJ/day	SD RAD	Wind-speed (m/s)	SD Wind	Wet Days	Mean ppt mm/ day	SD ppt	Cloud	SD Cloud	Beam Rad MJ/day	Beam SD	Diff Rad MJ/ day	Diff SD	SVP mbar	SD Svp
1	O 470	7.51	3.67	1.10	4.15	6.41	2.89	81.16	23.68	2.42	1.43	5.75	3.44	279	3.70	4.62								
	S 470	9.10	1.92^{**}	2.51	1.92^{**}	6.56	1.08^{**}	87.26^{**}	5.22^{**}	2.63	0.85^{**}	6.06	3.32	275	3.82	3.56^{**}	0.63	0.28	0.48	0.44	2.15	0.46	8.14	0.71
2	O 440	7.56	4.03	0.35	4.23	7.21	3.13	82.05	16.87	4.72	2.54	5.70	3.48	214	3.18	3.67								
	S 440	8.28	2.22^{**}	1.01	2.18^{**}	7.35	1.08^{**}	88.18^{**}	5.09^{**}	5.12	1.40^{**}	5.81	3.09^{**}	214	2.86	2.95^{**}	0.58	0.28	1.28	0.91	3.83	0.66	8.11	0.84
3	O 482	10.69	3.24	2.29	3.69	8.40	3.46	78.69	11.63	8.15	3.81	5.73	3.05	263	2.63	3.37								
	S 482	10.69	3.29	2.87	3.01^{**}	7.74	1.16^{**}	86.99^{**}	7.60^{**}	8.93	2.34^{**}	5.83	3.06	290	2.63	2.54^{**}	0.57	0.29	2.59	1.71	6.35	0.93	9.62	0.81
4	O 464	13.13	3.62	3.41	3.69	9.72	3.86	72.99	12.93	13.09	5.28	5.39	2.72	233	3.28	3.82								
	S 464	13.49	4.15^{**}	5.36	3.93	7.83	1.17^{**}	87.06^{**}	8.39^{**}	13.14	3.01^{**}	5.57	2.77	233	3.66	3.27^{**}	0.59	0.29	3.89	2.45	9.25	0.93	10.98	1.11
5	O 475	16.95	4.08	6.15	3.43	10.80	4.20	72.33	10.83	16.77	6.49	4.97	2.55	211	3.73	6.26								
	S 475	15.93	6.92^{**}	7.84	6.72^{**}	8.27^{*}	1.23^{**}	88.44^{**}	9.12^{**}	17.72	3.50^{**}	4.85	2.48	197	3.57	3.44^{**}	0.51	0.31	5.99	3.21	11.72	0.72	13.29	1.26
6	O 471	19.68	3.68	9.20	3.16	10.48	3.63	73.57	9.87	17.70	6.54	4.63	2.23	200	3.91	4.12								
	S 471	19.57	7.06^{**}	11.22^{*}	6.80^{**}	8.31^{*}	1.28^{**}	88.36^{**}	9.10^{*}	19.56	3.91^{**}	4.72	2.07	212	3.70	3.55^{*}	0.50	0.32	6.71	3.65	12.84	0.53	15.82	1.71
7	O 304	23.08	3.72	11.59	2.76	11.48	3.97	73.03	9.88	17.82	5.98	3.64	1.73	114	3.44	5.06								
	S 304	19.64^{**}	8.75^{**}	11.1	8.48^{**}	8.61^{**}	1.20^{**}	89.47^{**}	8.56^{**}	19.53	3.54^{**}	3.78	1.52^{*}	100	3.32	2.96^{**}	0.43	0.31	7.21	3.31	12.32	0.63	19.05	2.29
8	O 483	22.27	3.64	11.01	3.19	11.26	3.73	73.60	9.14	15.36	4.94	4.25	2.28	179	4.14	5.71								
	S 483	22.23	7.25^{**}	13.77^{**}	6.92^{**}	8.34^{**}	1.22^{**}	88.94^{**}	8.82	15.54	3.19^{**}	4.25	2.15	168	4.12	3.59^{**}	0.47	0.32	5.37	2.75	10.17	0.90	18.29	2.16
9	O 436	18.54	2.96	8.53	3.67	10.02	3.94	79.62	8.04	10.23	4.18	4.08	2.41	197	3.98	5.82								
	S 436	17.19	8.09^{**}	9.30	7.84^{**}	8.00^{*}	1.23^{**}	88.79^{**}	8.91^{*}	10.68	2.62^{**}	4.17	2.24	219	3.68	3.66^{**}	0.52	0.32	3.37	2.04	7.31	0.93	14.98	1.55
10	O 436	14.95	3.04	6.43	4.42	8.52	3.55	82.84	12.44	6.32	2.91	4.49	2.94	222	4.39	6.79								
	S 436	14.49	5.9^{**}	6.99	5.73^{**}	7.39	1.15^{**}	88.68^{**}	8.92^{**}	6.07	1.74^{**}	4.88	2.75	241	3.95	3.56^{**}	0.60	0.30	1.56	1.17	4.51	0.78	12.51	1.29
11	O 407	10.42	3.34	2.77	4.84	7.65	3.33	85.82	15.53	3.25	1.78	4.21	2.97	214	3.69	5.21								
	S 407	11.34	3.73^{*}	4.35	3.74^{**}	6.78	1.07^{**}	86.66	8.14^{**}	3.14	0.95^{**}	4.62	2.74^{*}	228	3.79	3.48^{**}	0.62	0.29	0.62	0.53	2.52	0.50	9.81	1.11
12	O 449	8.33	3.48	1.72	4.64	6.61	3.21	83.22	23.13	1.93	1.15	4.83	3.34	250	3.75	4.81								
	S 449	8.46	2.65^{**}	2.05	2.66^{**}	6.47	1.06^{**}	87.81^{**}	5.98^{**}	2.10	0.59^{**}	5.05	2.92^{**}	221	3.75	3.66^{**}	0.59	0.29	0.36	0.31	1.74	0.30	8.77	0.97

Table 6 Bracknell site.

Month	Days With Data	Max Temp (C)	SD Max Temp.	Min Temp (C)	SD Min Temp	Temp Amplitude	SD Amplitude	RH %	SD RH	RAD MJ/day	SD RAD	Wind-speed (m/s)	SD Wind	Wet Days	Mean ppt mm/day	SD ppt	Cloud	SD Cloud	Beam Rad MJ/day	Beam SD	Diff Rad MJ/day	Diff SD	SVP mbar	SD Svp
1	O 379	6.93	3.31	2.01	3.19	4.93	2.01	85.31	6.25	2.09	1.15	10.79	4.93	251	4.08	4.44								
	S 379	8.19	2.58**	1.89	2.52**	6.34	1.09**	87.26	5.67*	2.07	0.73**	10.89	4.65	221	4.24	4.05**	0.65	0.28	0.33	0.33	1.74	0.44	8.27	0.66
2	O 388	6.55	3.29	1.35	3.32	5.20	1.89	83.84	6.74	4.40	2.38	9.80	4.72	205	3.02	3.59								
	S 388	8.16	2.02**	0.84	1.91**	7.27*	1.09**	87.83**	5.44**	4.48	1.32**	9.72	4.53	200	2.83	2.85**	0.59	0.27	1.05	0.79	3.43	0.67	8.05	0.63
3	O 400	8.67	2.65	3.15	2.67	5.52	1.97	82.87	6.93	7.74	3.64	10.00	4.39	250	3.27	3.45								
	S 400	10.27	3.61**	2.76	3.42**	7.41	1.13**	86.13**	7.58*	7.81	2.14**	9.92	4.59	272	3.36	3.23	0.64	0.27	1.92	1.45	5.89	0.97	9.15	0.62
4	O 358	11.51	3.61	4.79	2.78	6.72	2.70	79.36	8.77	13.08	5.16	8.43	3.38	178	3.71	3.92								
	S 358	11.68	4.09**	3.87	4.06**	7.81	1.21**	87.01**	8.47	12.51	2.97**	8.49	3.31	174	3.95	3.74	0.59	0.30	3.55	2.34	8.96	0.99	10.84	1.02
5	O 383	15.16	3.64	7.68	2.51	7.48	2.76	77.07	8.87	17.21	5.98	7.65	3.02	172	3.71	4.88								
	S 383	16.51	5.02**	8.27	4.84**	8.38	1.24**	88.88**	8.43	17.60	3.52**	7.75	3.08	151	3.31	3.34**	0.48	0.31	5.91	3.10	11.69	0.79	13.09	1.26
6	O 362	17.09	3.44	10.30	2.20	6.79	2.64	80.23	8.18	17.46	6.70	7.22	2.86	170	4.17	6.18								
	S 362	17.36	7.35**	9.13	6.92**	8.17	1.30**	88.34**	9.22*	18.79	3.95**	7.65	2.63	172	3.82	3.47**	0.53	0.32	5.97	3.54	12.83	0.64	15.16	1.56
7	O 124	20.36	3.64	13.07	2.23	7.30	2.51	78.38	8.61	17.83	5.84	7.55	2.73	55	4.25	6.02								
	S 124	22.23	8.06**	13.86	7.92**	8.30	1.27**	88.43**	9.58	18.28	3.78**	7.20	2.46	45	4.22	3.25**	0.50	0.32	6.04	3.30	12.24	0.79	18.15	2.11
8	O 403	19.16	3.50	12.37	2.29	6.79	2.54	79.51	8.06	14.08	4.99	7.47	3.09	193	5.19	7.34								
	S 403	16.57*	8.73**	8.78**	8.43**	7.94	1.30**	88.91**	9.68**	13.97	3.20**	6.99	2.95	203	5.01	4.95**	0.57	0.32	4.15	2.65	9.82	0.98	17.48	2.15
9	O 383	16.31	2.64	10.14	2.34	6.17	2.16	81.86	6.63	9.59	3.76	7.93	3.48	203	4.74	5.87								
	S 383	17.01	6.38**	9.31	6.08**	7.80	1.26**	87.19**	9.42**	9.66	2.47**	7.67	3.16*	221	3.93	3.67**	0.57	0.31	2.76	1.85	6.90	0.96	14.61	1.50
10	O 383	13.21	2.75	7.54	3.14	5.68	2.06	84.17	6.34	5.38	2.61	8.31	3.92	229	5.53	6.68								
	S 383	15.07	4.53**	7.89	4.40	7.08	1.16**	87.23**	8.62**	5.11	1.66**	8.40	3.85	233	5.42	4.94**	0.66	0.28	1.13	1.00	3.98	0.83	12.24	1.15
11	O 361	9.72	2.80	4.61	3.24	5.11	1.94	87.20	5.67	2.60	1.43	8.20	3.74	206	4.61	5.27								
	S 361	10.5	3.36**	3.95	3.30	6.47	1.08**	86.82**	8.11**	2.47	0.83**	9.59	3.55	206	4.88	4.48*	0.67	0.28	0.41	0.41	2.07	0.49	9.96	0.88
12	O 401	7.68	3.24	3.03	3.47	4.65	1.90	87.00	5.9	1.50	0.84	9.30	4.22	240	4.97	5.83								
	S 401	8.59	2.41**	2.63	2.37**	5.97	1.09**	87.86	6.00	1.48	0.49**	9.85	4.09	233	4.94	4.82**	0.65	0.28	0.19	0.21	1.29	0.30	8.82	0.78

Table 7 Aughton site**.**

Month	Days With Data	Max Temp (C)	SD Max Temp.	Min Temp (C)	SD Min Temp	Temp Amplitude	SD Amplitude	RH %	SD RH	RAD MJ/day	SD RAD	Wind-speed (m/s)	SD Wind	Wet Days	Mean ppt mm/day	SD ppt	Cloud	SD Cloud	Beam Rad MJ/day	Beam SD	Diff Rad MJ/day	Diff SD	SVP mbar	SD Svp
1	O 464	5.61	2.24	1.48	2.71	4.14	1.69	85.04	6.88	0.90	0.57	18.89	8.58	407	5.25	5.07								
	S 464	6.72	1.91**	1.74	1.79**	4.99	1.21**	87.57*	4.95**	0.65	0.39**	17.13	8.04	406	4.79	4.50**	0.76	0.23	0.05	0.09	0.60	0.32	7.91	0.50
2	O 421	5.50	2.2	1.33	2.58	4.17	1.64	84.49	6.89	2.62	1.57	17.27	7.66	348	4.76	5.02								
	S 421	7.33	1.94**	0.92	1.86**	6.42*	1.01**	87.81**	4.82**	2.33	0.91**	16.90	7.15	325	4.43	4.02**	0.75	0.21	0.32	0.36	2.01	0.62	7.77	0.44
3	O 495	6.20	2.13	1.80	2.61	4.39	1.63	84.95	8.11	5.84	3.10	17.40	6.99	400	4.82	4.79								
	S 495	7.93	2.09	1.03	1.90**	6.83*	1.07**	87.02*	6.36**	5.27	1.66**	17.17	6.97	411	5.21	4.80	0.76	0.23	0.86	0.87	4.41	0.99	8.07	0.51
4	O 477	7.74	1.91	3.01	2.42	4.74	1.72	83.61	9.27	11.08	4.70	14.37	5.89	324	3.77	4.66								
	S 477	9.13	2.74**	1.74	2.67*	7.41**	1.21**	86.19*	7.14**	9.95	2.57**	15.60	5.61	321	3.84	3.42**	0.68	0.27	2.11	1.71	7.84	1.16	8.89	0.57
5	O 488	10.20	2.13	5.20	2.14	5.00	1.74	84.17	8.33	15.54	5.73	12.97	5.23	272	2.85	3.70								
	S 488	11.57	4.05**	3.50	3.86**	8.22**	1.34**	87.49**	8.57	15.78	3.52**	11.63	5.14	251	2.54	2.47**	0.52	0.31	4.47	2.77	11.32	1.07	10.35	0.72
6	O 510	12.25	2.01	7.42	1.89	4.83	1.67	86.28	7.73	16.19	6.64	12.10	4.92	303	3.17	4.16								
	S 510	13.16	4.84**	5.14*	4.61**	7.92**	1.33**	87.80	8.62**	17.27	3.90**	12.23	4.54*	327	3.19	2.97**	0.59	0.30	4.46	3.08	12.81	0.98	11.81	0.96
7	O 309	14.23	1.86	9.77	1.58	4.46	1.61	89.94	6.03	14.66	5.61	11.04	4.52	187	3.28	4.68								
	S 309	14.34	5.47**	6.30**	5.20**	7.96**	1.33**	87.66*	9.20**	16.22	3.74**	12.01	4.48	197	3.09	2.74**	0.58	0.30	4.24	2.89	11.98	1.10	13.52	1.20
8	O 489	14.32	1.67	9.92	1.72	4.41	1.52	89.55	5.99	11.86	4.69	11.41	4.43	340	3.62	5.30								
	S 489	15.52	6.66**	7.88*	6.40**	7.76**	1.30**	88.54	8.71**	12.02	3.00**	11.27	4.61	362	3.11	2.84**	0.61	0.29	2.94	2.18	9.08	1.14	13.64	1.27
9	O 414	12.28	1.78	7.88	2.36	4.40	1.71	86.95	7.17	7.74	3.59	14.27	5.92	325	4.54	4.83								
	S 414	13.51	4.85**	6.23	4.61**	7.21**	1.22**	87.78	8.57**	6.92	2.03**	13.86	5.39*	337	4.41	4.33**	0.69	0.27	1.37	1.23	5.56	1.06	11.98	0.93
10	O 465	10.08	2.01	5.97	2.58	4.12	1.68	86.75	6.98	3.56	2.00	15.62	6.50	396	5.35	6.32								
	S 465	11.33	3.74**	4.64	3.73**	6.57*	1.07**	86.41	8.48**	3.13	1.18**	15.88	6.33	393	5.43	5.15**	0.75	0.24	0.46	0.52	2.67	0.78	10.47	0.80
11	O 446	7.79	2.00	3.93	2.77	3.85	1.64	85.72	6.65	1.22	0.81	16.29	7.19	376	5.01	5.93								
	S 446	8.55	3.09**	3.05	3.08*	5.63	1.16**	85.69	7.82**	1.02	0.53**	17.30	7.45	367	4.96	4.66*	0.74	0.25	0.10	0.17	0.92	0.40	9.25	0.66
12	O 495	6.47	2.41	2.21	2.86	4.25	1.67	84.90	7.10	0.53	0.29	16.66	7.22	395	5.11	4.94								
	S 495	6.39	2.51	2.35	2.57*	3.97	1.29**	87.21*	5.56**	0.27	0.19**	16.59	7.37	404	4.61	4.37**	0.74	0.25	0.01	0.03	0.26	0.17	8.20	0.54

Table 8. Lerwick site.

Month	Days With Data	Max Temp (C)	SD Max Temp.	Min Temp (C)	SD Min Temp	Temp Amplitude	SD Amplitude	RH %	SD RH	RAD MJ/day	SD RAD	Wind-speed (m/s)	SD Wind	Wet Days	Mean ppt mm/ day	SD ppt	Cloud	SD Cloud	Beam Rad MJ/day	Beam SD	Diff Rad MJ/ day	Diff SD	SVP mbar	SD Svp
1	O 341	7.00	2.66	1.99	2.98	5.01	2.06	85.11	8.78	1.49	0.87	12.59	8.70	284	8.90	7.79								
	S 341	7.40	2.25^{**}	2.02	2.16^{**}	5.42	1.03^{**}	87.47^{*}	5.69^{**}	1.18	0.52^{**}	10.88	7.48^{**}	267	8.86	8.55	0.79	0.23	0.10	0.16	1.08	0.39	8.47	0.60
2	O 313	7.02	2.24	1.83	2.84	5.19	2.05	84.44	9.99	3.69	1.98	10.62	7.87	226	6.87	7.91								
	S 313	7.87	2.30	1.40	2.36^{**}	6.44	0.94^{**}	86.97^{*}	5.94^{**}	3.09	1.00^{**}	10.58	6.69^{**}	210	6.90	6.43^{**}	0.77	0.20	0.44	0.44	2.65	0.65	8.32	0.49
3	O 383	8.36	2.04	2.98	2.74	5.38	2.08	84.24	9.32	6.50	3.54	11.31	7.56	318	7.49	7.69								
	S 383	9.52	2.99^{**}	2.78	2.80	6.56	0.87^{**}	85.70	7.56^{**}	5.81	1.58^{**}	11.88	7.05	328	8.00	7.52	0.82	0.18	0.85	0.81	4.96	0.95	9.00	0.60
4	O 349	10.77	2.83	4.09	2.79	6.68	3.03	79.40	10.85	12.11	5.25	8.77	6.47	215	5.36	6.70								
	S 349	12.00	3.63^{**}	4.64	3.58^{**}	7.32	1.16^{**}	86.46^{**}	7.85^{**}	10.68	2.73^{**}	11.00	6.69	214	5.60	5.12^{**}	0.70	0.26	2.38	1.94	8.30	1.08	10.25	0.81
5	O 351	14.36	3.31	6.72	2.89	7.64	3.18	76.64	12.44	16.58	6.56	8.82	5.81	191	3.99	5.07								
	S 351	14.85	5.59^{**}	6.98	5.45^{**}	8.03	1.30^{**}	87.90^{**}	8.83^{**}	16.01	3.56^{**}	8.24	5.26^{*}	176	3.71	3.41^{**}	0.56	0.30	4.61	2.95	11.40	0.95	12.50	1.12
6	O 347	16.33	3.24	9.04	2.31	7.30	3.15	79.87	10.99	17.60	7.65	7.82	5.29	195	3.76	4.76								
	S 347	19.18^{**}	5.74^{**}	11.01^{*}	5.53^{**}	8.05	1.32^{**}	88.69^{**}	9.47^{**}	18.05	3.93^{**}	8.51	4.68^{*}	201	3.64	3.48^{**}	0.56	0.31	5.25	3.32	12.80	0.80	14.20	1.49
7	O 176	18.17	3.34	11.31	2.44	6.86	2.77	81.40	9.82	16.07	6.30	7.70	4.82	114	4.34	5.61								
	S 176	18.82	5.52^{**}	11.05	5.51^{**}	7.87	1.30^{**}	88.30^{**}	9.13	16.49	3.77^{**}	7.84	4.42	104	4.30	4.13^{**}	0.60	0.30	4.53	3.05	11.96	0.99	16.24	1.80
8	O 355	17.47	2.76	10.89	2.41	6.58	2.87	85.05	9.18	12.75	5.40	7.26	5.56	240	6.70	8.42								
	S 355	15.88	7.24^{**}	8.64^{*}	7.09^{**}	7.35	1.21^{**}	88.87^{**}	9.15	11.91	2.96^{**}	8.16	5.22	263	5.97	5.88^{**}	0.70	0.27	2.70	2.18	9.21	1.10	15.60	1.70
9	O 345	15.12	2.03	8.88	2.78	6.24	2.67	84.29	8.23	8.34	4.00	9.14	7.12	241	7.25	8.64								
	S 345	14.71	7.07^{**}	7.52	6.98^{**}	7.11	1.17^{**}	89.00^{**}	7.92	7.71	2.16^{**}	9.30	5.98^{**}	250	6.74	6.64^{**}	0.72	0.26	1.58	1.38	6.12	1.06	13.55	1.30
10	O 332	12.70	2.26	7.34	2.94	5.35	2.13	84.49	7.65	4.35	2.28	9.90	7.29	254	9.90	13.67								
	S 332	13.15	4.98^{**}	6.74	4.98^{**}	6.46	1.02^{**}	88.23^{**}	9.02^{**}	3.83	1.34^{**}	10.79	6.97	252	9.47	9.54^{**}	0.79	0.23	0.57	0.64	3.25	0.83	11.89	0.99
11	O 340	9.43	2.32	4.07	3.33	5.36	2.26	82.92	9.76	2.06	1.16	9.06	7.12	224	7.66	8.07								
	S 340	10.66	3.93^{**}	4.81	3.93^{**}	5.88	1.10^{**}	86.92^{**}	8.01^{**}	1.63	0.68^{**}	11.13	6.58	244	7.71	7.06	0.75	0.26	0.19	0.26	1.44	0.47	9.77	0.77
12	O 310	8.20	2.48	3.30	3.22	4.90	2.04	86.49	7.55	1.04	0.64	10.42	7.79	240	9.85	9.60								
	S 310	7.62	2.74^{*}	2.75	2.71^{**}	4.70	0.89^{**}	87.43	6.74^{*}	0.66	0.27^{**}	10.70	7.18	252	10.15	8.99	0.83	0.19	0.03	0.06	0.63	0.22	9.05	0.67

Table 9. Dunstaffnage site.

Month	Days With Data	Max Temp (C)	SD Max Temp.	Min Temp (C)	SD Min Temp	Temp Amplitude	SD Amplitude	RH %	SD RH	RAD MJ/day	SD RAD	Wind-speed (m/s)	SD Wind	Wet Days	Mean ppt mm/day	SD ppt	Cloud	SD Cloud	Beam Rad MJ/day	Beam SD	Diff Rad MJ/day	Diff SD	SVP mbar	SD Svp
1	O 495	4.70	2.95	-0.42	3.60	5.12	2.63	90.89	5.28	1.52	1.06	9.17	5.59	398	8.19	8.72								
	S 495	5.61	1.19**	0.11	1.17**	5.50	0.96**	89.53	3.57**	1.36	0.54**	8.04	4.82**	399	8.05	7.48**	0.80	0.22	0.12	0.19	1.24	0.39	7.25	0.62
2	O 454	5.09	2.95	-0.45	3.89	5.54	2.90	88.08	6.63	3.41	2.20	9.14	5.21	324	7.71	9.34								
	S 454	6.45	1.35**	0.21	1.28**	6.40	0.91**	88.64	4.08**	3.27	1.01**	9.09	4.86	302	7.32	6.97**	0.78	0.21	0.46	0.47	2.80	0.65	7.25	0.57
3	O 496	7.13	2.63	0.87	3.24	6.26	2.86	86.22	6.83	6.32	3.54	8.82	4.25	363	7.17	8.61								
	S 496	7.22	2.11**	0.46	2.00**	6.73	0.97**	85.70	6.59	6.31	1.84**	8.38	3.92*	367	8.04	7.41**	0.79	0.21	1.08	1.03	5.23	1.01	8.14	0.64
4	O 510	9.68	3.45	1.90	3.26	7.79	3.94	83.11	9.06	10.45	5.22	7.79	3.92	348	5.27	6.52								
	S 510	11.51	3.07**	4.12*	3.01*	7.23	1.12**	86.35**	7.48**	10.75	2.62**	8.44	3.81	348	5.45	4.79**	0.72	0.25	2.33	1.89	8.42	1.06	9.30	0.84
5	O 525	13.53	3.78	4.40	3.40	9.13	4.01	79.84	9.31	14.64	5.94	7.49	3.47	267	6.15	7.42								
	S 525	14.07	4.74**	6.46*	4.60**	7.70	1.23**	88.05**	8.68	15.34	3.50**	7.10	3.30	252	5.61	5.51**	0.64	0.28	4.04	2.82	11.30	0.98	11.27	1.04
6	O 508	15.85	3.59	7.18	3.17	8.68	3.82	81.56	8.79	15.43	6.50	6.95	3.04	299	5.24	6.32								
	S 508	16.71	5.35**	8.95	5.22**	7.65	1.26**	87.76**	9.15	16.97	3.88**	7.42	2.80*	318	5.24	5.01**	0.65	0.28	4.41	3.20	12.55	0.88	13.16	1.38
7	O 341	18.30	3.39	9.48	2.97	8.83	4.00	82.31	8.50	15.37	6.73	6.41	2.77	195	5.88	6.32								
	S 341	17.71	5.58**	10.0	5.37**	7.71	1.32**	89.22**	8.71	16.21	3.87**	6.82	2.72	197	5.77	5.16**	0.63	0.31	4.35	3.15	11.86	1.03	15.18	1.80
8	O 524	17.46	3.29	9.02	3.23	8.43	3.76	84.87	7.00	11.98	4.73	6.62	3.19	335	6.41	8.14								
	S 524	17.13	5.91**	9.58	5.82**	7.51	1.26**	89.00**	8.68**	12.53	3.13**	6.53	3.08	367	5.39	5.35**	0.66	0.29	3.10	2.41	9.43	1.05	14.78	1.60
9	O 509	14.65	2.53	6.65	3.66	8.01	3.66	86.67	6.19	8.41	3.91	6.83	3.81	323	6.61	8.89								
	S 509	14.11	5.86**	6.96	5.76**	7.26	1.20**	88.82*	8.48**	8.25	2.24**	6.68	3.50*	344	5.99	5.79**	0.69	0.28	1.85	1.53	6.40	1.02	12.49	1.14
10	O 496	11.24	2.70	4.27	4.13	6.96	3.26	89.44	5.14	4.36	2.42	7.55	4.43	353	8.54	9.79								
	S 496	10.77	3.91**	4.12	3.89	6.53	1.03**	86.78**	8.28**	4.13	1.37**	7.87	3.95**	372	8.49	7.83**	0.78	0.24	0.66	0.69	3.47	0.83	10.32	0.96
11	O 474	7.42	2.81	1.41	4.06	6.01	2.83	90.93	5.10	2.16	1.43	6.88	4.31	347	7.08	9.11								
	S 474	8.40	2.44**	2.33	2.41**	5.94	1.05**	85.90**	6.26**	1.85	0.73**	7.44	4.11	363	6.99	6.62**	0.76	0.25	0.23	0.31	1.62	0.48	8.48	0.74
12	O 495	5.56	3.13	0.13	4.17	5.43	2.47	92.17	4.95	1.16	0.79	7.84	5.04	372	8.74	11.06								
	S 495	6.04	1.43**	0.95	1.42**	5.08	0.93**	88.40**	4.56*	0.89	0.33**	8.05	4.72	370	8.36	7.88**	0.80	0.21	0.06	0.10	0.83	0.24	7.49	0.70

Table 10. Eskdalemuir site.

Month	Days With Data	Max Temp (C)	SD Max Temp.	Min Temp (C)	SD Min Temp	Temp Amplitude	SD Amplitude	RH %	SD RH	RAD MJ/day	SD RAD	Wind-speed (m/s)	SD Wind	Wet Days	Mean ppt mm/day	SD ppt	Cloud	SD Cloud	Beam Rad MJ/day	Beam SD	Diff Rad MJ/day	Diff SD	SVP mbar	SD Svp
1	O 357	6.87	3.64	1.04	3.51	5.83	2.29	89.20	8.18	2.25	1.15	8.57	7.59	208	2.76	3.32								
	S 357	8.58	2.22**	1.88	2.08**	6.59	1.10**	87.99	5.23**	2.16	0.74**	9.30	6.03**	195	2.66	2.48**	0.58	0.29	0.39	0.35	1.77	0.44	8.03	0.68
2	O 314	6.72	4.06	0.68	3.99	6.05	2.54	88.84	10.47	4.38	2.12	7.82	6.92	137	2.48	3.39								
	S 314	8.36	2.37**	0.87	2.24**	7.45	1.12**	87.59	5.46**	4.55	1.33**	8.49	5.96**	146	2.43	2.45**	0.54	0.30	1.14	0.82	3.41	0.66	7.99	0.76
3	O 371	9.68	3.21	2.67	3.19	7.02	2.71	84.84	9.27	7.51	3.16	8.88	6.41	188	3.23	3.71								
	S 371	10.78	3.55*	3.08	3.48*	7.59	1.14**	85.99	7.68**	7.98	2.09**	9.47	6.21	209	3.21	3.10*	0.60	0.28	2.08	1.43	5.90	0.97	9.32	0.76
4	O 391	11.91	3.61	3.85	3.22	8.06	3.40	81.36	10.70	11.70	4.72	8.59	6.00	190	3.58	4.49								
	S 391	12.54	3.95**	4.57	3.79**	7.81	1.19**	86.51**	8.56**	12.44	2.90**	9.61	5.89	194	3.62	3.20**	0.59	0.29	3.50	2.27	8.94	0.99	10.67	1.10
5	O 370	15.84	3.67	6.51	2.95	9.33	3.79	79.15	11.16	15.79	5.79	7.58	5.58	155	3.47	4.74								
	S 370	16.03	6.35**	7.89	6.09**	8.20	1.22**	88.45**	8.72**	17.02	3.41**	7.59	4.72**	151	3.54	3.36**	0.53	0.29	5.39	3.00	11.63	0.80	12.80	1.21
6	O 331	18.09	3.62	8.89	3.03	9.20	3.26	78.14	10.66	16.42	5.83	7.01	5.43	157	3.48	5.07								
	S 331	19.36	7.12**	10.99*	6.96**	8.25	1.29**	88.81**	8.83**	19.00*	3.89**	8.09	4.90*	159	3.46	3.21**	0.51	0.32	6.14	3.51	12.86	0.60	14.71	1.57
7	O 93	21.71	3.11	11.75	2.35	9.96	3.04	75.58	10.90	19.57	9.25	8.18	6.27	29	3.56	4.60								
	S 93	16.42**	9.65**	8.05**	9.54**	8.85	1.27**	87.24**	8.46**	19.70	3.69**	9.00	5.66	35	2.59	2.30**	0.35	0.33	7.40	3.33	12.30	0.69	18.42	2.25
8	O 304	20.93	3.43	11.07	2.94	9.86	3.37	76.58	11.06	13.22	4.67	6.76	5.17	123	4.08	7.33								
	S 304	19.53	7.84**	11.25	7.64**	8.29	1.26**	89.74**	8.52**	14.79	3.15**	7.18	4.87	123	3.99	3.88**	0.48	0.32	4.84	2.63	9.95	0.96	17.43	2.10
9	O 328	18.09	3.09	9.07	3.37	9.02	3.44	82.28	10.27	9.90	3.78	7.24	5.73	122	3.44	4.21								
	S 328	19.00	6.98**	10.55	6.78**	8.30	1.20**	88.45**	9.00**	10.45	2.40**	6.89	4.46**	136	2.78	2.58**	0.44	0.32	3.42	1.83	7.03	0.92	15.05	1.53
10	O 340	13.89	2.80	6.70	3.64	7.19	2.85	86.30	9.28	5.32	2.34	6.87	5.72	170	3.41	4.72								
	S 340	12.74	6.05**	5.05	5.85**	7.66	1.16**	87.91	8.80	5.68	1.62**	7.68	5.34	188	2.69	2.54**	0.52	0.31	1.54	1.05	4.14	0.77	12.12	1.09
11	O 240	9.11	2.85	3.40	3.37	5.72	2.45	89.62	8.61	2.55	1.35	6.40	5.92	132	2.82	3.96								
	S 240	9.38	3.95**	2.49	3.80*	6.82	1.07**	86.78**	7.88	2.64	0.84**	7.64	5.63	137	2.65	2.45**	0.58	0.30	0.51	0.43	2.13	0.48	9.40	0.76
12	O 306	7.83	3.28	2.15	3.47	5.68	2.40	90.89	8.06	1.51	0.84	6.93	6.90	167	3.53	4.89								
	S 306	8.43	2.97*	2.24	2.91**	6.15	1.07**	88.34*	5.07**	1.51	0.47**	7.55	5.49**	163	3.60	3.38**	0.60	0.29	0.21	0.21	1.30	0.28	8.63	0.79

Table 11. Cawood site.

Month	Days With Data	Max Temp (C)	SD Max Temp.	Min Temp (C)	SD Min Temp	Temp Amplitude	SD Amplitude	RH %	SD RH	RAD MJ/day	SD RAD	Wind-speed (m/s)	SD Wind	Wet Days	Mean ppt mm/day	SD ppt	Cloud	SD Cloud	Beam Rad MJ/day	Beam SD	Diff Rad MJ/day	Diff SD	SVP mbar	SD Svp
1	O 444	7.42	3.09	2.15	2.89	5.27	2.22	86.34	6.53	2.45	1.29	12.38	5.39	261	2.61	2.82								
	S 444	8.87	2.45**	2.12	2.35**	6.74	1.11**	87.43	5.69**	2.48	0.81**	12.65	5.38	268	2.49	2.36**	0.57	0.30	0.49	0.42	1.99	0.44	8.44	0.59
2	O 388	7.00	3.55	1.65	2.86	5.35	2.20	84.24	7.22	4.86	2.33	11.79	5.57	206	2.14	3.19								
	S 388	8.76	2.21**	1.15	2.07**	7.50*	1.10**	88.48**	5.22**	4.94	1.43**	12.03	5.26	211	1.98	1.88**	0.53	0.29	1.29	0.89	3.65	0.68	8.23	0.69
3	O 394	9.51	3.28	3.41	2.63	6.10	2.51	83.25	7.70	8.53	3.58	11.08	4.49	215	2.40	2.87								
	S 394	10.29	4.64**	2.52	4.26**	7.78	1.17**	86.33**	7.78	8.56	2.25**	10.72	4.31	244	2.40	2.39*	0.56	0.29	2.45	1.59	6.10	0.95	9.51	0.80
4	O 441	11.67	3.32	4.99	2.65	6.68	2.54	81.09	8.34	13.70	5.33	10.33	4.05	211	2.93	3.76								
	S 441	12.44	3.74**	4.37	3.60**	8.04	1.23**	87.29**	8.91	13.25	3.01**	11.22	4.01	219	2.94	2.68**	0.53	0.31	4.11	2.48	9.14	0.92	10.85	0.93
5	O 417	14.72	3.29	8.06	2.45	6.66	2.73	81.46	7.64	18.06	6.41	9.54	3.65	162	3.18	4.81								
	S 417	17.22*	4.64**	8.72	4.42**	8.51	1.20**	88.65**	8.88**	18.13	3.41**	10.01	3.49	149	2.73	2.50**	0.45	0.31	6.37	3.11	11.76	0.70	12.98	1.20
6	O 458	17.42	3.12	10.18	2.38	7.24	2.62	82.59	6.97	18.65	6.69	8.85	3.18	233	3.63	4.47								
	S 458	18.08	7.01**	9.78	6.66**	8.04	1.27**	87.88**	9.77**	18.53	3.90**	9.09	3.13	253	4.02	3.76*	0.57	0.30	5.75	3.48	12.78	0.65	15.29	1.56
7	O 155	20.49	2.81	12.46	2.44	8.03	2.44	79.21	6.77	18.60	5.39	8.29	2.66	63	3.34	5.34								
	S 155	22.28	6.49**	13.72	6.17**	8.67	1.29**	89.04**	9.10**	19.39	3.72**	8.17	2.55	49	3.77	3.10**	0.40	0.34	7.13	3.43	12.26	0.62	17.70	2.08
8	O 413	20.91	2.91	12.90	2.66	8.01	2.78	80.15	7.52	15.87	5.06	8.58	3.20	168	4.04	8.02								
	S 413	21.21	8.47**	12.76	8.23**	8.32	1.26**	88.19**	8.86**	15.17	3.20**	8.81	3.19	184	3.60	3.33**	0.48	0.32	5.11	2.73	10.06	0.91	18.52	2.20
9	O 403	17.87	2.58	10.95	2.79	6.92	2.62	83.00	6.83	10.02	3.87	9.29	3.98	212	3.93	6.02								
	S 403	17.58	6.83**	9.65	6.68**	7.90	1.25**	89.32**	8.67**	10.03	2.50**	9.43	4.00	240	3.55	3.37**	0.55	0.31	3.00	1.93	7.03	0.90	15.92	1.54
10	O 427	14.44	2.84	8.06	3.24	6.38	2.68	83.42	6.99	6.24	2.74	10.39	4.66	224	3.11	5.22								
	S 427	15.82	5.68**	7.87	5.44**	7.52	1.14	87.87**	9.01**	5.83	1.64**	10.35	4.47	249	3.08	2.94**	0.56	0.30	1.53	1.06	4.30	0.79	12.94	1.24
11	O 465	10.05	2.85	4.44	3.50	5.61	2.27	86.94	6.66	3.08	1.60	10.29	4.47	299	3.20	4.56								
	S 465	10.97	3.68**	4.15	3.59	6.68	1.06**	86.85	8.59**	2.77	0.86**	11.30	4.53	311	3.21	2.91**	0.63	0.28	0.51	0.46	2.26	0.48	10.15	0.84
12	O 493	7.99	2.92	2.90	3.08	5.09	2.26	87.33	6.84	1.90	1.53	11.24	5.33	317	2.78	3.42								
	S 493	9.65	2.66*	3.29	2.70**	6.32	1.08**	88.43	5.83**	1.79	0.54**	11.36	5.07	308	2.87	2.74**	0.59	0.30	0.28	0.26	1.51	0.29	8.92	0.65

Table 12. Hemsby site**.**

Month	Days With Data	Max Temp (C)	SD Max Temp.	Min Temp (C)	SD Min Temp	Temp Amplitude	SD Amplitude	RH %	SD RH	RAD MJ/day	SD RAD	Wind-speed (m/s)	SD Wind	Wet Days	Mean ppt mm/day	SD ppt	Cloud	SD Cloud	Beam Rad MJ/day	Beam SD	Diff Rad MJ/day	Diff SD	SVP mbar	SD Svp
1	O 431	6.43	3.69	1.25	3.49	5.18	2.13	90.66	7.31	2.51	1.36	10.82	6.74	264	2.75	3.27								
	S 431	7.88	2.01**	1.18	1.92**	5.86	1.76**	87.58**	4.87**	2.51	0.81**	10.82	6.00**	258	2.71	2.49**	0.59	0.29	0.48	0.43	2.04	0.43	8.19	1.31
2	O 391	6.65	4.23	0.85	3.81	5.79	2.14	88.47	7.73	4.91	2.41	10.88	6.77	197	2.65	3.05								
	S 391	8.43	1.95**	0.88	1.89**	6.37	1.87**	87.71	5.46**	4.95	1.47**	11.21	5.61**	198	2.67	2.64*	0.55	0.30	1.27	0.92	3.68	0.69	8.43	1.38
3	O 465	9.84	3.31	2.95	3.16	6.89	2.40	86.27	8.80	8.08	3.67	10.57	6.03	259	2.57	2.98								
	S 465	10.81	3.26	3.00	3.16	6.90	1.80**	85.66	7.46**	8.64	2.25**	11.03	5.62	286	2.66	2.62	0.57	0.29	2.43	1.61	6.21	0.96	9.86	1.49
4	O 450	12.35	3.78	3.99	3.16	8.36	2.97	79.09	11.53	13.11	5.44	8.95	4.60	227	3.02	4.04								
	S 450	13.70	3.85**	5.47	3.71**	7.29	1.79**	87.96**	8.37**	13.11	2.92**	9.22	4.94	230	3.01	2.62**	0.56	0.30	3.93	2.42	9.18	0.90	11.19	1.63
5	O 464	15.99	4.04	6.84	2.88	9.15	3.20	76.40	11.93	16.65	6.56	7.94	4.20	180	3.70	5.06								
	S 464	17.07	5.47**	8.83*	5.32**	7.80	1.79**	88.12**	9.03**	17.59	3.53**	8.00	4.01	177	3.60	3.33**	0.50	0.31	5.89	3.17	11.70	0.75	13.52	2.30
6	O 438	18.66	3.77	9.76	2.68	8.90	3.08	76.89	11.95	17.51	6.67	7.45	4.00	231	3.94	5.30								
	S 438	18.32	6.77**	10.24	6.55**	7.86	1.81**	89.14**	8.76**	18.54	3.88**	7.75	4.04	244	3.94	3.46**	0.58	0.30	5.76	3.49	12.78	0.61	16.00	2.60
7	O 125	22.35	3.48	12.16	2.42	10.19	2.70	74.81	11.13	17.68	5.55	7.54	3.24	50	3.15	4.10								
	S 125	20.51	10.87**	12.15	10.38**	8.43	2.13**	89.06**	9.42*	19.89*	3.53**	8.46	2.91	36	3.25	3.03**	0.38	0.30	7.56	3.22	12.33	0.59	21.27	3.92
8	O 461	22.23	3.79	12.28	2.64	9.95	2.82	75.54	11.42	15.15	5.12	7.52	4.13	158	4.71	6.58								
	S 461	20.56	8.17**	12.31	7.95**	8.19	1.79**	89.52**	8.18**	15.15	3.27**	7.62	4.17	173	4.76	4.40**	0.49	0.32	5.10	2.75	10.05	0.92	19.53	3.42
9	O 450	18.2	2.96	10.09	2.77	8.11	2.65	82.37	10.14	10.06	4.11	7.66	4.54	206	3.71	5.54								
	S 450	18.63	7.32**	10.35	6.95**	7.93	1.73**	88.80**	9.23*	10.51	2.61**	7.84	3.95**	232	3.37	3.19**	0.51	0.32	3.33	2.01	7.18	0.92	15.87	2.22
10	O 463	14.58	3.12	7.58	3.48	7.00	2.50	87.03	8.17	6.31	2.71	8.61	5.41	225	3.54	5.28								
	S 463	15.74	5.95**	7.92	5.80**	7.35	1.63**	88.05	9.32**	6.23	1.69**	8.83	4.79**	226	3.02	3.07**	0.50	0.32	1.79	1.13	4.44	0.78	13.20	1.96
11	O 419	9.77	3.19	4.12	3.60	5.65	2.14	91.38	6.91	3.09	1.62	8.41	5.11	251	3.00	4.43								
	S 419	10.66	3.57*	3.70	3.45	6.27	1.49**	86.06**	7.79**	2.94	0.91**	8.89	4.94	263	3.05	2.77**	0.62	0.28	0.57	0.50	2.37	0.49	9.95	1.47
12	O 430	7.46	3.49	2.57	3.71	4.89	2.10	91.53	6.74	1.81	1.02	9.60	6.59	252	3.01	4.03								
	S 430	9.66*	2.24**	3.19	2.11**	5.72	1.50**	88.07**	5.74**	1.92	0.54**	10.34	5.63**	229	2.91	2.82**	0.58	0.29	0.32	0.28	1.60	0.29	8.72	1.24

Table 13. Broomsbarn site.

Month	Days With Data	Max Temp (C)	SD Max Temp.	Min Temp (C)	SD Min Temp	Temp Amplitude	SD Amplitude	RH %	SD RH	RAD MJ/day	SD RAD	Wind-speed (m/s)	SD Wind	Wet Days	Mean ppt mm/day	SD ppt	Cloud	SD Cloud	Beam Rad MJ/day	Beam SD	Diff Rad MJ/day	Diff SD	SVP mbar	SD Svp
1	O 479	8.13	3.26	2.95	3.81	5.18	2.21	88.77	8.40	2.76	1.57	7.25	5.14	292	4.83	5.28								
	S 479	9.28	2.61**	2.75	2.49**	5.88	1.59**	87.92	6.69**	2.69	0.84**	7.42	4.50**	283	4.48	4.29**	0.67	0.26	0.47	0.45	2.22	0.46	8.97	1.18
2	O 448	7.74	3.25	2.15	3.75	5.59	2.35	87.65	9.17	5.40	2.71	7.37	5.33	207	4.39	4.95								
	S 448	8.46	2.94*	1.27	2.75**	6.31	1.72**	88.11	5.74**	5.04	1.47**	8.06	4.56**	226	4.37	4.26	0.64	0.27	1.16	0.93	3.88	0.69	8.79	1.30
3	O 494	10.05	2.37	3.82	3.17	6.23	2.72	84.38	10.86	8.85	4.05	7.48	4.43	248	3.66	4.58								
	S 494	11.38	3.82**	3.72	3.67**	6.84	1.63**	86.56*	8.17**	8.94	2.31**	7.69	4.01*	262	3.48	3.38**	0.60	0.29	2.50	1.70	6.43	0.93	9.97	1.16
4	O 506	12.35	2.90	4.78	3.02	7.57	3.06	79.33	12.20	14.72	5.54	7.66	4.36	229	3.94	4.11								
	S 506	13.33	4.13**	5.43	3.94**	7.11	1.65**	87.63**	8.52**	13.34	2.92**	8.58	4.28	244	3.76	3.35**	0.58	0.29	4.01	2.44	9.33	0.89	11.34	1.48
5	O 491	16.16	3.58	8.12	2.80	8.04	3.08	75.72	12.30	18.82	6.26	7.60	3.66	177	3.50	4.12								
	S 491	16.89	6.42**	8.47	6.07**	7.90	1.90**	87.76**	9.05**	18.42	3.46**	6.97	3.30*	164	3.31	3.02**	0.45	0.31	6.65	3.24	11.77	0.65	14.34	2.46
6	O 496	18.36	3.20	10.40	2.51	7.96	3.15	77.21	11.94	19.56	6.69	6.95	3.34	177	4.42	5.96								
	S 496	18.5	7.20**	10.10	7.03**	7.84	1.82**	88.84**	8.53**	19.80	3.92**	7.12	3.15	193	4.10	3.65**	0.49	0.32	6.97	3.69	12.83	0.52	15.94	2.31
7	O 144	21.31	3.33	12.88	2.40	8.43	3.20	76.19	11.31	19.21	6.02	6.08	3.11	46	3.35	5.96								
	S 144	20.27	8.91**	11.87	8.63**	7.67	2.26**	88.52**	9.03**	20.02	3.43**	6.28	3.05	50	2.71	2.27**	0.37	0.32	7.74	3.30	12.29	0.60	20.03	4.09
8	O 491	21.00	2.93	12.89	2.54	8.10	2.97	78.45	10.98	16.60	5.08	6.85	3.80	167	4.80	6.45								
	S 491	20.29	9.26**	12.11	8.89**	8.22	1.78**	87.98**	9.44**	15.66	3.33**	7.03	3.82	177	4.47	4.14**	0.48	0.31	5.46	2.85	10.20	0.89	19.03	2.97
9	O 480	18.40	2.20	10.87	3.01	7.53	2.94	81.57	9.86	11.34	4.34	6.99	4.02	190	4.94	5.92								
	S 480	19.17	7.51**	11.06	7.31**	7.90	1.78**	89.05**	9.08*	10.67	2.55**	6.63	3.73	223	4.56	4.40**	0.54	0.32	3.30	2.05	7.37	0.89	16.18	2.01
10	O 495	15.20	2.36	8.50	3.71	6.70	2.75	85.04	8.83	6.82	3.11	6.95	4.64	230	6.17	7.92								
	S 495	15.61	5.23**	8.09	5.06**	7.06	1.73**	87.54*	9.38	6.26	1.81**	6.88	4.11**	219	5.62	5.23**	0.59	0.31	1.65	1.22	4.61	0.81	13.67	1.65
11	O 415	11.30	2.84	5.13	4.23	6.17	2.80	88.47	8.06	3.55	1.92	6.35	4.61	207	5.65	6.72								
	S 415	11.02	4.91**	4.37	4.80	6.42	1.42**	88.36	8.32	3.26	0.95**	6.55	4.23*	200	5.20	4.87**	0.64	0.28	0.64	0.54	2.62	0.50	11.01	1.50
12	O 490	9.20	2.88	3.68	3.96	5.52	2.61	89.61	8.10	2.20	1.20	6.40	4.85	271	5.14	6.16								
	S 490	10.38	2.93	4.10	2.83**	5.79	1.35**	88.65	6.93**	2.08	0.60**	6.97	4.24**	254	5.57	4.84**	0.67	0.27	0.31	0.30	1.77	0.32	9.68	1.20

Table 14. Everton site.

Month	Days With Data	Max Temp (C)	SD Max Temp.	Min Temp (C)	SD Min Temp	Temp Amplitude	SD Amplitude	RH %	SD RH	RAD MJ/day	SD RAD	Wind-speed (m/s)	SD Wind	Wet Days	Mean ppt mm/day	SD ppt	Cloud	SD Cloud	Beam Rad MJ/day	Beam SD	Diff Rad MJ/day	Diff SD	SVP mbar	SD Svp
1	O 400	8.31	3.23	4.30	3.62	4.00	1.60	88.27	7.60	2.96	1.63	13.69	5.51	277	4.77	5.38								
	S 400	8.93	3.40	2.47	3.22**	6.04*	1.37**	88.35	6.16**	3.04	0.88**	14.28	4.92*	263	4.44	4.27**	0.68	0.27	0.54	0.49	2.50	0.46	9.38	1.24
2	O 396	7.81	3.34	3.26	3.49	4.55	1.78	86.05	8.54	5.70	2.81	12.60	5.85	228	4.21	4.45								
	S 396	9.26	2.90**	2.17	2.71**	6.45	1.65	88.74**	5.71**	5.41	1.56**	11.11	5.45	239	4.27	4.18	0.65	0.28	1.27	1.01	4.14	0.71	9.10	1.15
3	O 493	10.23	2.28	5.28	2.50	4.95	1.95	86.05	8.62	9.77	4.26	11.59	4.87	271	3.59	5.01								
	S 493	11.17	4.21**	3.55	4.02**	6.82	1.65**	86.24	8.40	9.33	2.35**	11.45	4.65	275	3.77	3.81**	0.61	0.28	2.65	1.76	6.68	0.92	10.36	1.03
4	O 479	12.10	2.89	6.41	2.34	5.69	2.22	83.15	9.62	15.37	5.83	11.15	4.47	254	3.89	4.26								
	S 479	12.59	4.70**	4.73	4.55**	7.10	1.72**	86.47**	8.23**	13.45	3.00**	11.95	4.40	258	4.23	3.62**	0.61	0.30	4.00	2.57	9.45	0.85	11.52	1.43
5	O 494	15.78	3.77	9.20	2.28	6.58	2.45	81.24	9.65	19.78	6.43	10.54	3.87	184	3.84	6.13								
	S 494	15.37	6.03**	7.10*	5.81**	7.91	1.77**	89.06**	8.64**	18.28	3.58**	10.62	3.70	185	3.73	3.47**	0.49	0.31	6.48	3.36	11.80	0.65	14.32	2.41
6	O 477	17.96	3.42	11.61	1.94	6.35	2.53	82.63	9.15	20.72	6.94	10.13	3.87	201	4.14	5.67								
	S 477	17.65	6.82**	9.34*	6.53**	7.99	1.74**	88.25**	9.37	19.78	4.06**	9.93	3.80	213	4.26	3.75**	0.50	0.33	7.01	3.84	12.77	0.50	16.39	2.66
7	O 247	20.85	3.32	14.24	1.60	6.61	2.49	80.97	10.43	20.20	6.50	10.08	3.90	82	2.97	5.33								
	S 247	21.57	7.97**	12.69	7.78**	8.32	2.05**	89.03**	8.50**	20.66	3.29**	10.32	3.59	71	2.77	2.58**	0.35	0.31	8.34	3.25	12.32	0.51	19.10	3.05
8	O 433	20.58	3.18	14.06	1.88	6.53	2.30	80.69	9.01	17.78	5.31	9.58	3.88	158	3.98	6.15								
	S 433	20.52	8.78**	12.14	8.41**	8.13	1.71**	88.60**	8.79	16.32	3.18**	9.80	3.98	150	3.95	3.68**	0.45	0.31	5.98	2.85	10.34	0.80	18.91	2.74
9	O 419	18.21	2.48	12.53	2.04	5.68	2.08	82.76	8.13	12.17	4.45	11.01	4.82	194	5.51	5.97								
	S 419	18.67	6.81**	10.76	6.66**	7.60	1.67**	87.88**	8.76	10.78	2.76**	10.61	4.67	238	4.97	4.86	0.59	0.31	3.25	2.17	7.53	0.93	16.81	2.23
10	O 430	15.14	2.44	10.45	2.54	4.69	1.85	83.75	7.83	6.87	3.12	12.26	5.70	245	4.81	6.40								
	S 430	16.55	5.47**	9.05	5.29**	7.19*	1.58**	88.26**	9.01**	6.72	1.83**	11.95	5.27	259	3.97	3.92**	0.59	0.31	1.83	1.31	4.89	0.77	14.18	1.60
11	O 419	11.14	2.66	6.70	3.22	4.44	1.69	85.22	8.23	3.90	1.96	12.25	5.48	268	5.09	5.60								
	S 419	11.75	4.09**	5.06	4.05**	6.27	1.34**	87.67*	9.17*	3.54	1.02**	13.02	5.55	281	4.76	4.66**	0.67	0.27	0.69	0.60	2.85	0.52	10.99	1.25
12	O 405	9.11	2.75	5.09	3.40	4.01	1.72	88.31	7.62	2.48	1.39	12.70	5.47	248	5.09	6.09								
	S 405	11.22*	2.63	4.86	2.44**	5.93	1.35**	88.71	6.95*	2.41	0.68**	12.81	4.96*	246	5.39	5.03**	0.68	0.27	0.39	0.38	2.03	0.33	9.81	1.28

Table 15. Jersey site

APPENDIX II

Symbols, Units and Abbreviations

The following notation is common to all equations:

est - estimated

h - hour of day after midnight

J - Julian day

mT - month

obs - observed, marked as [INPUT] in the text.

rn_0 - random number [0,1]

Inputs

alt_0 - base elevation (m)

alt - elevation of site (m)

δT - first-order autocorrelation of mean daily air temperature for each month [correlation $J:J^{-1}$] [eq. B1]

δT - observed first-order autocorrelation of mean observed daily air temperature for each month [correlation $J:J^{-1}$] [default value = 0.65] [eq. B1]

δW - first-order autocorrelation of mean daily wind speed for each month [correlation $J:J^{-1}$] [default value = 0.65] [eq. B1]

As – aspect [radians] [eq. I6.2]

L - latitude [radians]

Long – longitude [radians]

MJ - number of days per month [eq. C1]

PE - mean observed precipitation for each rainfall event per month [millimetres] [eq. C5.2]

RJ - number of rain days per month [eq. C1]

Sl – slope [radians] [eq. I6.2]

ST - standard deviation of the mean observed daily air temperature [degrees Celsius] [eq. B1]

SW - standard deviation of mean daily wind speed [m s^{-1}] [eq. J1]

XT - mean observed daily air temperature [degrees Celsius] [eq. J1]

XW - mean daily wind speed [m s^{-1}] [eq. J1]

Constants

σ - Ångström turbidity factor [eq. E3]

A - coefficient of maximum clear-sky transmittance characteristics [0.016] [eq. B2]

C_{sky} - coefficient of maximum clear-sky transmittance with ΔT increase [2.4] [eq. B2]

P_{range} - rainfall range [>5,10,15,20,25,50,75,100 mm converted to inches] [eqs. C6.1, C6.2]

S' - solar constant [1367.0 W m^{-2}] [eq. D9]

Symbols

α - Ångström turbidity factor	[eq. E1]
b – gamma distribution parameter	[eq C5.2]
β - Ångström factor	[eq. E2]
c – equation of time parameter	[eq. D4.2]
C - cloudiness	[eq. F1]
$C1_0$ – intermediate parameter to approximate solar radiation on tilted surface	[eq. I4.1]
Cts_0 – intermediate parameter to approximate solar radiation on tilted surface	[eq. I4.2]
Ctz_0 – intermediate parameter to approximate solar radiation on tilted surface	[eq. I5]
Cts_i - intermediate parameter to approximate daily tilted:flat ratio of beam sun	[eq. I6.2]
Ctz_i - intermediate parameter to approximate daily tilted:flat ratio of beam sun	[eq. I6.3]
ΔT - air temperature amplitude	[eq. B2]
δ - standard lapse rate (K m^{-1}) (6.5 K $100m^{-1}$)	[eq. L1]
Dayl - daylength	[eq. D7]
Ds - solar declination	[eq. D1]
$(\frac{\overline{d}}{d})^2$ - actual distance between sun and the earth	[eq. D8]
• IP - sum of wet days in a given month with rainfall within a specified range	[eq. C6.1]
EqT – equation of time	[eq. D4.1]
ev - saturated vapour pressure at a given air temperature	[eq. F2]
FWD - fraction of wet days per month	[eq. C1]
g – acceleration due to gravity (9.81m s^{-1})	[eq. L1]
GMT – Greenwich Mean Time [in hours]	[eq. D3]
H – height of sun	[eq. D6]
hs - solar sunrise/sunset angle	[eq. I3]
hs_i – intermediate parameter to approximate daily tilted:flat ratio of beam sun	[eq. I6.4]
0IP – wet/dry day [0 - dry day; 1 - wet day]	[eq. C4]
P_0 – standard sea level atmospheric pressure (1013mb)	[eq. L1]
P_{dur} - duration per rainfall event	[eq. C6.2]
$\overline{P}_{dur}$ - mean rainfall duration	[eq. C6.1]
PWD - transitional probability of a wet day followed by a dry day	[eq. C2]
PWW - transitional probability of a wet day followed by a wet day	[eq. C3]
R_{gas} – universal gas constant for air (287 J kg K^{-1})	[eq. L1]
R - terrestrial radiation on a horizontal surface at an elevation of 274 m asl	[eq. G1]
Rh – relative humidity	[eq. K1]
R_{dif} - diffuse radiation	[eq. I6]
R_{dir} - direct [beam] radiation	[eq. I5]
R_{so} - extra-terrestrial radiation	[eq. D9]
SR – time of sunrise	[eq. D2]

S_{mp} – sunrise hour fraction [eq. I2]

S_{r+1} - next hour after sunrise [eq. I1]

ST – solar time [eq. D3]

SE – solar elevation [eq. D5]

T'_0 – standard sea level temperature (288K) [eq. L1]

Td - diffuse transmission coefficient [eq. H2]

Tfr – daily tilted:flat ratio of beam sun [eq. I6.1]

T_{mean} - mean air temperature [eq. B1]

TotJ – total number of days in the year [365,366] [eq. D1]

Tt - total transmission proportion [dimensionless] [eq. H1]

u[z] - wind speed

APPENDIX III: EQUATIONS

A: GENERAL EQUATIONS

The uniform random number [0÷1] is given by:

$$rn_n = \frac{\left(rn_o^{0.135} - (1 - rn_0)^{0.135}\right)}{0.1975} \quad \text{[A1]}$$

B: AIR TEMPERATURE

Mean daily air temperature [in degrees Celsius] is given after Haith et al. [1984]:

$$T_J^{est} = XT_{mT}^{obs} + \bullet T_{mT}^{obs} \bullet (T_{J-1}^{est} - XT_{mT}^{obs}) + ST_{mT}^{obs} \bullet rn_{0_J} \bullet (1 - (\bullet T_{mT}^{obs})^2)^{0.5} \quad \text{[B1]}$$

Air temperature amplitude [in degrees Celsius] is given by modifying Bristow and Campbell [1984]:

$$\bullet T_J^{est} = \left[\frac{\text{nlog}\left(1 - \frac{Tt_J^{est}}{\bullet}\right)}{-A}\right]^{\left(\frac{1}{C_{sky}}\right)} \quad \text{[B2]}$$

Maximum air temperature [in degrees Celsius] is given by:

$$Tmax_J^{est} = T_{mean_J}^{est} + \left(\frac{\bullet T_J^{est}}{2}\right) \quad \text{[B3]}$$

Minimum air temperature [in degrees Celsius] is given by:

$$Tmin_J^{est} = T_{mean_J}^{est} - \left(\frac{\bullet T_J^{est}}{2}\right) \quad \text{[B4]}$$

C. PRECIPITATION

The fraction of wet days per month is after Geng et al. [1986] and is given by:

$$FWD_{mT}^{obs} = (\frac{RJ_{mT}^{obs}}{MJ_{mT}^{obs}}) \quad [C1]$$

Transitional probabilities for the first-order Markov chain.

The transitional probability of a wet day followed by a dry day per month is after Geng et al. [1986] and is given by:

$$PWD_{mT}^{est} = 0.75 \bullet FWD_{mT}^{obs} \quad [C2]$$

The transitional probability of a wet day followed by a wet day per month is after Geng et al. [1986] and is given by:

$$PWW_{mT}^{est} = 0.25 + PWD_{mT}^{est} \quad [C3]$$

Markov chain parameters

Determining a wet/dry day is given by modifying Richardson and Wright [1984]:

if IP_{J-1} = 1 then if $(rn1_J - PWW_J^{est})$ ≤0IP = 1 [wet day]

>0IP = 0 [dry day]

= 0 then if $(rn1_J - PWD_J^{est})$ ≤0IP = 1 [wet day]

>0IP = 0 [dry day] [C4]

Amount of rainfall on a wet day

The rainfall amount [in millimetres] on a wet day is generated using a special case of the gamma probability distribution function [an exponential] has been developed, as follows:

$$P_{IP_J=1}^{Est} = 0 - b \bullet n\log[rn(0,1)] \quad [C5.1]$$

where b is:

$$b = \frac{Pe_{mT}^{obs^2}}{1 + \frac{(rn(0,1) - 0.5)}{2}} \quad [C5.2]$$

Mean monthly duration per rainfall event [1/h] is given by:

$$\overline{P}_{dur_{mT}}^{est} = \frac{\sum_{i=1}^{n} IP = 1_{mT}^{est}}{1.39 \bullet [(P_{range} + 0.1)^{-3.55}]} \quad [C6.1]$$

Duration per rainfall event [in minutes] is given by:

$$P_{dur_J}^{est} = \overline{P}_{dur_{mT}}^{est} \bullet (\frac{P_J^{est}}{P_{range}}) \bullet 60 \quad [C6.2]$$

Rainfall intensity [millimetre hour^{-1}] is given by:

$$P_{in_J}^{est} = \frac{(\frac{P_J^{est}}{P_{dur_J}^{est}})}{60} \quad [C7]$$

D: EXTRA-TERRESTRIAL SOLAR RADIATION

Approximations of the total solar radiation reaching the earth are generated using spherical geometry.

Solar declination [radians] is given by:

$$Ds_t = 23.45 \bullet \frac{\bullet}{180} \bullet \sin\left(\frac{\bullet}{180} \bullet \left[\frac{(360 \bullet J)}{TotJ^{-1} - 80}\right]\right)$$ [D1]

Sunrise [dawn] [in hours] is given by:

$$SR_J = 12 - \frac{Dayl_J}{2}$$ [D2]

Solar time [in hours] is given by:

$$ST_J = GMT + EqT + \left[\frac{(180 \bullet Long)}{\bullet \bullet 15}\right]$$ [D3]

The equation of time [in hours] is given by:

$$EqT = \frac{[(-107.7 \bullet \sin(C)) + 596.2 \bullet \sin(2 \bullet C) + 4.3 \bullet \sin(3 \bullet C) - 12.7 \bullet \sin(4 \bullet C) - 429.3 \bullet \cos(c) - 2 \bullet \cos(2 \bullet C) + 19.3 \bullet \cos(3 \bullet C)]}{3600}$$

[D4.1]

where C is a variable [radians] given by:

$$C = (279.575 + 0.986 \bullet J) \bullet \frac{\bullet}{180}$$ [D4.2]

Solar elevation [in radians] is given by:

$$SE = \operatorname{asin}[\cos(L) \bullet \cos(Ds_J) \bullet \cos(H) + \sin(L) \bullet \sin(Ds_J)]$$ [D5]

The height of the sun at a specified time of day [in radians] is given by:

$$H = 15 \bullet (ST_J - 12) \bullet \frac{\bullet}{180}$$ [D6]

Daylength [in hours] is given by:

$$Dayl_J = \left\{\operatorname{acos} - \left[\frac{\sin(Lat) \bullet \sin(Ds_J) - \sin\left(0.833 \bullet \frac{\bullet}{180}\right)}{\cos(L) \bullet \cos(Ds_J)}\right] \bullet \frac{180}{\bullet}\right\} \bullet \frac{2}{15}$$ [D7]

The sun-earth distance is after Spencer [1971]:

$$\left(\frac{\bar{d}}{d}\right)^2 = 1.00011 + 0.034221 * \cos(\frac{2 \bullet \bullet \bullet (J-1)}{365}) + 0.00128 * \sin(\frac{2 \bullet \bullet \bullet (J-1)}{365}) + 0.000719 * \cos(2 * \frac{2 \bullet \bullet \bullet (J-1)}{365}) + 0.000077 * \sin(*2 * \frac{2 \bullet \bullet \bullet (J-1)}{365})$$ [D8]

The extra-terrestrial radiation [in W m^{-2} day^{-1}] is given by:

$$Rso_J^{est} = \frac{\left(\frac{\bar{d}}{d}\right)^2 \bullet S' \bullet Sin(SE) \bullet 2 \bullet Dayl_J}{\left[\bullet \bullet \sin\left(\frac{\bullet}{2}\right)\right] \bullet 3600}$$ [D9]

E: ATMOSPHERIC CHARACTERISTICS ATTENUATING SOLAR RADIATION

The Ångström turbidity factor [α] [in W m^{-2}] is related to aerosol size and their optical characteristics influencing diffused transmission is given by modifying Nikolov and Zeller [1992]:

$$\alpha = 32.9835 - 64.884 \bullet [1 - 1.3614 \bullet \cos(L)] \bullet 4.1842 \bullet 100 \bullet 100$$ [E1]

The Ångström turbidity factor [β] is related to the maximum clear-sky atmospheric transmittance characteristics is given by modifying Nikolov and Zeller [1992]:

$$\bullet = 0.715 - 0.3183 \bullet [1 - 1.3614 \bullet \cos(L)]$$ [E2]

The Ångström turbidity factor [σ] is related to the light absorption effects by cloud cover is given by Nikolov and Zeller [1992]:

$$\bullet = 0.03259$$ [E3]

F: GENERATING CLOUDINESS

The method approximates the formation of clouds on the basis of the atmosphere's saturated vapour pressure. Clouds are assumed to form every day, with rainfall occurring only on designated wet days.

After Nikolov and Zeller [1992] the cloudiness [in tenths] is given by:

$$C_J^{est} = 10 - 2.5 \bullet \left(\frac{ev_J^{est}}{P_J^{est}}\right)^{0.5}$$ [F1]

After Murray [1967] and Gueymard [1993] the mean saturation vapour pressure [in Pascals] at mean air temperature T is given by:

$$ev_J^{est} = 6.1078 \bullet \exp\left[\frac{17.269 \bullet T_{mean_J}^{est}}{T_{mean_J}^{est} + 237.3}\right]$$ [F2]

The mean saturation vapour pressure [in Pascals] at mean air temperature T below 0 degrees Celsius (over ice) is given by:

$$ev_J^{est} = \exp\frac{\left[\frac{[-6140.4]}{273 + Tmean_J^{est}} + 28.916\right]}{100}$$ [F3]

G: TOTAL SOLAR RADIATION AT THE EARTH'S SURFACE

After Nikolov & Zeller [1992] the total solar radiation at the earth's surface is:

$$R_J = Rso_J \bullet \left(b - s \bullet C_J^{est}\right) - a \qquad [G1]$$

H: DIRECT AND DIFFUSE SOLAR RADIATION AT THE EARTH'S SURFACE

After Lui & Jordan [1960] the total transmission proportion is:

$$Tt_J = \frac{R_J}{Rso_J} \qquad [H1]$$

Diffuse transmission coefficient is given by:

$Td_J =$ If $Tt_J < 0.07$ then $Td_J = 1$

If $Tt_J \bullet$ 0.07 < 0.35 then $Td_J = 1 - 2.3 \bullet \left(Tt_J - 0.07\right)^2$

If $Tt_J \bullet$ 0.35 < 0.75 then $Td_J = 1.33 - 1.46 \bullet Tt_J$

If $Tt_J \bullet$ 0.75 then $Td_J = 0.23$ [H2]

I: SOLAR RADIATION CORRECTED FOR SLOPE AND ASPECT

After Duffie and Beckman [1991] correction of solar radiation for slope and aspect is as follows:

The next hour after sunrise is given by:

$$S_{r+1_J} = \mathrm{int}(SR_J + 1) \qquad [I1]$$

The sunrise hour fraction is given by:

$$S_{mp_J} = SR_j + \frac{S_{r+1_J} - SR_j}{2} \qquad [I2]$$

The sunrise hour angle [in radians] is given by:

$$hs_J = \frac{15 \bullet (S_{mp_J} - 12) \bullet \bullet}{180} \qquad [I3]$$

Intermediate parameters for approximating accumulated solar radiation on a tilted surface are given by:

$$C1_0 = \sin(Ds_J) \bullet \left(\sin(L) \bullet \cos(Sl) - \cos(L) \bullet \sin(Sl) \bullet \cos(As)\right) \qquad [I4.1]$$

$$Cts_0 = \left[C1_0 + \left(\cos(Ds_J) \bullet \cos(hs) \bullet \cos(L) \bullet \cos(Sl) + \sin(L) \bullet \sin(Sl) \bullet \sin(As)\right) + \left(\cos(Ds_J) \bullet \sin(Sl) \bullet \sin(As) \bullet \sin(hs)\right)\right] \bullet \left(S_{r+1} - SR_J\right) \qquad [I4.2]$$

The intermediate parameter for approximating accumulated solar radiation on a flat surface is given by:

$$Ctz_0 = \left(\cos(L) \bullet \cos(Ds_J) \bullet \cos(hs) + \sin(L) \bullet \sin(Ds_J)\right) \bullet \left(S_{r+1} - SR_J\right) \qquad [I5]$$

The daily ratio of beam sun on a tilted/flat surface is given by:

$$Tfr_J = \left(Cts_o + \sum_{i=1}^{11} Cts_i\right) \Big/ \left(Ctz_o + \sum_{i=1}^{11} Ctz_i\right) \qquad [I6.1]$$

where:

$$Cts_i = C1_0 + \left(\cos(Ds_j) \bullet \cos(hs_i) \bullet \cos(L) \bullet \cos(Sl) + \sin(L) \bullet \sin(Sl) \bullet \cos(As)\right) + \left(\cos(Ds_j) \bullet \sin(Sl) \bullet \sin(As) \bullet \sin(hs_i)\right) \qquad [I6.2]$$

and

$$Ctz_i = \cos(L) \bullet \cos(Ds_J) \bullet \cos(hs_i) + \sin(L) \bullet \sin(Ds_J) \qquad [I6.3]$$

and

$$hs_i = 15 \bullet (t - 12) \bullet \frac{\bullet}{180}$$ With t = 0.5, 1.5, 2.5...11.5 as i = 1,2,3...11 [I6.4]

Direct [beam] radiation [in W m^{-2} day^{-1}] is given by:

$$Rdir_j = Tfr_J \bullet R_j \bullet (1 - Tt_j) \qquad [I5]$$

After Monteith [1973] diffuse radiation [in W m^{-2} day^{-1}] is given by:

$$Rdif_J = \cos^2\left(\frac{Sl}{2}\right) \bullet (R_J \bullet Tt_J) \qquad [I6]$$

J: WIND SPEED

Mean wind speed [in m s^{-1}] is given after Haith et al. [1984]:

$$u(z)_J^{est} = XW_{mT}^{obs} + \bullet W_{mT}^{obs} \bullet (W_{J-1}^{est} - XW_{mT}^{obs}) + SW_{mT}^{obs} \bullet rn_{1_J} \bullet (1 - (\bullet W_{mT}^{obs})^2)^{0.5} \qquad [J1]$$

K: RELATIVE HUMIDITY

Relative humidity [in %] is given by:

$$Rh_J^{est} = \left(\frac{E_J^{est}}{ev_J^{est}}\right) \bullet 100 \qquad [K1]$$

Where:

$$E_J^{est} = \min(1, ev_J^{est} - 0.66 \bullet (Tdb_J^{est} - Twb_J^{est}) \qquad [K2]$$

$$Tdb_J^{est} = \left(Twb_J^{est} + \partial T_J^{est}\right) \qquad [K3]$$

$$\partial T_J^{est} = \max(0, rn_o \bullet Tsd_J^{est} + Tampwd_J^{est} \qquad [K4]$$

$$Tsd_J^{est} = abs\left(\frac{Twb_J^{est}}{5}\right) \qquad [K5]$$

For winter months (December – January) in the UK the following apply:

$$\text{Tampwd}_J^{est} = 0.0587 \bullet \text{Twb}_J^{est} + 0.3845 \qquad \text{[K6]}$$

$$\text{Twb}_J^{est} = 1.0695 \bullet \text{Tmean}_J^{est} - 1.2073 \qquad \text{[K7]}$$

For the remaining months (March – November) in the UK the following apply:

$$\text{Tampwd}_J^{est} = 0.1351 \bullet \text{Twb}_J^{est} + 0.2891 \qquad \text{[K8]}$$

$$\text{Twb}_J^{est} = 0.9513 \bullet \text{Tmean}_J^{est} - 0.5788 \qquad \text{[K9]}$$

A UK site correction factor is given by:

$$\text{Rh}_J^{est} = \min(100, \frac{Rh_J^{est}}{Rh_{corr}}) \qquad \text{[K10]}$$

Where:

$$\text{Rh}_{corr} = \max(0.9172 - 0.0031 \bullet \text{Tmean}_J^{est^2} + 1.0.0377 + \text{Tmean}_J^{est} + 0.9172) \qquad \text{[K11]}$$

L: ATMOSPHERIC PRESSURE

After the US Standard Atmospheric method, atmospheric pressure (in mbar) is given by:

$$P_J^{est} = P_0\left(\frac{\left[T_0^{'} - \delta(\text{alt} - \text{alt}_0)\right]^{\frac{g}{\delta R_{gas}}}}{T_0^{'}}\right) \qquad \text{[L1]}$$

Appendix 1-I. *Energy sub-model report.*

A REVIEW OF FORESTRY WORKING PRACTICES, WOOD PROCESSING METHODS AND IMPLICIT FOSSIL ENERGY INPUTS IN EUROPE

Eva Sedo, Ari Pussinen, Jari Liski and Timo Karjalainen

European Forest Institute

July 2002

Report Number:

2002 Annual Report

Title:

A review of forestry working practices, wood processing methods and implicit fossil energy inputs in Europe

Authors:

Eva Sedo, Ari Pussinen, Jari Liski and Timo Karjalainen

Address:
European Forest Institute
Torikatu 34,
FIN-80100 Joensuu
FINLAND

Introduction

The actual working paper is a review of forestry working practices, wood processing methods and implicit fossil energy inputs. This data is collected in order to respond to the requirement in developing an energy inputs sub-model, that is part of the Modelling Component of the broader project MEFYQUE, the acronym for: "Forecasting the dynamic response of timber quality to management and environmental change: an integrated approach". The whole project is carried out in the framework of the specific research and technological development programme "Quality of Life Management of Living Resources".

The energy sub-model will be a policy-level energy sub-model, linked explicitly to the wood product sub-model and integrated with a process energy analysis sub-model, as well as appropriate databases underpinning sub-model operation. The model will predict energy inputs and flows of carbon related at the stand scale, accounting for stand management and harvesting operations, as well as energy costs related to production and processing of specific wood products and product mixes. The energy budget sub-model will be nested within the large-scale scenario model to permit up-scaling of these estimates to regional level.

Methodology

Data has been compiled from several different sources. Research has been done mainly through internet, bibliography and contacting directly to some manufacturers, as well as to some other European Institutions. Each source is commented. Some data have been analysed in order to clarify tendencies and relevance and it is shown in figures and tables added in the report. Averages and standard deviations calculated for some of the data are not included in the tables, but they are in the excel version. Nevertheless, tendencies are discussed in the report.

Countries have been separated in three different groups: Nordic and Baltic countries, Central European countries, and Southern European countries. The groups as following:
- *Nordic and Baltic countries*: Finland, Iceland, Norway, Sweden, Estonia, Latvia, Lithuania.
- *Central European countries*: Austria, Czech Republic, Hungary, Liechtenstein, Poland, Slovakia, France, Germany, Luxembourg, Switzerland, Belgium, Denmark, Ireland, Netherlands, United Kingdom.
- *Southern European countries*: Albania, Bosnia Herzegovina, Bulgaria, Croatia, Cyprus, Greece, Israel, Italy, Malta, Portugal, Romania, Slovenia, Spain, The former Yugoslav Republic of Macedonia, Turkey, Yugoslavia.

Not all data is for all countries, and some tables include only the countries with data available.

Results about overall data

First data collected is overall data for each country (table 1): Population, gross domestic product (GDP), total land area, total and exploitable forest area.. It countinues with general data about forests in European countries such as tree species composition (table 2), growing stock on forest, annual increments (table 3) and fellings (table 4) in order to give an overview of general situation of forest in those countries. Next figures show the results of some of this data. Exact numbers are given in some of the figures, and concrete data of all figures and sources are in the tables.

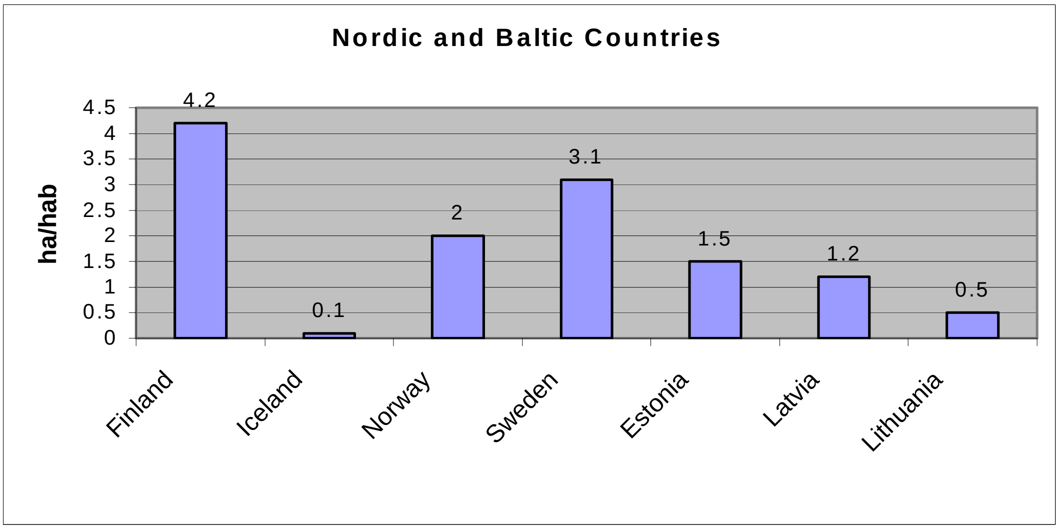


Figure 1: Hectares of forest per capita in Nordic and Baltic countries. (TBFRA 2000 database)

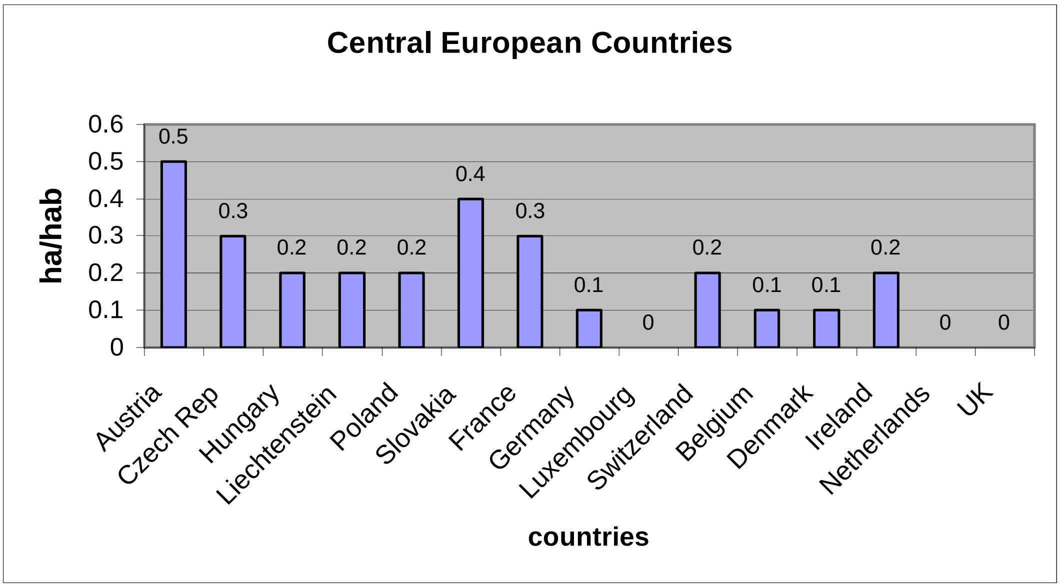


Figure 2: Hectares of forest per capita in Central European countries (TBFRA 2000 database)

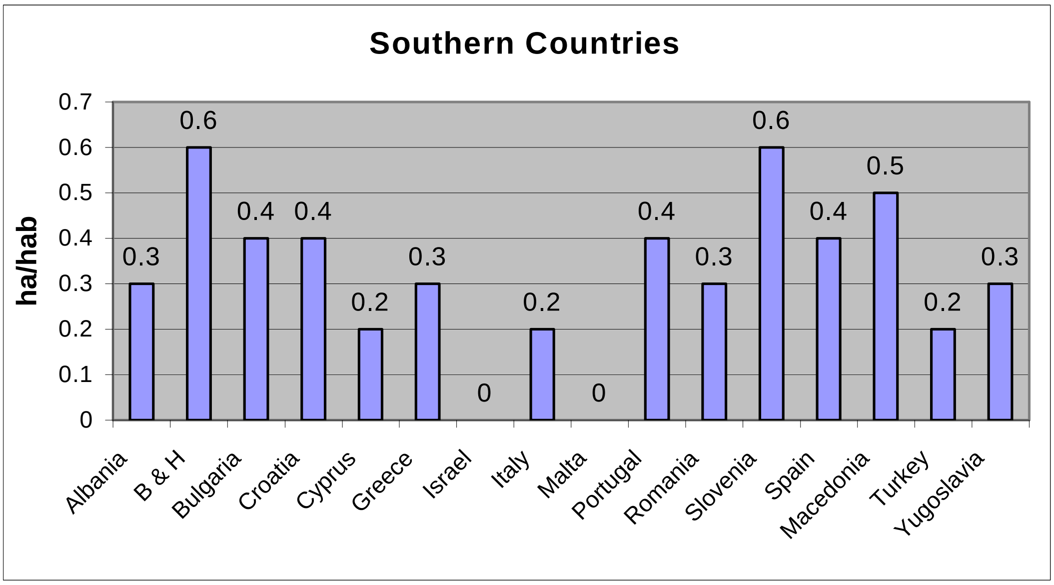


Figure 3: Hectares of forest per capita in Southern European countries. (TBFRA 2000 database)

Data about Malta is not available, and Israel has a very small amount of hectares per inhabitant. As seen in figures 1, 2,and 3, the highest values are in Nordic countries: Finland, followed by Sweden and the Baltic countries Estonia and Latvia.

In next figures it is shown the tree species composition in European countries (table 2). Nordic and Baltic countries are basically characterized by coniferous species, while in Central and Southern countries the share of broadleaved and mixed forest is much higher, mainly in Southern countries such as Yugoslavia, Croatia or Albania.

Figure 4: Tree species composition in Nordic and Baltic countries. (TBFRA 2000 database)

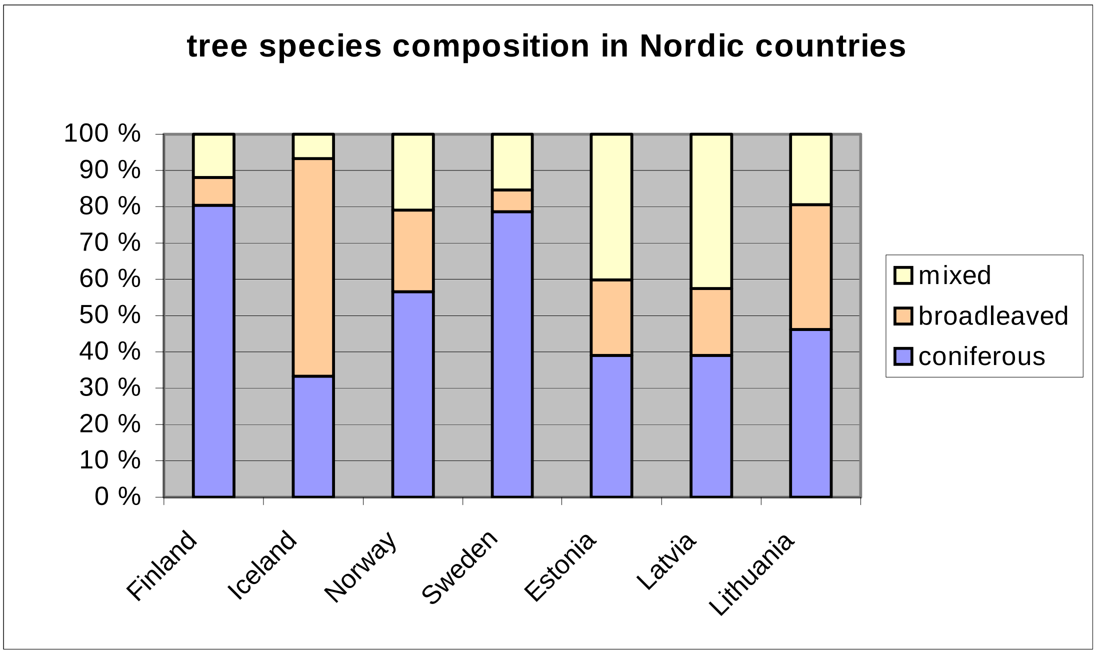


Figure 5: Tree species composition in Central European countries. (TBFRA 2000 database)

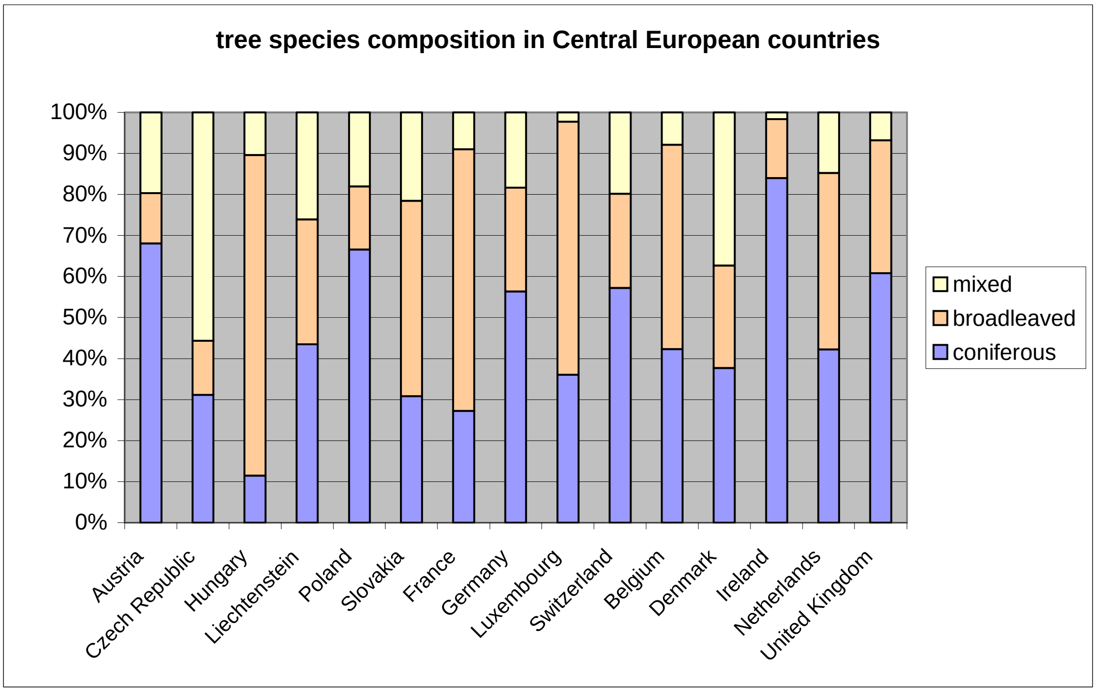
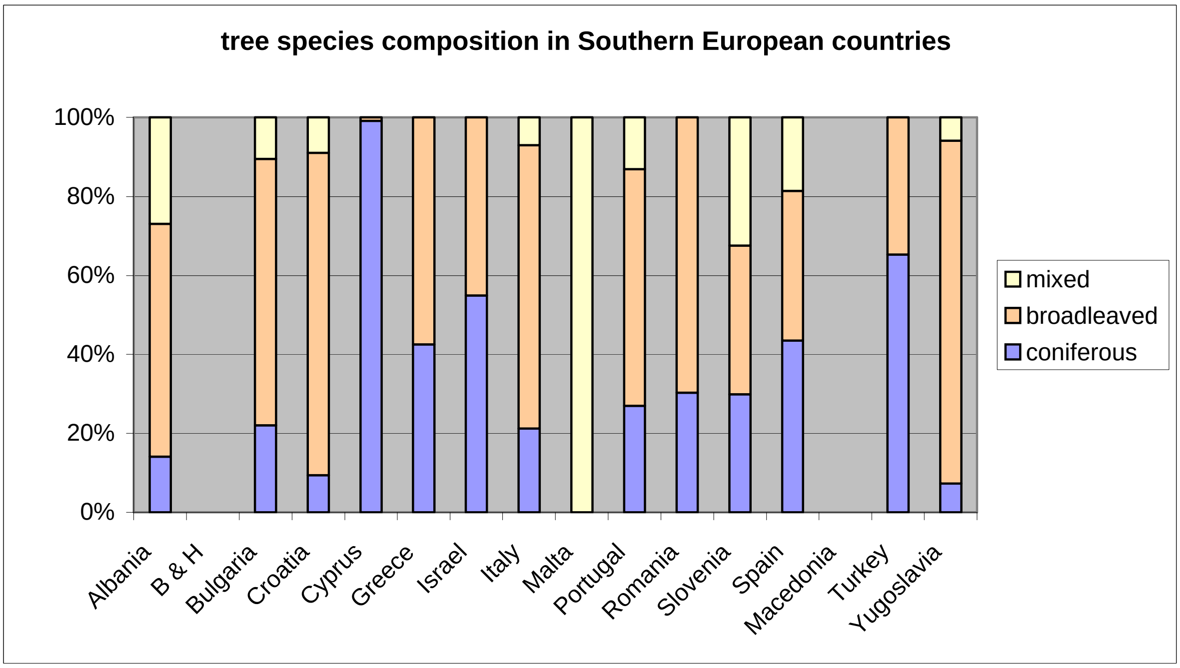


Figure 6: Tree species composition in Southern European countries. (TBFRA 2000 database)



For Bosnia and Herzegovina and for Macedonia there is no data available regarding tree species composition. And in the case of Malta, all forest is mixed, although it is a really small amount of forest.

Results on growing stock and fellings in European forests

Figures 7, 8 and 9 show the growing stock in national European forests (table 3). Switzerland has the highest level of growing stock volume (336,62 m^3/ha), followed by Austria (285,76 m3/ha), Slovenia (282,60 m3/ha) and Germany (268,16 m3/ha). Generally, highest values are found in Central European countries.

Figure 7: Growing stock in Northern national forests. (TBFRA 2000 database)

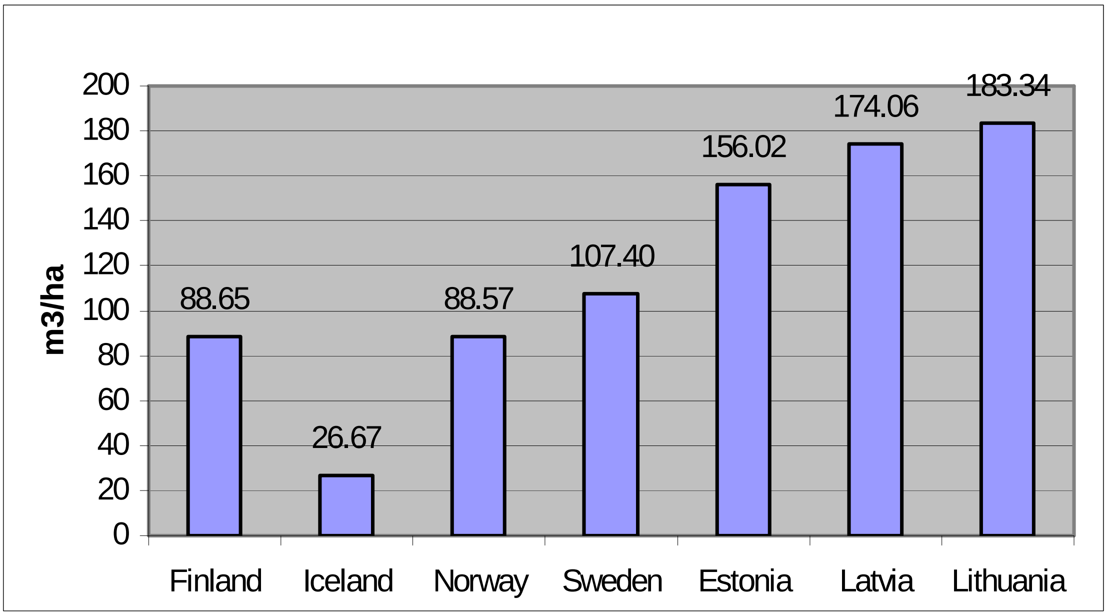


Figure 8: Growing stock in Central European national forests. (TBFRA 2000 database)

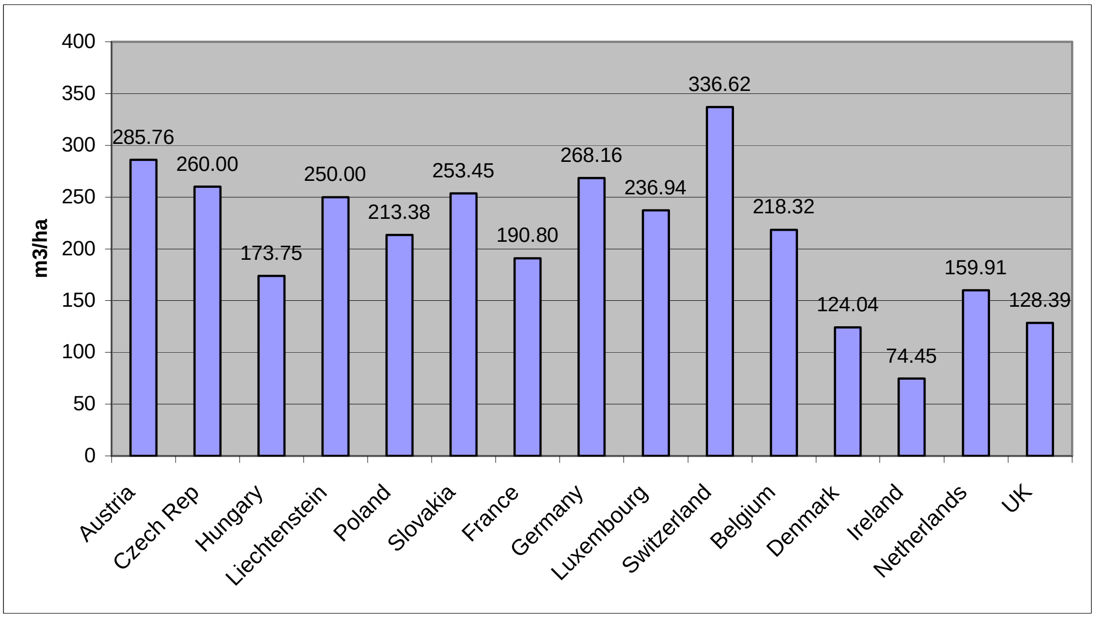
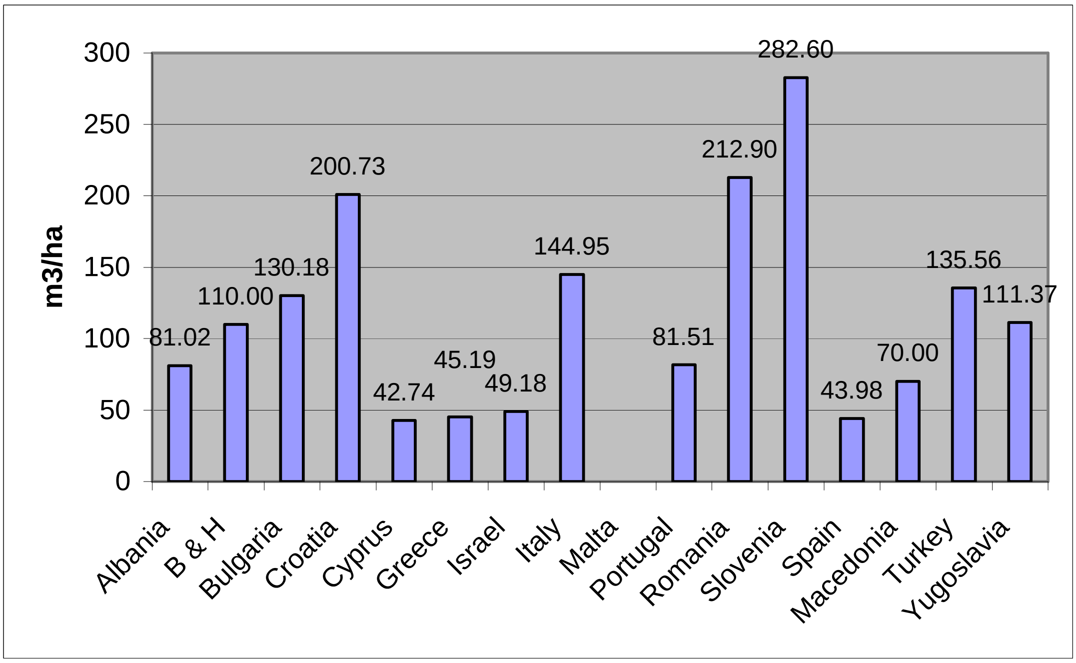


Figure 9: Growing stock in Southern European national forests. (TBFRA 2000 database)



General data on fellings has been collected also for most European countries (table 4). Data is analysed separately for coniferous and broadleaved species and in totals and for commercial use. The results show that Nordic countries are the main ones in felling coniferous forest (mainly Sweden and Finland) followed by some Central European countries such as France and Germany. About broadleaved species, the most important are France and Germany again, and then come Nordic countries, Finland first.

Taking into account only forest available for wood supply the tendencies are similar, although in countries such as France, the difference between total broadleaved and broadleaved for commercial use are quite big. Next figures show these results.

Figure 10: Fellings from total forest in Nordic and Baltic countries. (TBFRA 2000 database)

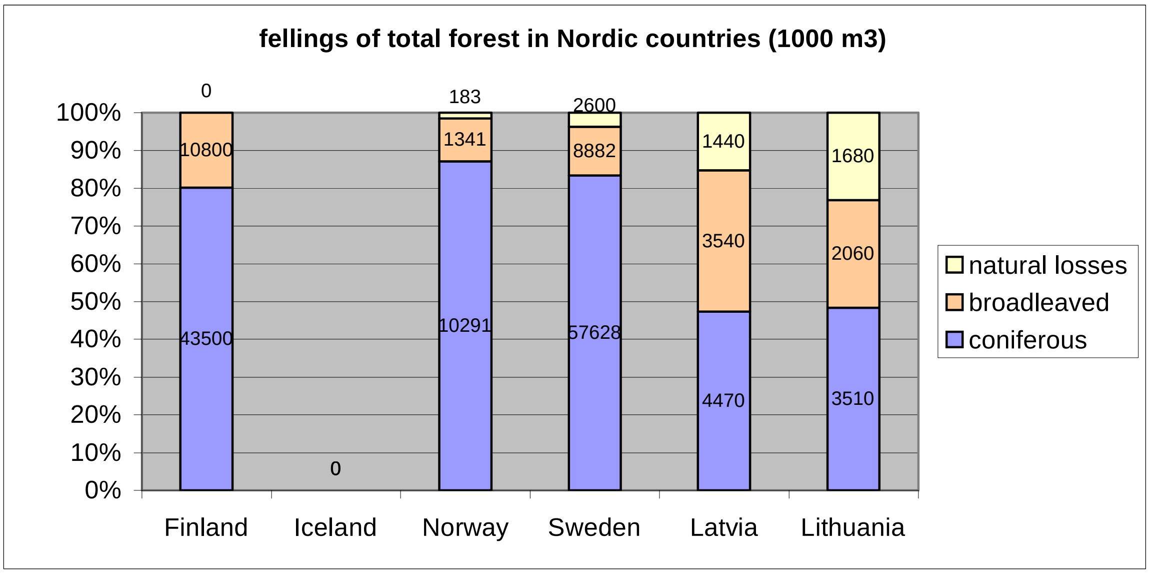


Figure 11: Fellings from total forest in Central European forest. (TBFRA 2000 database)

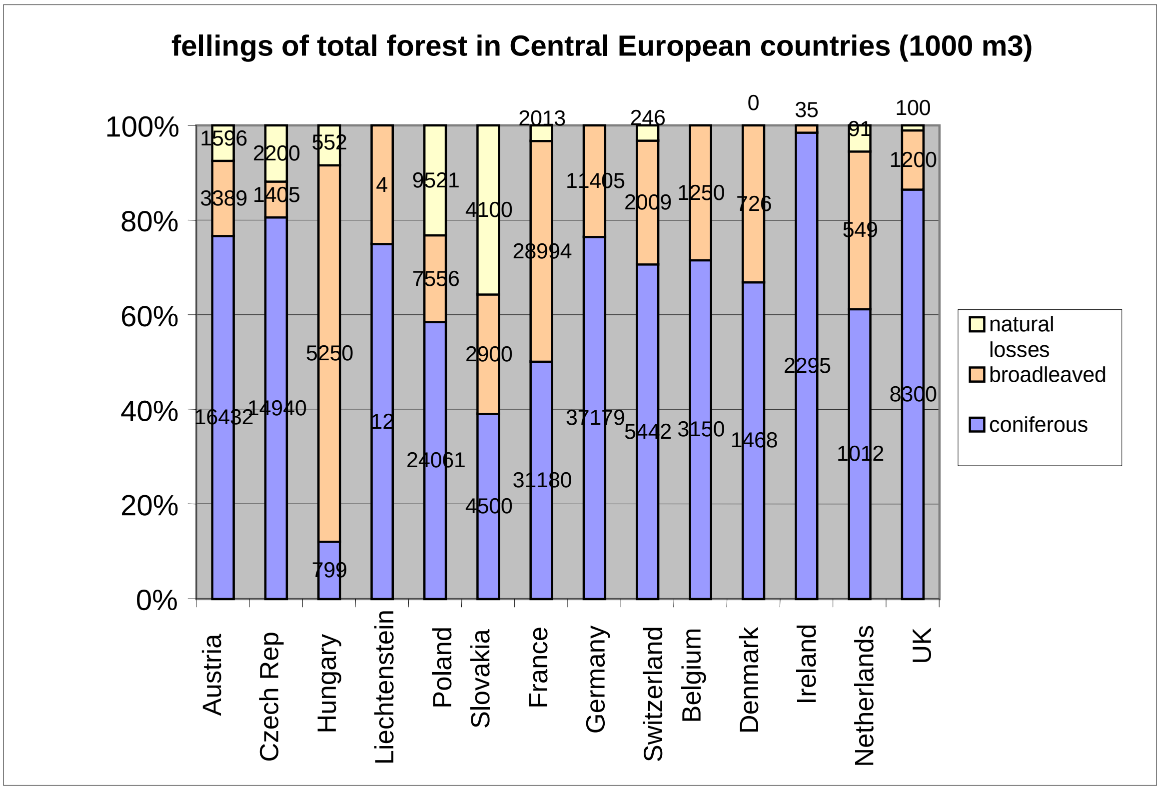


Figure 12: Fellings from total forest in Southern European countries. (TBFRA 2000 database)

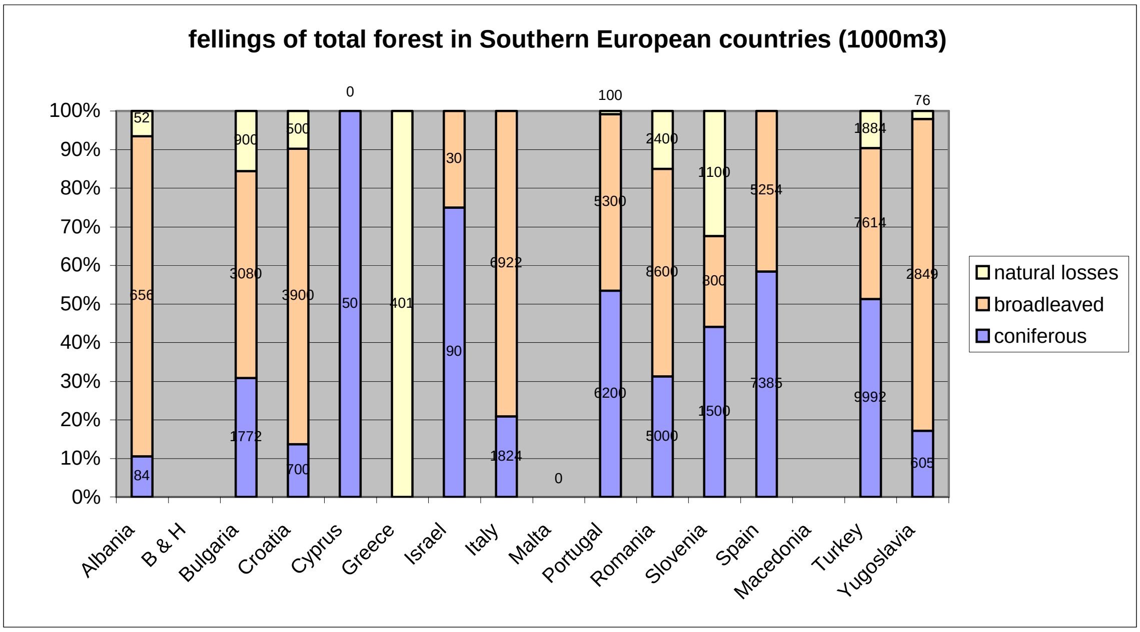


Figure 13: Harvest volume distributed to roundwood from final cuttings, thinnings and not classified (m3 o.b./ha). (Schwaiger and Zimmer, 2000).

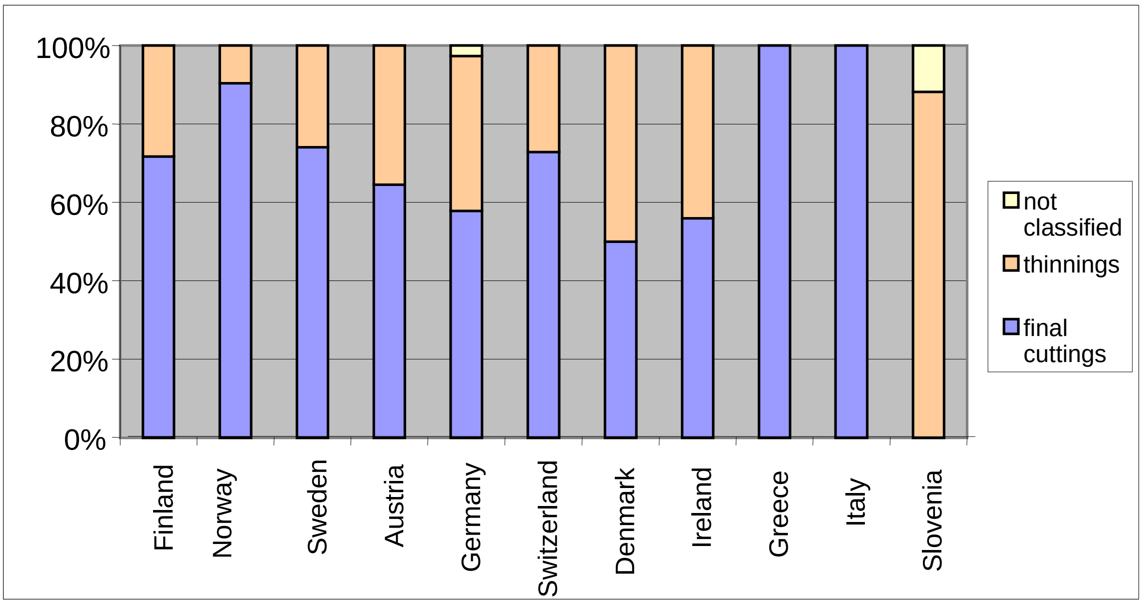


Figure 13 shows the amount of volume coming from different forestry methods in some of the European countries (table 5). Data is approximated, taken from Schwiger and Zimmer report. The most notable thing is that Slovenia processes nearly 90% of the harvested volume from thinnings. By the other side, the total amount harvested in Greece and Italy comes from Final cuttings. Nordic countries and Switzerland have all large amounts coming from final cuttings, and in Denmark half the amount comes from final cuttings, and half from thinnings.

Results on forest industry

About forest industry, data related to production by commodities has been collected for most European countries, for several years (tables 10 to 14). Averages and standart deviations have been calculated in order to analyse the data and find out the tendency along five years (from 1995 to 1999).

General patterns: Brownwood and sawnwood productions stem mainly from Nordic countries such as Finland and Sweden, and some Baltic countries such as Estonia and Latvia show a clearly rising tendency. France and Germany, in Central Europe, are also large producers of these commodities.

Fuelwood is mainly produced in Italy, Turkey and other Southern countries, although it seems that Turkey shows a light dropping tendency in the last years. On the contrary Sweden shows a rising tendency, and Austria, Germany and France are large procucers in Central Europe.

About both wood to chemical and to mechanical pulp, Finland and Sweden are the largest producers in Europe. Finland is so in plywood too, not farly followed by France and Germany, as well as Italy in the south. Spain is increasing its production lately. Southern and Central countries are the main producers of veneer, particleboard and also fibreboard.

Data has been analysed also in order to get an estimation of the amount of large size wood produced. Two kinds of percentage have been calculated:

- firstly, in order to know the contribution of each country compared with its own total production by commodities;
- secondly, is to calculate the contribution of each country to large size wood production in the total production of this kind of wood in all Europe.

According to these results Germany and Sweden are the main contributors to large size wood production, followed by Finland and France. Countries such as Austria or Holland have largest shares when compared within their own countries, but the contribution to the total large size wood production in Europe is rather small. The clearest example is Holland, which contribution is only 0,39% although it represents 23,03% of its domestic production.

Table 1: Percentage of large size wood production in Northern Europe

% large size wood (sawnwood + veneer) in Northern Europe		
country	% of national commodities production	%of total commodities production in Europe
Finland	15.16	11.37
Iceland		0.00
Norway	17.51	2.45
Sweden	17.45	15.06
Estonia	10.48	0.68
Latvia	19.46	2.50
Lithuania	17.52	1.19

Table 2: Percentage of large size wood production in Central Europe

% large size wood (sawnwood + veneer) in Central Europe		
Country	% of national commodities production	% of total commodities production in Europe
Austria	31.45	8.63
Czech Rep	18.60	3.48
Hungary	5.52	0.30
Poland	17.78	5.95
Slovakia	13.40	0.96
France	19.38	10.26
Germany	22.64	15.35
Switzerland	21.00	1.45
Belgium*	13.12	1.25
Denmark	10.34	0.33
Ireland	19.57	0.70
Netherlands	23.03	0.39
U K	17.74	2.36

Table 3: Percentage of large size wood production in Southern Europe

% large size wood (sawnwood + veneer) in Southern countries		
country	% of national commodities production	% of total commodities production in Europe
Albania	6.60	0.03
Bulgaria	7.22	0.28
Croatia	17.04	0.66
Cyprus	18.28	0.01
Greece	8.41	0.22
Israel	0.00	0.00
Italy	12.71	2.20
Malta		0.00
Portugal	13.17	1.81
Romania	11.39	2.10
Slovenia	16.61	0.55
Spain	13.88	3.38
Turkey	14.54	4.10

Next aspect analysed is roundwood imports. Sweden, Finland and Austria are the main importers of roundwood, and also in the Southern countries Spain and Italy are quite large importers of roundwood. (table 15)

Table 4: Import of roundwood (FAO, 2001).

Import of roundwood (Cum/year) of largest importers	
Country	*Average (1995-2000)*
Finland	8515940
Norway	3030600
Sweden	8760400
Austria	6079620
France	1929300
Germany	2253200
Italy	4801720
Portugal	1626960
Spain	3779400

Results on transport and forest operations

Data from transport and forest operations has been collected also for some countries. It has been compiled mostly from Schwaiger and Zimmer report. Some of this data consists in approximated values since it has been taken directly from figures. This is the case of data about the share of different trasportation systems referred to the volume of wood in some European countries, in percentages, (figure 14 in next page and table 7) as well as data about the share of different harvesting and hauling processes (table 5 and 6, and table 6).

In harvesting operations, the percentage shows the share of the two main processes: First the wide-spread motor manual cutting with motor saws and second the more mechanized one with harvesters. In Northen countries, where stands are more even relating to the tree species and diametres of the stems harvested, harvester is much more common. This is due to the higher productivity it could reach in such conditions. Productivity of harvesters depends very strictly on the mean tree diameter and in Schwaiger and Zimmer study the mean productivity supposed was 13 m^3/h. Its use is also increasing in Central European countries such as Austria or Germany.

In motor-manual harvesting process productivity is mostly higher in thinnings. But it is widely used in final fellings in countries like Greece, Italy, Slovenia, Switzerland, Austria and Germany. And it is decreasing its use in Northern countries.

Table 5: Harvesting processes. (Schwaiger and Zimmer, 2000)

	Share of different harvesting processes (%)	
Country	Motor-manual	Mechanised
Finland	40	60
Norway	32	68
Sweden	2	98
Austria	87	13
Germany	70	30
Switzerland	98	2
Denmark	50	50
Ireland	7	93
Greece	100	0
Italy	100	0
Slovenia	100	0

In order to describe <u>hauling in European countries</u>, five different processes have been taken into consideration according to Schiwaiger and Zimmer report: Hauling by man and animals, tractors, mechanized harvesting process (forwarder), cableway, and log line.

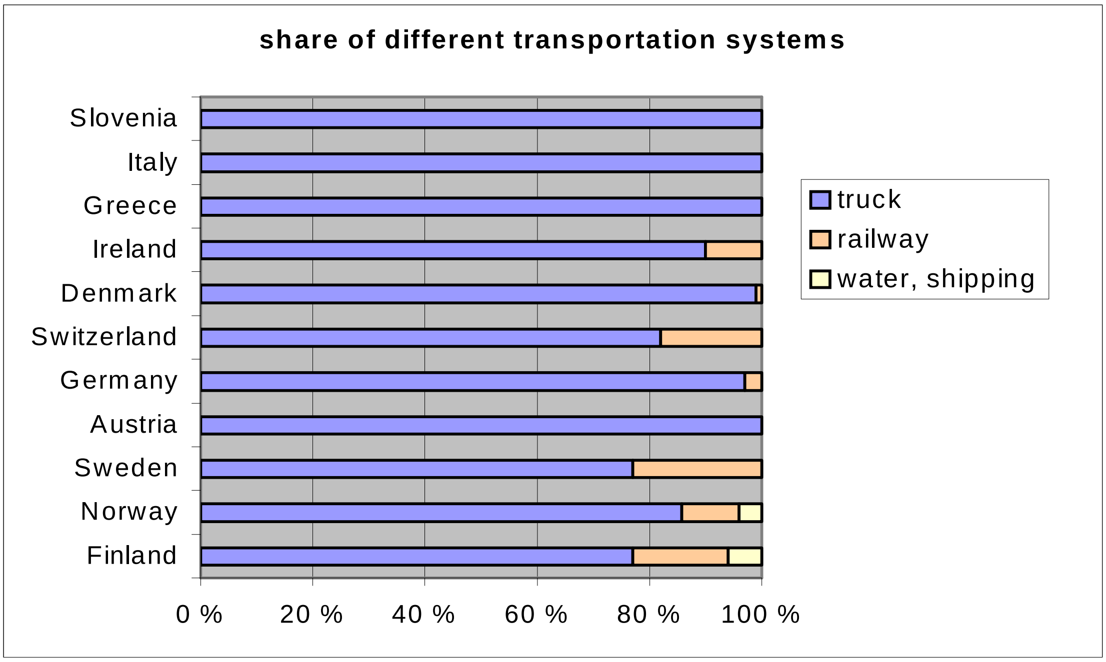
Table 6: Share of hauling processes. (%). (Schwaiger and Zimmer, 2000)

country	manual and animals	tractor	forwarder	cableway	log line	others
Finland	0	16	84	0	0	0
Norway	3	29	68	0	0	0
Sweden	0	0	100	0	0	0
Austria	8	60	14	17	1	0
Germany	0	70	30	0	0	0
Switzerland	1	73.5	5	9.5	7	4
Denmark	6	50	44	0	0	0
Ireland	10	5	80	5	0	0
Greece	30	70	0	0	0	0
Italy	0	100	0	0	0	0
Slovenia	6	88	0	6	0	0

Hauling by man and animals (mainly horses) is quantitatively important in Greece, Ireland, Austria or Slovenia. Fuel consumption was set zero, and it was taken into account that horses need energy, biomass, and related CO_2 and CH_4 emissions have been considered. Hauling by tractors: agricultural ones, specific forest tractors or skidder is very widespread in all Central European countries. In order to construct the table 6 from Schwaiger and Zimmer report on GHG emissions from each forest operation, data for the tractor ”Mahler Unifant” was used. In the case of forwarder, it is mostly combined with the mechanised harvesting process, and for calculating the GHG emissions and fuel consumption data for the forwarder ”Timberjack 810B” was used. Cableway is quantitatively important in hilly countries like Austria, Switzerland, and Slovenia. In some countries such as Southern Germany, this process is applied but no data for the amount of wood logged is available. Process log line, is a kind of slide for stems, it requires slopes and therefore it is restricted to mountainous regions. It is quantitatively important only in Switzerland and Austria. In this case no fuel consumption and GHG emissions were calculated, since wood moves mainly by gravity, although the process is often combined with a tractor or a skidder.

Data from the kind of roundwood transportation and related fuel consumption and emission factors have been collected from the same source. Fuel consumption and related GHG emissions not only depend on distances but also on the transport system.

Figure 14: Share of different transportation systems (%). (Schwaiger and Zimmer, 2000)



As seen in figure 14, roundwood transport by ships is only used in Northern countries like Finland (5-6%) and Norway (4%) Mainly roundwood is transported by truck and the total weight permitted by law for the trucks varies widely in different countries, and also depending on the number of axles.

In Nothern countries, where the rate of mechanizated forest operations in thinnings and final fellings are higher, fuel inputs for harvesting are also higher. In alpine countries like Switzerland and Austria, the rate of mechanizated operations is lower due to the steep slopes. Austria has higher rates of motor manual harvest operations. For hauling processes the difference between countries is small because the processes are quite similar in every country.

Countries that use agricultural tractors with lower productivity in hauling operations instead of forwarders, exceed the energy input of those countries with forwarders, this is the case of Austria, Italy and Slovenia.

Except in countries of highly mechanizated forest harvesting, energy efforts of hauling processes exceed those of harvesting operations. And energy inputs of transportation operations per cubic metre of timber are generally higher in all countries. (Schwaiger and Zimmer)

In order to calculate the results of table 8 (GHG emissions for different forest operation processes in Europe) the total amounts of CO_2 emissions per kg fossil fuel are multiplied with the appropiate fuel consumption per m^3 of timber. Total emissions of CH_4 and N_2O are calculated in the same way as described for CO_2. The latter are then multiplied with the factors 21 and 310 to account for their relative forcing compared with CO_2; time period assumed: 100 years; and added to the total CO_2 emissions resulting in total GHG emissions (CO_2 equivalents). Highest emission rates for harvest operations are assessed for Sweden, lowest for Italy and Slovenia. (Schwaiger and Zimmer)

Finally, it is important to know the hauling distances in order to calculate the emissions of each transportation system. These data are available for Great Britain and Finland and have been taken from the Tore Högnäs report. For Britain the figures are estimates based on interviews with people involved in the sector. For Finland the figures are based on an annual survey carried out by Metsäteho Oy. The results are the following:

Table 7: The distribution of different transportation sequences for volumes delivered to the mills in Great Britain and Finland. (1999)

Sequence	Great Britain		Finland	
	%	distance, mile	%	distance, mile
Road	95	67	80	64
Railway	3	248	16	183
Waterway	2	108	4	165
Total	100	73	100	87

Source: Tore Högnäs, 2001

Road transportation is very dominant in Britain, although waterway transportation may be a significant sequence in some organisations. Due to the small number of observations, the average distances for rail and water only have indicative status.
In Finland road transportation is also the most common sequence, although rail transportation is important, too. The distances for road transportation and even for rail are close to those in Britain. Waterway trasportation distances in Finland exceed those in Britain.

Results on emission factors:

In order to obtain up-to-date information about emission factors from forest machinery and other mobile sources, an application for that data was sent via e-mail to the main producers. Some data was compiled directly contacting to the manufacturers such as Ponsse and Timberjack, and other data was compiled straight from the web pages of other enterprises.

Silviculture:
In this case data has been used from Karjalainen and Asikainen report, in order to compile fuel consumption and productivity for some silvicultural work, later used to build up formulas to get emissions from these activities.

Table 8: Productivities and fuel consumptions of silvicultural activities (1993)

Method	Performance	Productivity (ha/h)	Fuel consumption (l/h)
Scarifier	Scarification	0,72	22
Manual, clearing saw	Tending of seedling stands	0,083	0,5

Source: Karjalainen and Asikainen.

Harvesters and forwarders:
Exact emission factors for Ponsse harvesters and forwarders have been obtained. Their product range consists of two harvesters (ERGO, Beaver) and three forwarders (Buffalo, Bison, Caribou). In these five machines, two Mercedes Benz engines are used: In Ergo and Buffalo a six-cylinder MB OM906LA, and in Bison, Caribou and Beaver a four-cylinder MB OM904LA.

Table 9: Emission factors from Ponsse engines:

engines	CO (g/kWh)	HC (g/kWh)	NOx (g/kWh)	PM (g/kWh)
six-cylinder MB OM906LA (180 kW)	0.85	0.12	4.99	0.077
four-cylinder MB OM904LA (125kW)	0.55	0.27	8.43	0.069

At this time OM906LA meets the requirements of the EUROMOT Stage II and EPA Tier II. The OM904LA meets EUROMOT Stage I and EPA Tier II. Actual emission components for the engines and Euromot limits are in the excel database.

Regarding Timberjack engines, it has been estimated that, for one of their harvesters (770 model), 97% of CO_2 emissions expose during the operation phase, which means 650 tons during whole 770's life cycle. In the case of NO_x emissions 98% of them release during operation phase and that is 7,5 tons.

Data about the exhaust emissions from harvest and transport has been collected also from the study of Dimitrios Athanassiadis. It has been compiled data on exhaust emissions for harvest and transport 1000 m^3 ub depending on the kind of fuel used and rapeseed based oil.

Table 10: Emission factors for harvesters and forwarders. (Athanassiadis, 2000)

	Fuel type	CO_2 (ton)	CO (kg)	HC (Kg)	NO_x (kg)	PM (kg)
Forwarders	EC3	3.67	17.01	3.67	32.2	2.66
	EC1	3.79	15.02	3.2	31.8	2.33
	RME	4.54	12.96	1.38	45.6	2.32
Harvesters	EC3	4.43	20.44	4.45	38.8	3.2
	EC1	4.58	18.06	3.88	38.3	2.81
	RME	5.47	15.59	1.7	54.9	2.79

Tables 23 and 24 compile information about primary energy consumption and emissions emitted per unit of production for the manufacture of forest machines and about energy inputs and associated emissions to air per unit of production for the different life cycle phases of the machinery.

According to that study, from the energy input in operation of harvesters and forwarders, 11% of energy consumption is due to the production phase. An average of 80% of energy use and emissions to air during the life cycle of forest machinery is due to the operation phase. And about 6% of the machinery's life cycle energy consumption was due to activities connected with the production of these vehicles (raw material acquisition and intermediate processing, fabrication of individual components, assembly of the vehicles and associated transports)

Spare emissions varied depending on the kind of fuel used (rapeseed methyl ester, environmental class 1, environmental class 3, diesel fuels).

The manufacturing part of the forest machinery was found to contribute only modestly to the total environmental impact of timber harvesting and terrain transportation. Nevertheless, energy consumption and emissions for the manufacture of the machinery should always be considered when the environmental load of harvesting systems is examined.

The use of biodegradable alternatives instead of mineral chainsaw and hydraulic oil is very important.

Trucks:

In order for an engine to be approved in accordance with the current European Union legislative requirements (table 11) it must be tested according to a given test cycle that simulates actual driving conditions. The specific emission ratings obtained are given in g/kWh.

Table 11: Legal requeriments (g/kWh) (*Scania on the environment*, No 1/2000)

Engine	**NO_x**	**PM**	**HC**	**CO**	**applies from**
Euro 1	9	0.4	1.1	4.5	1993
Euro 2	7	0.15	1.1	4	1996
Euro 3	5	0.1	0.66	2.1	2001

Data from Scania: On the basis of the ratings above, Scania has produced representative figures for each respective engine range:

Table 12: Typical values Scania, based on certification data (g/kWh)

Engine	**NO_x**	**PM**	**HC**	**CO**	**CO_2**
Euro 1	7.5	0.2	0.5	1.2	661
Euro 2	6.6	0.07	0.3	0.7	655
Euro 3	4.7	0.09	0.3	0.6	670

The ratings for Euro 3 engines are based on the new European steady state test cycle (ESC), where as the Euro 2 values are based on the 13-mode cycle (ECE R49).

Certification rate is good for quick comparisons between different engines within the same legal requirement, but this is only an estimated reality. The individual driver's driving style, for instance, can account for a difference up to 20% in fuel consumption. Choosing the right engine (truck) for a given transport assignment is therefore far more important than choosing the engine with the lowest certification rating.

Following emission factors specify the quantity of emissions released in relation to i.e. the amount of fuel consumed. In this way parameters that influence the fuel consumption, such as kind of loads, terrain or driving style, are taken into account.

Table 13: Emission factors for Scania engines (g/litres fuel)

	NO_x		Particulates		HC		CO		CO_2	
Engine	std	low sulphur	std	Low sulphur	std	low sulphur	std	low sulphur	std	low sulphur
Euro 1	30	26	0.79	0.57	2	2.2	4.8	5	2700	2600
Euro 2	27	23	0.27	0.19	1	1.1	2.9	3	2700	2600
Euro 3	19	16	0.36	0.26	1.2	1.3	2.2	2.3	2700	2600

Std: standard diesel: approx. 300 ppm
Low sulphur = 10 ppm

Data from Volvo: The environmental impact of manufacture does not differ appreciably between model variants. All production plants which build the Volvo FH and Volvo FM in Europe are certified under ISO 14001 or registered under EMAS.
At present there are no standardised methods for declaring the expected on-road consumption. However, a few examples are given in tables below in order to provide an indication of the fuel consumption of various vehicles under different operating conditions.
Emission levels are stated in grams per kilowatt-hour in legislation. However, in order to provide an indication of the magnitude of emissions in practical terms, data from Volvo is expressed in grams per 100 km for a number of typical vehicle combinations operating under different traffic conditions. The figures showed are based on measurements carried out in accordance with the relevant certification standards. As with fuel consumption, emissions from traffic may differ from these values.

Table 14: Volvo FM, Euro 3, MK 1, in distribution service (urban distribution). GVW (Gross Vagon Weight)18 tonnes.

Fuel consumption (litres)	22
CO_2 (kg)	57
HC (g)	9
CO (g)	48
NO_x (g)	370
PM (g)	4

Table 15: Volvo FM7 with exhaust filter in distribution service (urban distribution). GVW (Gross Vagon Weight) 18 tonnes.

Fuel consumption (litres)	22
CO_2 (kg)	57
HC (g)	2
CO (g)	4
NO_x (g)	370
PM (g)	1

Table 16: Volvo FH12, Euro 3, MK1, in long-haul service. GVW (Gross Vagon Weight) 40 tonnes.

Fuel consumption (litres)	31
CO_2 (kg)	81
HC (g)	25
CO (g)	71
NO_x (g)	530
PM (g)	6

In order to compare the engines of both companies and obtain the average, Scania and Volvo, data from the latter has been converted to grams per litre. Data used has been taken from the table 16, Volvo FH12, which is a Euro 3 engine, with a GVW of 40 tonnes. And data from Scania is taken from table 11.

Table 17: Emissions from Scania and Volvo trucks, comparision. (g/litre).

Emissions	Scania	Volvo	Average
CO_2	2700	2612	2656
HC	1,2	0,8	1
CO	2,2	2,3	2,25
NO_x	19	17,1	18,05
PM	0,36	0,18	0,27

As shown in the table, values from Volvo trucks are lower than Scania's trucks, and the biggest difference is found in particulates. But it is important to bear in mind that driving technique, speed and tyre pressure are some of the factors which influence fuel consumption and exhaust emissions. In addition to adopting an economical style of driving, it is also important to ensure that the truck is maintained correctly and that the air deflectors, for example, are correctly installed. A transport information system enables every vehicle to be used more efficiently and the number of empty runs minimised, reducing both operating costs and environmental impact.

Next comparison is based on the same data, but this time units are g/tonne-Km in order to use those results, and their average in formulas for the modelling approach:

Table 18: Emissions from Scania and Volvo trucks (g/tonne-km), and average.

	Scania	Volvo	average
NO_x	0,2	0,13	0,165
Particulates	0,004	0,0015	0,0027
HC	0,01	0,006	0,008
CO	0,02	0,018	0,019
CO_2	29	20,25	24,62

In order to calculate numbers for Volvo trucks, it has been used data from table 16 and data from table 25 for Scania engines. In both cases data is from 40 tonnes trucks and for 100 km long-haul distribution. Again the largest difference is found in particulates.

Emission standards for passenger cars have been collected assuming that some trips to the forest areas are needed during the exploitation period as well as for the regeneration and thinnings. Emissions are different depending on the fuel and model.

Table 19: Emission standards for passenger cars (grams/km).

Petrol	as from (2):	CO	HC	NO_x	
EURO I*	1.7.1992	4.05	0.66	0.49	
EURO II*	1.1.1996	3.28	0.34	0.25	
EURO III	1.1.2000	2.3	0.2	0.08	
EURO IV	1.1.2005	1	0.1	0.08	
Diesel	as from (2):	CO	HC	NO_x	PM
EURO I*	1.7.1992	2.88	0.2	0.78	0.14
EURO II*	1.1.1996	1.06	0.19	0.73	0.1
EURO III	1.1.2000	0.64	0.06	0.5	0.05
EURO IV	1.1.2005	0.5	0.05	0.25	0.025

Source: EU Energy and Transport in Figures 2001, European Commission.
as measured on new test cycle for application in year 2000

Euro III and IV (Directive 98/69/EC): standards also apply to light commercial vehicles (less than 1350 kg)

The above dates refer to new vehicle types; dates for new vehicles are 1 year later. From the same source have been also collected emission standards for heavy duty vehicles (lorries).

Emissions from chainsaws have been collected from The United States Environmental Protection Agency webpage. Some data from these emissions is taken from EFI Discussion paper for COST project. Such tables also compile basic process data for other forestry machinery: consumption (l/h), productivity (m^3/h), fuel consumption (kg/m^3) and emission factors (g/kg fuel).

In order to take into account the emissions coming from the transport of wood products to the customer, there has been collected some data about rail and waterborne transport.

Table 20: Energy consumption and emissions for railway transport:

	Energy consumption	CO_2 emissions	CH_4 emissions	N_2O emissions
Electric trains	0,0044 kWh/t-km	290 g/kWh		
Diesel trains	0,36 MJ/t-km	74,1 g/MJ	2 mg/MJ	3 mg/MJ

Source: Liikenne ja ympäristo, Tilastokeskus, SVT Ympäristö 1992:2, Helsinki: s.81, Taulukko 5.6

About railway freight transport, some data has also been collected from ***VTT*** for Finland, regarding emissions from carbon oxides, hydrocarbons, nitrogen oxides, particulates, among others, as well as fuel and electricity consumption. Next table shows these results:

Table 21: Emissions and energy consumption of Finnish freight railway traffic, 2000 (t/a). (1)

	CO	HC	NO_x	PM	SO_2	CO_2	Fuel Consumption	Energy consumption (GJ/a)	Electricity cons. (MWh/a)
electric locomotives	30	3.8	63	8.9	57	30075	0	681697	189360
diesel locomotives	310	136	2437	47	39	101364	31999	1350366	0
Shunting/ diesel locomotives	85	39	445	20	9.1	23735	7505	316710	0
TOTAL	425	179	2945	75.8	105	155174	39504	2348773	189360

Source: VTT

(1) emissions from electric locomotives is share of emissions in power stations corresponding to use of electricity by locomotives.

A summary of rail emission factors for diesel trains has been also collected from the UK Department of the Environment, Transport and the Regions. Environmental impact from rail transport varies, depending on whether the trains are run on electricity or diesel. Today, most railways are electric.

Electricity can be considered more or less environmentally friendly depending on how it is produced (coal power plants, hydroelectric power, nuclear power, etc.). Electric power plants using fossil fuel emit carbon dioxide and nitrogen oxides and other pollutants and the proportion varies with the different modes of electricity production. It is therefore difficult to make an overall assessment of level of air pollution from rail in each country. Diesel-powered trains generate pollution similar to other modes of transport using diesel engines, i.e. relatively low levels of carbon dioxide emissions and comparatively high levels of nitrogen oxides and particulates.

Table 22: Summary of rail emission factors

Diesel locomotive type	Power Cars/ Train (most frequent number per train)	NO_x Range (gr/km per powered car)	NO_x Factor (gr/km per train)
Passenger DMU	1-6 (2)	12 to 31	40
Passenger HST 125	2 (2)	-	97
Passenger Loco	1 (1)	-	64
Freight	1-4 (1)	51-170	170

Source: United Kingdom Department of the Environment, Transport and the Regions.

Notice that data in the table above comes from the UK Department of the Environment, Transport and the Regions, and it can't be used directly as data from the whole Europe. In UK approximately 70 % of energy used on the railways is derived from diesel. The remaining 30% comes from electrical energy generated in power stations. But even the balance between diesel and electric power varies considerably throughout the UK. A generic emission factor for all rail types for NO_x (as NO_2) of 89 g/kg has been calculated, based on total NO_2 attributable to rail transport of 35,000 tonnes NO_2 divided by total rail distance travelled (passenger and freight): 391 million train-kilometres.

However, in the absence of any data enable to a more accurate figure to be determined, NO_x emissions from diesel can be taken to be in the order of 80 g/km per train.

The emissions per train will be dependent on the number of power cars per train. For rail freight, single power car trains are becoming more common as the new, more powerful locomotives are introduced.

About waterborne transport some data on emissions has been collected also for the UK, from the UK Dept. of ETR. However this data doesn't distinguish between passenger ships and freight transport. This table is located in the excel version.
For low speed freight transport, shipping offers an energy-efficient alternative. Emissions measured per tonne and kilometre are small although emissions in relation to energy consumption are high. Bunker oil currently used in ships contains high levels of sulphur causing considerable amounts of emissions of sulphur dioxides.
So far, not many ships are equipped with catalytic converters, so nitrogen oxide emissions are also high. (Euroest).

Table 23: Energy consumption and emissions from shipping

Energy consumption	CO_2	CH_4	N_2O
MJ/t-km	g/ MJ	mg/ MJ	mg/ MJ
0,324	77,4	2	2

Source: Liikenne ja ympäristo, Tilastokeskus, SVT Ympäristö 1992:2, Helsinki: s.81, Taulukko 5.6.

By the other side, for emissions from shipping we can also use the mean value of 20 gCO_2/ t-km. This value has been taken from Kai Lundén, 1992

Results on energy in Europe:

Data about the use of energy in Europe and related gas emissions has been collected and analysed also in this report.

In table 9 is represented the CO_2 estimate emissions in Gg from all energy (fuel combustion and fugitive emissions), from traditional biomass burned for energy and from industrial processes. Data is available for some of the European countries, although for some other countries it is missing. The source used is the Second Communication from the European Community under the UN framework convention on Climate Change. In accordance to this source, emissions coming from *industrial processes* are those gas emissions produced from a variety of industrial activities which are not related to energy.

The main emission sources are industrial production processes, which chemically or physically transform materials. During these processes, many different GHG, including CO_2, CH_4, N_2O, and PFC's, may be released.

In some instances, emissions from industrial processes are produced in combination with fuel combustion emissions and it may be difficult to decide whether a particular emission should be reported within the energy or industrial sector. There is a criterion they use described in the Revised 1996 Reference Manual of the IPCC Guidelines for National Greenhouse Gas Inventories.

According to this data Germany is the largest emitter of CO_2 from fuel combustion and fugitive emissions and from industrial processes, although it seems that the amount of CO_2 released is decreasing in both cases. Germany is followed by the United Kingdom, that shows a decreasing tendency also in the emissions coming from all energy cluster. Italy, France and Spain are, in this order, the following largest emitter countries. There is not available data about emissions from traditional biomass burned for energy for most of the countries. For those we have data, Finland has the highest amounts, and then Spain.

Tables 16 and 17 show the energy production per country: Electricity (includes data of total gross production, that is also production from industrial enterprises that produce energy mainly for its own use), crude oil, natural gas and soft coal.

Germany and the UK are the main electricity producers in Europe and tend to increase. About crude oil, Norway and the United Kingdom are the largest producers, for natural gas are again United Kingdom and Netherlands, and Poland for soft coal.

Regarding **wood energy** consumption, data has been analysed mainly from the best estimation in the basis of available databases in Europe and OECD countries from FAO, and also from data from FAO Forest Products Yearbook. The methodology used for construction of the best estimates is described in detail in the working paper of FAO: The role of wood energy in Europe and OECD, in section A2. These are the tables 18 to 22.

According to these tables, France is the largest wood energy consumer of all EU countries in absolute terms. Other large consumers are Austria, Finland and Sweden, as well as Germany and then there are Southern countries such as Spain, Portugal and Italy.

With a high level of uncertainty, in the same report has been approximated an annual growth of 1,0% in wood energy consumption in the EU-12 countries and 1,5% in EU-15.

New States Members have very high shares of wood energy in total energy supply (between 12-18%). Because of that, the share of wood energy in total supply in EU-15 is almost twice as high as in EU-12. Nevertheless, for the EU-12 and EU-15 the share of total wood energy of the total removals does not differ a lot, 41% as compared to 48%. That is because this does not only come from direct forest removals. For EU-15, almost 60% of wood energy is derived from indirect woodfuels and wood derived products such as black liquor.

Sweden and France have similar amounts of wood energy, but their consumption is much lower when compared with total energy supplies. In France the share of wood energy is 4% of total energy supplies and in Sweden is 16%.

In Finland and Sweden black liquor constitutes about 50% of the total wood energy consumption. By the other side, in France 70% of the total wood energy consumption comes from direct forest residues. This coincides with the large shares of households in total wood energy consumption in France. In Sweden industry and transformation sector constitute almost 70% of total wood energy consumption.

In general, wood energy consumption in the EU is still mainly a household matter. The household component varies between over 60% for EU-15 to over 70% for the EU-12.

Regarding the use of **energy in production lines**, and related **emissions** of fossil carbon, data has been collected from Jari Liski et al. report. This data is about Finland's industries, and since although production lines are similar in all countries, the shares of primary energy are different so they are also emissions. According to such results, mechanical pulp and paper production line is the one that consumed much more fossil fuels per unit of raw material. Emissions of fossil carbon were also the largest in that production line, next to recycled pulp and paper.

Table 24: Use of energy in production lines (kWh/Mg carbon in raw material) and related emissions of fossil carbon (Mg fossil carbon/Mg carbon in raw material).

Production line	Origin of primary energy				Fossil carbon emissions
	Fossil fuel	Biofuel	Non-C energy	Total	
Sawmill	2.2	1.5	0.69	4.4	0.032
Plywood mill	5.8	9.3	3.5	18.6	0.069
Mechanical pulp and paper	16.5	3.1	16.7	36.3	0.48
Chemical pulp and paper	5.4	14.2	1.1	20.6	0.13
Recycled pulp and paper	8.7	0.06	2.1	10.8	0.48

Source: Liski, Jari et al. Which rotation length is favourable to carbon sequestration?

Some energy indicators have been collected from International Energy Agency for most European countries. Data on total primary energy supply (TPES) is available for most of the countries for years 1998 and 1999 although for earlier years is not available for them all.

According to such data countries with largest amounts of total primary energy supply are Germany, France, United Kingdom, Italy and Spain, the last two with a clear rising tendency, while the others tend to drop or stabilise.

Regarding the data about the CO_2 emissions per toe of TPES, countries that get larger values are Southern countries such as Greece, Israel and Yugoslavia, and in general those Southern countries have largest values than the rest of Europe. However, Estonia in the Baltic region and Poland and Czech Republic as Central European countries, have even larger values than the previous. Denmark and Ireland have large values too, but they have shown a clear dropping tendency during the last years. Nordic countries have, in general, low values.

These CO_2 emissions specifically mean CO_2 from the combustion of the fossil fuel components of TPES (i.e., coal and coal products, crude oil and derived products, natural gas and peat), while CO_2 emissions from the remaining components of TPES (i.e., electricity from hydro, other renewables and nuclear) are zero. Emissions from the combustion of biomass-derived fuels are not included in accordance with the IPCC greenhouse gas inventory methodology. TPES, by its definition, excludes international marine bunkers.

Data about CO_2, CH_4 and N_2O emissions from 1991 to 1998 for the 15 European countries in Tg of CO_2 equivalents. It has been taken from a report from the European Environment Agency. In the excel document there is also a table with the total amounts for each country, per year. According to this data the countries that release larger amounts of greenhouse gases are, in the following order, Germany, United Kingdom, France, Italy and Spain.

There are large variations in CO_2 emission trends between Member States. Only three of them reduced their emissions between 1991 and 1998, theses are Luxembourg, Germany and the United Kingdom, the countries that increased the releases are Ireland, Portugal and Spain.

The economic restructuring of the five new Länder mainly caused the German emissions. These emission reductions may not be sustained at similarly high level in the future. Other factors positively influencing the reduction of emissions in Germany were increasing efficiency in power and heating plant, the substitution of lignite by natural gas and gas oil, and reduced energy consumption in final consumption sectors. In UK, the reduction was mainly due to the liberalisation of the energy market and the following switches from oil and coal to gas in electricity production (Bernd Gugele et al., EEA).

CH_4 emissions decreased almost steadily during these years. The most important reason is the emission control in landfills, and also leak reductions in gas distribution systems and coal mining reductions.

N_2O emissions declined slightly. In 1998, the largest emitter was France, followed by the United Kingdom and Germany. Agricultural emissions are difficult to quantify and control. These were reduced slightly, but emissions from industrial processes declined much more.

Modelling approach

Forest	→	Silvicultural activities	→	emissions and energy consumption
Logging	→	Fellings haulings	→	emissions and energy consumption
Long distant transportation	→	long distance transportation to mill	→	emissions and energy consumption
Production	→	production of wood products	→	emissions and energy consumption
Wood products transportation	→	transportation of wood products to consumer	→	emissions and energy consumption
				Σ total emissions and Σ total energy

Table 25: Detailed modeling approach

Stage	**Activity**	**Input parameter**	**Data on emissions or energy consumptions**
Forest	Silviculture	Establishment -management	-Scarification (1) -Tending of seedling stands (2)
Logging	Felling	Manual or mechanised	Chainsaw (3)
			Harvester (4)
	Hauling	Manual	Manual and animals (5)
		Mechanised	Tractor (6)
			Forwarder (7)
			Cableway (8)
			Log line (9)
			Others
	Other	Mechanised	Car (petrol, diesel) (10)
Long distance transportation to mill	Transport	Land	Truck (16)
			Railway (electricity, diesel) (17)
		Waterway	Shipping (18)
Production Processes	Industry	Production lines	Sawmill (11)
			Plywood mill (12)
			Mechanical pulp and paper (13)
			Chemical pulp and paper (14)
			Recycled pulp and paper (15)
Long distance transportation to the consumer	Transport	Land	Truck (16)
			Railway (electricity, diesel) (17)
		Waterway	Shipping (18)

Formulas to calculate emissions:

(1) <u>Scarification</u>: $E_1 = a * 1/b * c * d$

Where, E_1: emissions per hectare (g/ ha).

a: scarifier fuel consumption (l/ h) from table 8.

b: productivity (ha/ h) from table 8.

c: fuel density (0,7336 kg/ l)

d: emissions from forwarder engines from table 31 from annexes (gr/ kg fuel).

(2) Tending of seedling stands: E_2 = a * 1/b * c * d
Where, E_2: emissions per hectare (gr/ ha).
a: clearing saw fuel consumption (l/ h) from table 8.
b: productivity (ha/ h) from table 8.
c: fuel density (0,7336 kg/ l)
d: emissions from motor saw engines from table 31 from annexes (g/ kg fuel).

(3) Chainsaws: E_3 = a * 1/b * c * d
where, E_3: emission factor (g/m^3)
a: consumption (l/h)
b: productivity (m^3/h)
c: fuel density: 0,7336 kg/l
d: emissions (g/kg)

(4a) Harvester: E_{4a} = a * 1/b * c
where, E_{4a}: emission factor (g/m^3)
a: emissions, taken from table 7 (report) in g/kW hb: productivity: parameter from forest model: cubic metres harvested per hour (m^3/h).
c: engine power in kW. (Data available in manufacturers webpages) Some examples are given in next table:

Engine	Power (kW)*
Timberjack 770	82
Timberjack 1070	123
Timberjack 1270	163
Timberjack 1470	183

* maximum power. We must take into account when using the formula that machines hardly ever run at their maximum power, so this value should be substituted by an average value.

(4b) Harvester: E_{4b} = a * 1/b * c * d
where, E_{4b}: emission factor (g/m^3)
a: consumption (l/h)
b: productivity (m^3/h)
c: fuel density: 0,7336 kg/l
d: emissions (gr/kg)

(5) manual and animals: none

(6) Tractor: E_6 = a * 1/b * c * d
where, E_6: emission factor (g/m^3)
a: consumption (l/h)
b: productivity (m^3/h)
c: fuel density: 0,7336 kg/l
d: emissions (gr/kg)

(7a) Forwarder: E_{7a} = a * 1/b * c
where, E_{7a}: emission factor (g/m^3)
a: emissions taken from table 7 (report) (g/kW h)
b: productivity: parameter from forest model: cubic metres forwarded per hour (m^3/h).
c: engine power in kW (data available in some manufactures webpages). Some examples are given in next table:

Engine	Power (kW)
Timberjack 610	82
Timberjack 1110C	113
Timberjack 1710B	160

* maximum power. We must take into account when using the formula that machines hardly ever run at their maximum power, so this value should be substituted by an average value.

(7b) Forwarder: $E_{7b} = a * 1/b * c * d$
where, E_{7b}: emission factor (g/m^3)
a: consumption (l/h)
b: productivity (m^3/h)
c: fuel density: 0,7336 kg/l
d: emissions (gr/kg)

(8) Cableway: : $E_8 = a * 1/b * c * d$
where, E_8: emission factor (g/m^3)
a: consumption (l/h)
b: productivity (m^3/h)
c: fuel density: 0,7336 kg/l
d: emissions (gr/kg)

(9) Log line: none

(10) Passenger car: emission standards for passenger cars are in table 19 of the report, in gr/km.

(11) Sawmill: $E_{11} = a * b * c$
where, E_{11}: emission factors (g/m^3)
a: fossil carbon emissions from table 24 (report) (Mg fossil carbon/ Mg carbon in raw material)
b: dry wood density (Mg/m^3)
c: carbon concentration **(**kg/kg)

(12) Plywood mill: $E_{12} = a * b * c$
where, E_{12}: emission factors (g/m^3)
a: fossil carbon emissions from table 24 (report) (Mg fossil carbon/ Mg carbon in raw material)

b: dry wood density (Mg/m^3)
c: carbon concentration (kg/kg)

(13) Mechanical pulp and paper: $E_{13} = a * b * c$
where, E_{13}: emission factors (g/m^3)
a: fossil carbon emissions from table 24 (report) (Mg fossil carbon/ Mg carbon in raw material)

b: dry wood density (Mg/m^3)
c: carbon concentration **(**kg/kg)

(14) Chemical pulp and paper: $E_{14} = a * b * c$
where, E_{14}: emission factors (g/m^3)
a: fossil carbon emissions from table 24 (report) (Mg fossil carbon/ Mg carbon in raw material)
b: dry wood density (Mg/m^3)
c: carbon concentration **(**kg/kg)

(15) Recycled pulp and paper mill: $E_{15} = a * b * c$
where, E_{15}: emission factors (g/m^3)
a: fossil carbon emissions from table 24 (report) (Mg fossil carbon/ Mg carbon in raw material)

b: dry wood density (Mg/m^3)
c: carbon concentration (kg/kg)

(16) Trucks: E_{16}= a * b
E_{16}: Emission factors (g/Mg).a: Emission factors in g/tonne-km

from table 18 (report)
b: transportation distance (km)

(17a) Electric trains: E_{17a} = a * b * c
where: E_{17a}: emissions (g/Mg)
a: energy consumption (kWh/ tonne-km) (table 20)
b: emissions (g/kWh) (table 20)
c: transportation distance (km)

(17b) Diesel trains: E_{17b} = a * b* c
where: E_{17b}: emissions (g/Mg)
a: energy consumption (MJ/ t-km) (table 20)
b: emissions (g/MJ) (table 20).
c: transportation distance (km)

(18a) Ships: E_{18a} = a * b * c
where: E_{18a}: emissions (g/Mg)
a: energy consumption (MJ/ tonne-km) (table 23)
b: emissions (g/MJ) (table 23).
c: transportation distance (km)

(18b) Ships: E_{18a} = a * b W
where: E_{18b}: emissions (g/Mg)
a: CO_2 emissions according to Kai Lundén, 1992 gCO_2/ t-km)
b: transportation distance (km)

Next table shows the direct global warming potentials (GWP) in a mass basis, relative to carbon dioxide.

Table 26: Direct Global Warming Potentials

Gas		Time horizon (years)		
		20	100	500
Carbon dioxide	CO_2	1	1	1
Methane	CH_4	62	23	7
Nitrous oxide	N_2O	275	296	156

Source: *Climate Change 2001,* IPCC.

This table includes the gases for which the lifetimes have been adequately characterised. In the case of carbon monoxide (CO), it has a small direct GWP, and as in the case of CH_4, the production of CO_2 from oxidised CO can lead to double counting of this CO_2, and is therefore not considered here.

List of figures:

List of tables:

References

Athanassiadis, Dimitrios. 2000 *Resource Consumption and Emission Induced by Logging Machinery in a LC Perspective*. Swedish University of Agricultural Sciences.

ECoNETT - *Rail transport and the Environment* - Section 5.2 - http://www.greenglobe21.com/econett/rail/rail0013.htm

European Environment Agency: *Are we moving in the right direction? Indicators on transport.* http://reports.eea.eu.int/ENVISSUENo12/en/page007.html

European Commission: *EU Energy and Transport in Figures 2001.* http://europa.eu.int/comm/energy_transport/etif/transport

European Community. *Second Communication form the European Community under the UN framework convention on Climate Change*, June 1998.

European Union. *Annual Energy Review*, 1999.

FAO and United Nations Economic Commission *Forest Products Statistics, Timber Bulletin* 1995-1999. Volume LIII (2000), No. 2

FAO Forestry Department: *State of the world's forests, 1999*. Webpage: http://www.fao.org/forestry/fo/sofo/sofo99/pdf/sofo_e/coper_en.pdf

FAO Forestry Department. *The role of wood energy in Europe and OECD*. March 1997 Wood energy today for tomorrow. Regional Studies. Working paper FOPW/97/1.

FAOSTAT on-line forestry database. Forestry data: http://apps.fao.org/page/collections?subset=forestry

Finnish Statistical Yearbook of Forestry, 2000, METLA, Finnish Forest Research Institute.

Högnäs, Tore. *A comparison of timber haulage in Great Britain and Finland*, Vantaa 2001. Forestry publications of Metsähallitus 39.

Houghton, J.T. et al. *Climate Change 2001, the Scientific Basis.* Report of the Intergovernmental Panel on Climate Change (IPCC), Cambridge University Press.

Instituto Nacional de Estadistica (Spain), WebPages: http://www.ine.es/inebase

International Energy Agency. *Energy policies of EIA Countries, 1998 Review.* http://www.iea.org/pubs/reviews/files/enpo198/08-rv98.htm

International Energy Agency. *Key World Energy Statistics from the EIA*. 2001 Edition. http://www.iea.org/statist/key2001/keyworld-2001.pdf

International Energy Agency. *Key World Energy Statistics from the EIA*. 2000 Edition. http://www.iea.org/statist/keyworld/keystats.htm

Karjalainen et al. *Energy, Carbon and Other Material Flows in the Life Cycle Assessment of Forestry and Forest Products.* Achievements of the Working Group 1 of the COST Action E9. European Forest Institute. Discussion Paper 10, 2001.

Karjalainen, Timo and Asikainen, Antti. *Greenhouse gas emissions from the use of primary energy in forest operations and long-distance transportation of timber in Finland.* Faculty of Forestry, University of Joensuu.

Liikenne ja ympäristö, Tilastokeskus, SVT Ympäristö 1992:2, Huhtikuu 1992, Helsinki: s.81, Taulukko 5.6.

Liski, Jari et al. *Which rotation length is favourable to carbon sequestration?* Canada Journal Forets Resources.

Lundén, Kai, 1992. Merenkulku ja ympäristö. Laivaliikenteen päästot. Turun yliopiston merenkulkualan koulutuskeskuksen julkaisuja, B44, Turku 1992.

OECD Statistics webpage: http://www.oecd.org/std/gdp.htm

Ponsse webpage: http://www.ponsse.fi

Scania Company: *Scania and the environment*, No. 1/2000 from the Scania web-page: http://www.scania.com/environment

Schwaiger and Zimmer, 2000. *A comparison of fuel consumption and GHG emissions from forest operations in Europ*e. Results of Task 4 in the COST Action E9 "Life Cycle Assessment of Forestry and Forest Products".

Swedish Environmental Protection Agency, Euroest Project (Environmentally Sustainable Transport in Europe) http://www.euroest.environ.se/fact-modes.htm

TBFRA 2000 Database. United Nations, 2001.

United Kingdom Department of the Environment , Transport and the Regions: http://www.dtlr.gov.uk/itwp/mms/vol2/14.htm

http://www.transtat.dtlr.gov.uk/tables/tsgb00/2/20800.htm (*Transport Statistics Great Britain: 2000 Edition)*.

UNECE: http://www.unece.org/trade/timber/tim-fact.htm

United States Environmental Protection Agency (EPA) WebPages: http://www.epa.gov./OMSWWW/equip-ld.htm

Volvo webpage: http://www.volvo.com

VTT Finland: http://www.vtt.fi/rte/projects/lipastoe/railie/railie.htm
http://www.vtt.fi/rte/projects/lipastoe/railie/paastkee.htm

***Appendix 2-A**. Physico-mechanical Analysis*

Progress Summary of Physico-Mechanical Analysis carried out by BRE

(Working paper)

Keith Maun (BRE)

July 2003

Appendix to WP6 - Analyses of Wood Physico-Mechanical Properties in Laboratory Conditions

Logs of a commercial size and shape were sawn into battens at LOCKERBIE and TROON. The sawn output was subsequently kiln-dried at BRE to a nominal 18% MC, free to, move, (i.e. no load on individual battens). The origin of the material processed at each sawmill is shown in Table 1.

At BRE the sawn material was handle in two packs of battens, one labelled Lockerbie and the other Troon.

The Lockerbie pack was sawn from 59 logs, to give 118 battens 100 mm wide (2 from each log) and 24 battens 75 mm wide, with two 75 mm battens cut from each of certain logs. In the Troon pack there were 107 battens in this pack, of various widths from 100 mm to 250 mm wide, with between 2 and 5 battens sawn from each log, although the majority of logs produced only 2 battens. Battens wider than 100 mm were sawn down at BRE to leave a central portion 100 mm wide.

The 75 mm battens from Lockerbie and the off-cuts from reducing the width of the Troon battens have been sent to Dr. Joris van Acker at Gent University, for small clear strength testing.

From each batten, about 250 or 300 mm was sawn from the end with the orientation quadrant marks (the base end for almost all of the Lockerbie logs, but the upper end for the Troon logs). The ends of the 100 mm battens were used to determine the original position of the battens in the log. The angle and distance of the centre of the battens from the pith, the spacing of the growth rings, proportion of juvenile wood, angle of north from the batten axis and density for each batten.

The main lengths of the 100 mm wide battens have been measured to determine distortion on drying (twist, spring, bow and cup), stress graded, their inherent grain angle and the number and size of substantial knots in the central 800 mm portion of each batten recorded.

Currently, compression wood is being assessed visually. Initially, the sawn surfaces of the battens were too rough and stained to be evaluated visually for compression wood. Also, the battens had been sawn to rather variable thickness. Hence, the faces of the main lengths of the battens have been planed down (equally from both sides) to 41 mm. They will be stress graded again, to produce more consistent results from the more regular thickness and the extent of compression wood on the surface is being assessed visually.

Table 1. *Progress of sampling material*

Site name	Site number	Species	Total trees felled	Sawmill used for scanning and sawing	Number of logs scanned	Number of logs sawn	Number of battens	Number of battens analysed (see table 3 for detail)	Number of sample sent to U of G	Tops to be scanned	
Straits	FR01	OK	6								
Total Lockerbie			54+	Lockerbie	+ =196	51	135	135	23	?	
Coalburn	FR02	SS	8	Lockerbie	+	4	6	6	-	?	
Tummel	FR03	SS	9	Lockerbie	+	-	-	-	-	?	
Rannoch	FR04	SP	9	Lockerbie	+	-	-	-	-	?	
Grizedale	FR05	OK	6						-		
Thetford	FR06	SP	9	Lockerbie	+	8	19	19	-	?	
Clunes	FR07	NS	9	Troon	59	45	107	107	?	?	
Sawley (site 1)	FR08	SS	10	Lockerbie	+	16	43	43	6	?	
Sawley (site 2)		SS		Lockerbie	+	17	57	57	17	?	
Hope Sherwood	FR10	SP	9	Lockerbie	+	6	10	10	-	?	
Headley 1				BRE							
Headily 2				BRE							
Belgium 1				Scotland	Very poor	Shape	Chipped				
Italy 1				BRE	Currently	being	Scanned				
Italy 2				BRE	10	Currently	Being	Scanned			
Italy 3				BRE	Currently	being	Delivered				

The main effort of BRE in this WP was to gather data a fast as possible to provide a data base which could be used to improve the accuracy of their existing predictive models for stiffness (Machine Stress Grade) and drying distortion. Towards this end BRE have measured over 10000 data points to give to give over 6000 values on which to base the growth descriptive variables for their models. The data points are set out in detail in tables 2 and 3.

Table 2. *Number of data-points collected - Lockerbie*

Lockerbie				
Test	Data points each batten	For each batten the number of values used for model variables	Total data points	Total number of values used for model variables
Slope of grain	4	2	576	288
Knots	Variable	Variable	340	340
Batten position from log	2	2	288	288
Moisture	1	1	144	144
Compression Wood	24	8	(3456)*	(1315)*
Other factors	5	5	720	720
Distortion Twist	1	1	144	144
Distortion Bow	1	1	144	144
Distortion Spring	1	1	144	144
Distortion Cup	1	1	144	144
Growth rings	2	1	288	144
Stress grade information	26	14	3744	2016
Cumulative Total	**39 + variable**	**24 + variable**	**6676**	**4516**

* Currently being assessed

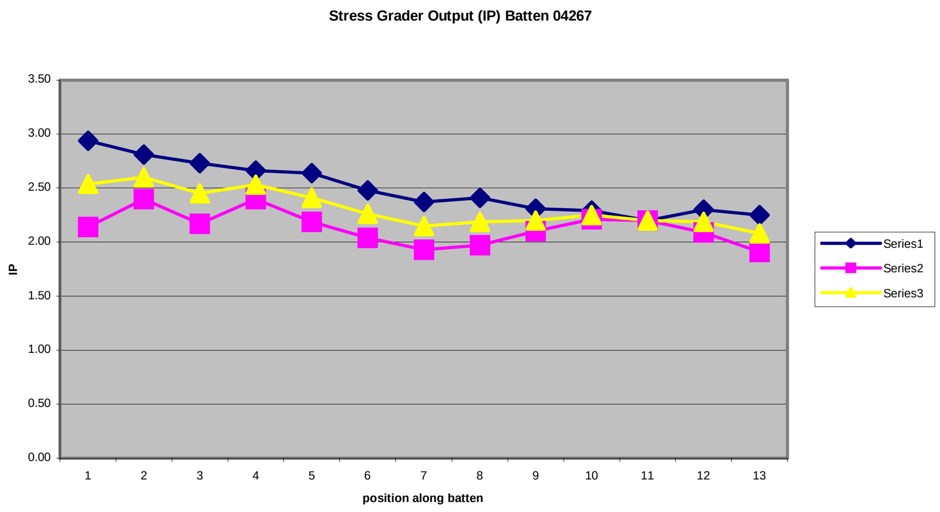
Table 2. *Number of data points collected - Troon*

Troon				
Test	Data points each batten	For each batten the number of values used for model variables	Total data points	Total number of values used for model variables
Slope of grain	4	2	428	214
Knots	Variable	Variable	350	350
Batten position from log	2	2	214	214
Moisture	1	1	107	107
Compression Wood	24	8	(2568)*	(856)*
Other factors	5	5	535	535
Distortion Twist	1	1	107	107
Distortion Bow	1	1	107	107
Distortion Spring	1	1	107	107
Distortion Cup	1	1	107	107
Growth rings	2	1	107	107
Stress grade information	26	14	2782	1498
Cumulative Total	**39 + variable**	**24+ variable**	**4952**	**3453**

* currently being assessed

An example of the data collected Is shown for the stress grading information in Figure 1. Twenty-six (26) data points are collected for each batten to give 13 values of stiffness for the individual stress grade spans plus an average for the batten, giving 14 values that can be used for model variables.

Figure 1. *Example stress grader results.*



The number of battens assessed, to date, for each growth characteristic are shown in table 3

Table 3a. *Number of battens measured for each growth characteristic.*

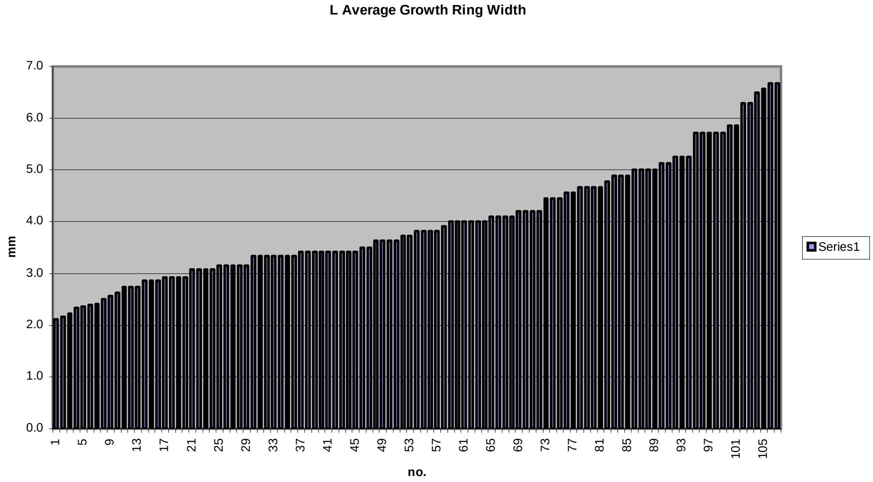
Site	Species	Number of battens	Stress Graded	Slope of grain	Twist Drying distortion	Spring Drying distortion	Bow Drying distortion	Cup Drying distortion	Knots+
Coalburn	SS	6	6	6	6	6	6	6	6
Thetford	SP	22	22	22	22	22	22	22	22
Sawley (site 1)	SS	40	40	40	40	40	40	40	40
Sawley (site 2)	SS	57	57	57	57	57	57	57	57
Hope	SP	14	14	14	14	14	14	14	14
Clunes	NS	107	107	107	107	107	107	107	107

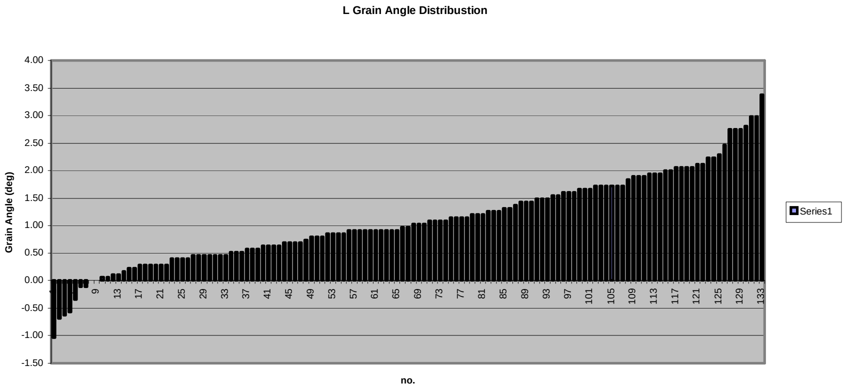
Table 3b. *Number of battens measured for each growth characteristic - continued.*

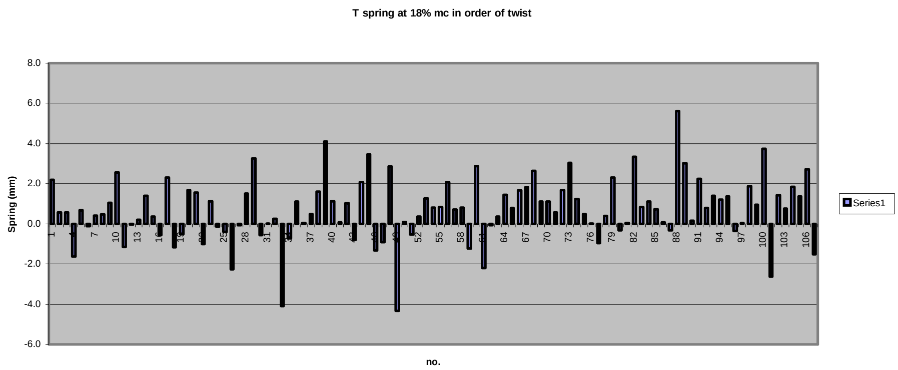
Site	Species	Number of battens	Compression Wood on four faces	Angle of centre of the batten to pith	Growth rate	Distance of centre of the batten to the pith	Density	Percent juvenile wood	Details of compression wood on each face	Angle of axis of batten to north point
Coalburn	SS	6	0	6	6	6	6	6	6	6
Thetford	SP	22	0	22	22	22	22	22	22	22
Sawley (site 1)	SS	40	0	40	40	40	40	40	40	40
Sawley (site 2)	SS	57	0	57	57	57	57	57	57	57
Hope	SP	14	0	14	14	14	14	14	14	14
Clunes	NS	107	30	107	107	107	107	107	107	107

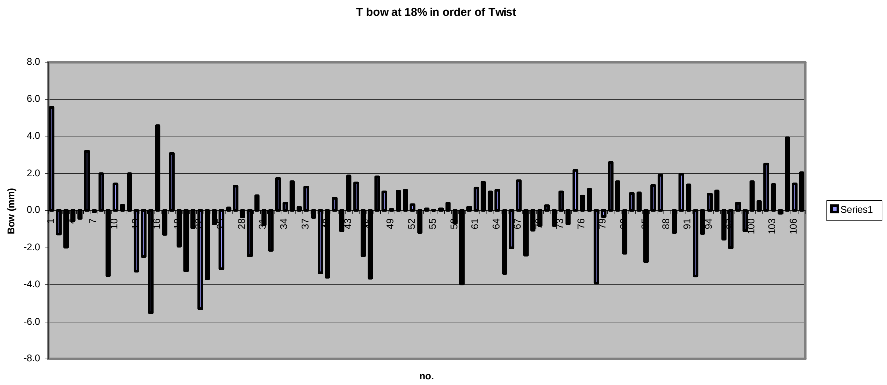
For the models to give accurate predictions they need to account for a high percentage of the variation of values for each growth characteristic. To do this they must be based on data describing the complete population of the material being modelled. The following graphical outputs are samples for some growth factors and indicate the variation of derived values for the descriptive variables.

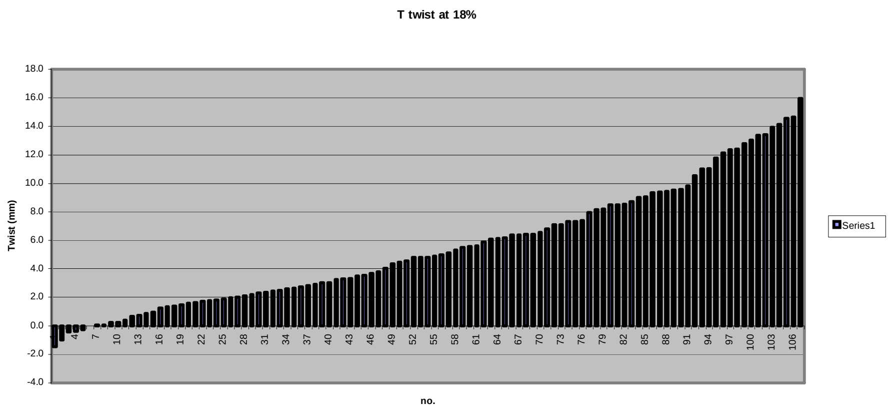
Figure 2. *Example data for various growth factors.*











BRE have completed an initial analysis that compares growth characteristics between sites. This based on mean values for growth factors except compression wood, data for which is currently being collected. Table 4 gives the mean values for some growth feature.

Table 4. *Mean and Standard Deviation Values for growth characteristics – Averages for each site*

Forest	# Battens	Species	Sawmill used for scanning and sawing	Total Trees felled	Grain Angle Inner face		Grain Angle Outer Face	
					Average	StDev	Average	StDev
Coalburn	6	SS	Lockerbie	8			1.69	1.02
Thetford	22	SP	Lockerbie	9			0.72	0.46
Sawley (site 1)	40	SS	Lockerbie	10			1.40	0.88
Sawley (site 2)	57	SS	Lockerbie	10			0.96	0.72
Hope	14	SP	Lockerbie	9			1.29	0.81
Clunes	107	NS	Troon	9			0.9	0.6

Forest	Twist (mm)		Bow (mm)		Spring (mm)		Cup (mm)	
	Average	StDev	Average	StDev	Average	StDev	Average	StDev
Coalburn	11.17	4.15	3.66	1.72	2.30	1.11	0.36	0.33
Thetford	5.02	2.73	2.35	2.13	2.22	2.44	0.46	0.23
Sawley (site 1)	6.59	3.39	2.20	2.91	2.11	1.84	0.50	0.22
Sawley (site 2)	6.59	3.39	2.20	2.91	2.11	1.84	0.50	0.22
Hope	3.24	2.82	2.83	1.83	2.18	2.28	0.40	0.25
Clunes	5.6	4.1	1.6	1.3	1.3	1.1	0.1	0.2

Table 4. *continued*

Forest	Knots			Distance from pith to centre of battens mm		Av width growth ring, mm		Moisture Content (%)	
	Average	% Knot free (faces)	% Knot free (battens)	Average	StDev	Average	StDev	Average	StDev
Coalburn	17.9	88	68	27.0	18.7	7.6	1.0	19.28	6.05
Thetford	30.2	55	0	26.0	9.6	7.3	1.4	20.43	4.66
Sawley (site 1)	26.7	70	30	29.8	9.2	5.1	1.1	20.39	1.79
Sawley (site 2)	29.4	59	8	30.4	13.9	5.4	0.9	20.39	1.79
Hope	21.8	73	15	27.6	16.4	3.5	31.1	20.73	1.41
Clunes	21.9	83	47	35.2	30.6	4.0	1.1	15.9	2.1

Forest	Angle of north from the broad axis of the batten, degrees			Angle of the centre of battens from the pith, degrees		Juvenile wood squares (of 200 on 100 x 50 mm)		Density (kg/m^2)	
	Average	StDev	% 0 degrees	Average	StDev	Average	StDev	Average	StDev
Coalburn	124.7	79.5	50	190.7	89.3	184.8	16.8	398.1	40.6
Thetford	84.2	72.8	62	174.4	96.0	187.8	18.5	332.9	48.4
Sawley (site 1)	105.9	47.6	54	181.9	92.5	148.4	39.6	409.6	34.7
Sawley (site 2)	89.9	57.0	51	161.6	89.2	155.2	33.9	394.1	39.7
Hope	62.7	52.1	50	143.1	91.5	142.9	41.7	426.6	33.0
Clunes	91.9	48.7	57	179.2	83.5	128.0	49.9	375.5	31.7

The comparisons between sites on the basis of significant differences between mean values is currently being completed, so in this report only comment based on the magnitude of the mean values can be made.

Upon evaluation of the results obtained so far no apparent differences were noticed between forests with respect to batten grain angle. Despite their being a slight spread of values for this data all values fall within the error of measurement.

Distortion measurements are fairly constant for Thetford, Sawley (both) and Clunes, with approximately 6mm for twist. Coalburn shows a 40% increase in twist compared to the later four forests, along with a slight increase in bow and spring distortion. A 50% decrease in twist was also deduced from the Hope forest, however bow, spring and cup measurements fall within the data spread of Thetford, Sawley (site 1 & 2), Clunes, and Coalburn.

No real differences in knot sizes were observed although Thetford, Sawley (site 2) and Hope all show a low percent of knot free battens. Coalburn and Clunes have a high percent of knot free battens with Coalburn producing the highest at 68%.

Assessment of the battens position from within the log showed that on average they were cut approximately from the same position although high standard deviations were achieved for Coalburn, Hope and Clunes, suggesting different percentages of heart, sap and juvenile wood.

Variations in average width of growth rings are apparent with Coalburn and Thetford averaging the highest at approximately 7mm and Hope the lowest at 3.5mm.

Moisture contents are comparative for each of the Lockerbie forests at 20%, whereas an average of 16 was obtained from the Clunes forest in Troon.

Measured dry densities have produced a spread of data with Thetford and Hope producing more variable results. Both forests have produced Sitka Spruce specimens, however, their mean densities were 333 and 427 kg/m^2, respectively. Densities for Coalburn, Sawley (site 1 & 2) and Clunes all fall within their deviations at approximately 390 kg/m^2.

Within this WP BRE have assisted U of G to design a test to determine the tensile strength of very small samples cut from the tops of trees and infant trees. All the testing was carried out in BRE's laboratory using the Minimat tensile tester. The work was conducted, jointly, by staff from BRE and U of G. After working together for 1 week, BRE completed the testing on their own, over the following month, by determining MOR and MOE for 450 small samples.

Appendix 2-B. *Light model Description*

Light-model Description

Working paper

Vincent Budts (UIA)

Gaby Deckmyn (UIA)

May 2003

Contents

1 Introduction to the light model

The concept is from the sun-shade paper of DePury. We calculate for an individual tree (or this might be a representative of a category of trees). Of this tree we know the shape (egg shape, height and radius known). LA is evenly distributed within the tree. We also know the overall LA in each layer (so, of all trees summed). We calculate according to DePury (but with the change in sunlit leaves receiving full irradiance). The incoming radiation depends on the neighbouring trees (average of light in a specific layer) and on the number of leaf-layers above the considered leaf layer. Therefore, in the middle section of the tree the light will have passed more leaf-layers compared to the outer sections. After calculating for all the sections of each layer, the weighted averages per layer are calculated.

2 Solar geometry

Input:
λ : Latitude
$Long_{stand}$: Standard longitude of timezone
$Long_{local}$: Local longitude
t_{day} : Time of the day
t_{year} : Day since beginning of the year

Local parameters:
Γ : day angle
timeequation : equation that gives a function for the variation in the period of rotation of the earth
Solarnoon : Exact solar-noon on a local longitude (summer-time involved)
Solardeclination : Solar declination angle

Output:
$\sin\beta$

Equations:

$$\Gamma = 2\pi \frac{(t_{year} - 1)}{365} \tag{1}$$

$$timeequation = 0.017 + 0.428\cos\Gamma - 7.531\sin\Gamma - 3.349\cos(2\Gamma) - 9.731\sin\Gamma \tag{2}$$

$$Solarnoon = 12 + \frac{(4(Long_{stand} - Long_{local}) - timeequation)}{60} \tag{3}$$

$$Solardeclination = \frac{-23.4\pi}{180}\cos\frac{2\pi(t_{year} + 10)}{365} \tag{4}$$

$$\sin\beta = \sin\lambda .\sin(Solardeclination) + \cos\lambda .\cos(Solardeclination).\cos(Solarnoon) \tag{5}$$

3 Beam & diffuse Irradiance

This section gives the total beam and the diffuse irradiance on each layer. All these values need to be placed in the irradiance matrix. There are 5 subsections needed to get all the necessary input parameters.

3.1 Leaf Area Index, LAI

The LAI and the distribution of leaves over the different layers are given by using an equation for a half-ellipsoid as measuring for the volume of the canopy.

Input:
h : Height of the tree

LAI_{canopy} : Total leaf area Index
B : Radius of crown on his basis
h_2 & h_1 : Begin and end height of the layer.
S_{ground} : Groundarea
B(startlayer) : Radius of the external surface of the canopy which receives beam light.
Beam(startlayer) : irradiance

Local parameters:
Volume : Volume of a tree
Volume(layer) : Volume of 1 leaf-layer

Output :
LAD(layer)
LAD
LAI(layer)
LAD(startlayer)
LAI(startlayer)

Equations

$$Volume = \frac{2\ h\pi\ B^2}{3} \tag{6}$$

$$Volume(layer) = \frac{\pi\ B^2}{h^2}\left(h^2(h_2 - h_1) - \frac{h_2{}^3 - h_1{}^3}{3}\right) \tag{7}$$

$$Volume(layer)(startlayer) = \frac{\pi\ B(startlayer)^2}{h^2}\left(h^2(h_2 - h_1) - \left(\frac{h_2{}^3 - h_1{}^3}{3}\right)\right) \tag{8}$$

$$Volume(startlayer) = \frac{2\pi\ hB(startlayer)^2}{3} \tag{9}$$

$$LAD = \frac{LAI_{canopy} \cdot S_{ground}}{Volume} \tag{10}$$

$$LAD(layer) = \frac{LAD \cdot Volume(layer)}{Volume} \tag{11}$$

$$LAI(layer) = \frac{LAI_{canopy} \cdot Volume(layer)}{Volume} \tag{12}$$

$$LAD(startlayer)\frac{LAD \cdot Volume(layer)(startlayer)}{Volume(layer)} \tag{13}$$

$$LAI(startlayer) = \frac{LAI \cdot Volume(startlayer)}{Volume} \tag{14}$$

$$LAI(startlayer)(layer) = \frac{LAI \cdot Volume(layer)(startlayer)}{Volume(layer)} \tag{15}$$

3.2 Light Extinction

We try to estimate a correct factor for the extinction of the different light patterns.

Input:
h : Height of the tree
B : Radius of crown on his basis
leafscatt : Leaf scattering coefficient of PAR

Output:
k_{beam}
$k_{beam+scatt}$
k_{diff}

Equations

$$k_{beam} = 4\frac{\left(1+\frac{a}{b}\sqrt{1-\frac{a^2}{b^2}}\right)}{\sin\sqrt{1-\frac{b^2}{a^2}}} \qquad (16)$$

$$k_{beam+scatt} = k_{beam}\sqrt{1-leafscatt} \qquad (17)$$

$$k_{diff} = 0.719 \ \ (or\ other\ const\ value) \qquad (18)$$

3.3 Beam Light Above The Canopy

The beam irradiance falling on a canopy is different for each position of the canopy. Each layer, which receives a new part of beam irradiance, acts as if it was the top of the canopy with only a lower value for the beam irradiance above the canopy, this is because the outside region of a canopy is under influence of his direct neighbours.

Input :
I_e : Extra-terrestrial Irradiance
sinb : Elevation (eqn 5)
a : 0.72 (constant value: between 0.1[overcast sky] and 0.72 [cloudless sky])
LAD : Cumulative LAD on a particular layer

Local parameters:
k : Extinction of beam irradiance in gap conditions.

Output :
Beam(0)(startlayer)
Beam(0)(above canopy)

Equations:

$$Beam(0)(abovecanopy) = a^m I_e \sin b \qquad (19)$$

With, $m = \frac{P/p_0}{\sin b}$ (20)

for LAD =1 to 40

$$Beam(0)(startlayer) = aBeam(0)(abovecanopy)\exp(-kLAD) \qquad (21)$$

3.4 Diffuse Light Above The Canopy

At this place we try to find a value for the diffuse irradiance above the canopy. This is estimated from the weather conditions.

Input:
P : Atmospheric pressure
P_0 : Atmospheric pressure at sea level
sinb : Elevation (eqn 5)
Beam(0)(startlayer) : Beam irradiance above layer of investigation (eqn 21)
a : 0.72 (constant value : between 0.1[overcast sky] and 0.72 [cloudless sky])
f_a : the proportion of attenuated radiation that reaches the surface as diffuse radiation
m : Optical air mass (eqn 20)
Beam(0)(above canopy) : Beam irradiance above canopy

Output :
Diffuse(0)(startlayer)

Equations:

For startlayer = 1 to 40

$$Diffuse(0)(startlayer) = f_a(1-a^m)Beam(0)(startlayer)\sin b \qquad (22)$$

Next startlayer

and,

$$Diffuse(0) = f_a(1-a^m)Beam(0)(abovecanopy)\sin b \qquad (23)$$

3.5 Reflection of Light

Input:
leafscatt : Leaf scattering coefficient of PAR
k_{beam} : Extinction coefficient of beam irradiance (eqn 16)
Diffuse(0) : Diffuse Irradiance (eqn 23)

Local parameters:
$\text{Refl}_{horizontal}$: Reflection coefficients for beam irradiance on horizontal leaves
ph_{diff} : diffuse photon radiance of the sky

Output :
Refl_{beam}
Refl_{diff}

Equations

$$\text{Refl}_{horizontal} = \frac{1-\sqrt{1-leafscatt}}{1+\sqrt{1-leafscatt}} \qquad (24)$$

$$Refl_{beam} = 1 - \exp\left(\frac{2Refl_{horizontal}\cdot k_{beam}}{1+k_{beam}}\right) \qquad (25)$$

$$Refl_{diff} = \frac{1}{Diffuse(0)}\int_{a=0}^{\frac{p}{2}} ph_{diff}\cdot Refl_{beam}\,da \qquad (26)$$

With $ph_{diff} = \dfrac{Diffuse(0)}{2p}$ (27)

At this place we can continue with the section 3 itself.

Input:
k_{beam} : Extinction of the beam irradiance (eqn 16)
k_{diff} : Extinction of the diffuse irradiance (eqn 18)
$k_{beam+scatt}$: Extinction of the beam(+scatt) irradiance (eqn 17)
leafscatt : Leaf scattering coefficient of PAR
$Refl_{beam}$: Reflection coefficient for beam irradiance (eqn 25)
$Refl_{diff}$: Reflection coefficient for diffuse irradiance (eqn 26)
Beam(0)(startlayer) : Beam irradiance above the layer where the individual beam reaches the canopy (eqn 21)
Diffuse(0)(startlayer) : Diffuse irradiance above the canopy (eqn 22)
LAI(startlayer)(layer) : LAI of all leaves receiving beam irradiance from Beam(0) in the layer (eqn 15)
LAI (layer) : LAI of the layer (eqn 12)

Local parameters:
$Beam_{withoutscatt}(layer)(startlayer)$: Beam irradiance that falls in on a layer without the provision of leaves that scatter a part of the beam irradiance.
BEAM : Matrix of the different beam irradiance values on each layer (each value crossed a different number of layers).
Beam(x)(y), Diffuse(x)(y) : *x*: layers passed to get on the layer we are measuring; *y*: startlayer.
DIFFUSE : matrix of the different diffuse irradiance values on each layer (eqn 6)

Output:
total(layer)
Beam(layer)
Diffuse(layer)

Equations:

For layer = 1 to 40
For startlayer = 1 to 40

$$Beam_{withoutscatt}(layer)(startlayer) = (1 - Refl_{beam})k_{beam}Beam(0)(startlayer) \cdot \exp(-k_{beam}LAI(layer)) \quad (28)$$

$$Beam_{scatt}(layer) = (1 - Refl_{beam+scatt} \cdot LAI(layer)) \cdot \exp(-k_{beam+scatt} \cdot LAI(layer)) \quad (29)$$

Next startlayer
Next layer

Put all the $Beam_{scatt}(layer)(startlayer)$ in a matrix in accordance with its layer/startlayer value, thus;

$$BEAM = \begin{pmatrix} Beam(0)(1) & 0 & 0 & \cdots \\ Beam(1)(1) & Beam(0)(2) & 0 & \cdots \\ Beam(2)(1) & Beam(1)(2) & Beam(0)(3) & \cdots \\ \vdots & \vdots & \vdots & \ddots \end{pmatrix}$$

For all Beam(layer)(startlayer), such that layer = startlayer

$$Beam(layer) = \frac{\sum Beam_{scatt}(startlayer)(layer)LAI(startlayer)(layer)}{LAI(layer)} \quad (30)$$

For layer = 1 to 40
For startlayer =1 to 40

$$Diffuse(layer) = (1 - Refl_{diff})k_{diff} \cdot Diffuse(0)(startlayer) \cdot \exp(-k_{diff} \cdot LAI(layer)) \quad (31)$$

$$Total(layer) = Beam(layer) + Diffuse(layer) \quad (32)$$

Next startlayer
Next layer

Put all the Diffuse(layer)(startlayer) in a matrix in accordance with its layer/startlayer value

$$DIFFUSE = \begin{pmatrix} Diffuse(0)(1) & 0 & 0 & \cdots \\ Diffuse(1)(1) & Diffuse(0)(2) & 0 & \cdots \\ Diffuse(2)(1) & Diffuse(1)(2) & Diffuse(0)(3) & \cdots \\ \vdots & \vdots & \vdots & \ddots \end{pmatrix}$$

For all Beam(layer)(startlayer), such that layer = startlayer

$$Diffuse(layer) = \frac{\sum Diffuse_{scatt}(startlayer)(layer) \cdot LAI(startlayer)(layer)}{LAI(layer)} \quad (33)$$

bring Total(layer) in I on place (X . . . . . .)
bring Beam(layer) in I on place (. . .X . . .)
bring Diffuse(layer) I on place (. . . . . . X)

4 Matrix Derivation

In this section we consider all the measurements of total, diffuse and beam irradiation from the previous section. We have given the command to put the values into a matrix that has a (40 X 3) form.

Input:
Total(layer) : The total irradiance in each layer
Beam(layer) : Beam irradiance in each layer
Diffuse(layer) : Diffuse irradiance in each layer

Local parameters :
I : Matrix with the layer per layer measured values of total, beam & diffuse irradiance

Output:
Total
Beam
Diffuse

Equations:

The initial form of the matrix is given by

$$I = \begin{pmatrix} Total(0) & Beam(0) & Diffuse(0) \\ 0 & 0 & 0 \\ \vdots & \vdots & \vdots \end{pmatrix}$$

After one measurement we get the following matrix

$$I = \begin{pmatrix} Total(0) & Beam(0) & Diffuse(0) \\ Total(1) & Beam(1) & Diffuse(1) \\ 0 & 0 & 0 \\ \vdots & \vdots & \vdots \end{pmatrix}$$

After the 40th measurement we have the full matrix with a value for each irradiance on each layer, the columns can be summed to give totals values.

$$Total = \sum_{layer=1}^{40} Total(layer) \quad (34)$$

$$Beam = \sum_{layer=1}^{40} Beam(layer) \quad (35)$$

$$Diffuse = \sum_{layer=1}^{40} Diffuse(layer) \quad (36)$$

5 Irradiance on each layer

This section estimates the irradiance absorbed by the sunlight and the shaded fraction of the canopy.

Input :
Beam(0)(startlayer) : Beam irradiance above the canopy (eqn 21)
cos α : mean cos leaf angle in each leaf class with uniform leaf angle distribution,
and $\overline{\cos\alpha}$ its vector
sinb : Elevation (eqn 5)
leafscatt : Leaf scattering coefficient for PAR
Diffuse(0)(startlayer) : Diffuse irradiance above the canopy (eqn 22)
$Refl_{diff}$: Reflection coefficient of diffuse irradiance (eqn 26)
k_{diff} : Extinction of the diffuse irradiance (eqn 18)
k_{beam} : Extinction of the beam irradiance (eqn 16)
$Refl_{beam}$: Reflection coefficient of beam irradiance (eqn 25)
$k_{beam+scatt}$: Extinction of the beam irradiance with scattering (eqn 17)
LAD(startlayer) : LAD of the fraction of layer that receives beam irradiance from Beam(0), (eqn 13)
LAD(layer) : LAD of the investigated layer (eqn 11)
LAD : Cumulative LAD on the layer height (eqn 11)

Local parameters:
BeamIrradiance : the beam fraction of absorbed irradiance by sunlit leaves
Diffusefraction : the fraction of absorbed irradiance which came from diffuse irradiance by sunlit leaves
Scatteredfraction : the scattered fraction of the absorbed irradiance by sunlit leaves

Output:
Sun(layer)
Shade(layer)
Total(layer)

Equations:

For each layer
For startlayer = 1 to layer

$$Total(layer)(startlayer) = \left(1 - Refl_{beam}\right) \cdot Beam(0)(startlayer) \cdot \left(1 - \exp(-k_{beam+scatt} \cdot LAD)\right) + \left(1 - Refl_{diff}\right) \cdot Diffuse(0)(startlayer) \cdot \left(1 - \exp(-k_{diff} \cdot LAD)\right) \quad (37)$$

Next startlayer
Next layer

$$Total(layer) = \frac{\sum_{startlayer=1}^{layer} Total(layer)(startlayer) LAD(startlayer)}{LAD} \quad (38)$$

For startlayer =1 to layer

$$Sun(layer) = BeamIrradiance + Diffusefraction + scatteredfraction \quad (39)$$

$$BeamIrradiance = \frac{(1 - leafscatt) \cdot Beam(0)(startlayer) \cdot \overline{\cos \alpha}}{\sin \beta} \quad (40)$$

$$Diffusefraction = Diffuse(0)(startlayer) \cdot (1 - Refl_{diff}) k_{diff} \frac{(1 - \exp(-(k_{diff} + k_{beam}) \cdot LAD))}{k_{diff} + k_{beam}} \quad (41)$$

$$Scatteredfraction = Beam(0)(startlayer) \cdot (1 - Refl_{beam}) \frac{(1 - \exp(-(k_{beam+scatt} + k_{beam}) \cdot LAD)) k_{beam+scatt}}{k_{beam} + k_{beam+scatt}}$$
$$- (1 - leafscatt) \frac{(1 - \exp(-2k_{beam} \cdot LAD))}{2} \quad (42)$$

Next startlayer

$$Sun(layer) = \frac{\sum_{startlayer=1}^{layer} Sun(layer) \cdot LAD(startlayer)}{LAD(layer)} \quad (43)$$

$$Shade(layer) = Total(layer) - Sun(layer) \quad (44)$$

5.1 Sun/shade leaf area

We divide the leaves in a sun and a shade fraction. We can get a distribution from the LAI(layer)

Input:
LAI(layer) : LAI from total leaves in each layer (eqn 12)
kbeam : Beam extinction coefficient (eqn 16)
LAI_{cum}(layer) : Cumulative LAD above the layer examined

Output :
LAI_{sun}(layer)
LAI_{shade}(layer)

Equations:

For layer = 1 to 40

$$LAI_{sun}(layer) = \exp(-k_{beam} \cdot LAI_{cum}(layer)) \cdot LAI(layer) \quad (45)$$

$$LAI_{shade}(layer) = [1 - \exp(-k_{beam} \cdot LAI_{cum}(layer))] \cdot LAI(layer) \quad (46)$$

Next layer

6 Canopy Irradiance

In this section the total absorbed irradiance by the whole canopy is measured. To get this result we use the same equation as in eqn 5, except for the LAD, which is the cumulative LAI of the whole canopy instead of the cumulative LAI above a particular layer.

Input:
Beam(0)(startlayer) : Beam irradiance above the canopy (eqn 21)
$\cos\alpha$: mean cos leaf angle in each leafclass with uniform leaf angle distribution
sinb : Elevation (eqn 5)
leafscatt : Leaf scattering coefficient for PAR
Diffuse(0)(startlayer) : Diffuse irradiance above the canopy (eqn 22)
$Refl_{diff}$: Reflection coefficient of diffuse irradiance (eqn 26)
k_{diff} : Extinction of the diffuse irradiance (eqn 18)
k_{beam} : Extinction of the beam irradiance (eqn 16)
$Refl_{beam}$: Reflection coefficient of beam irradiance (eqn 25)
$k_{beam+scatt}$: Extinction of the beam irradiance with scattering (eqn 17)
LAI_{canopy} : LAI on the canopy
LAI(startlayer) : LAI of all leaves receiving beam irradiance from Beam(startlayer) (eqn 14)

Local parameters:
BeamIrradiance : the beam fraction of absorbed irradiance by sunlit leaves
Diffusefraction : the fraction of absorbed irradiance which came from diffuse irradiance by sunlit leaves
Scatteredfraction : the scattered fraction of the absorbed irradiance by sunlit leaves

Output:
$Total_{canopy}$
Sun_{canopy}
$Shade_{canopy}$

Equations:

For startlayer = 1 to 40

$$Total_{canopy}(startlayer) = (1 - Refl_{beam}) \cdot Beam(0)(startlayer) \cdot \left(1 - \exp\left(-k_{beam+scatt} \cdot LAI_{canopy}\right)\right) + (1 - Refl_{diff})Diffuse(0)(startlayer) \cdot \left(1 - \exp\left(-k_{diff} \cdot LAI_{canopy}\right)\right) \quad (47)$$

Next startlayer

$$Total_{canopy} = \frac{\sum_{startlayer=1}^{40} Total_{canopy}(startlayer) \cdot LAI(startlayer)}{LAI_{canopy}} \quad (48)$$

For startlayer = 1 to 40

$$Sun_{canopy}(startlayer) = BeamIrradiance + diffusefraction + scatteredfraction \quad (49)$$

$$BeamIrradiance = \frac{(1 - leafscatt) \cdot Beam(0)(startlayer) \cdot \overline{\cos\alpha}}{\sin b} \quad (50)$$

$$Diffusefraction = Diffuse(0)(startlayer) \cdot (1 - Refl_{diff}) \cdot k_{diff} \frac{\left(1 - \exp\left(-(k_{diff} + k_{beam}) \cdot LAI_{canopy}\right)\right)}{k_{diff} + k_{beam}} \quad (51)$$

$$Scatteredfraction = Beam(0)(startlayer)(1 - \mathrm{Re}\ fl_{beam}) \cdot \frac{(1 - \exp(-(k_{beam+scatt} + k_{beam})LAI_{canopy})) \cdot k_{beam+scatt}}{k_{beam} + k_{beam+scatt}} - (1 - leafscatt)\frac{(1 - \exp(-2k_{beam} \cdot LAI_{canopy}))}{2} \quad (52)$$

Next startlayer

$$Sun_{canopy} = \frac{\sum_{startlayer=1}^{40} Sun_{canopy}(startlayer) \cdot LAI(startlayer)}{LAI_{canopy}} \quad (53)$$

$$Shade_{canopy} = Total_{canopy} - Sun_{canopy} \quad (54)$$

Growth Model: Simulation of Bole for Log-sections - Stem geometry

Gaby Deckmyn (UIA)

Tim Randle (FR)

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The stand growth model (WP7) needs to simulate the stem discs within the bole of trees, which can then be sub-divided into 2.5-m logs in order to link with the BRE M3 model. Initial results are described in Annex II (Section 2.3.4.1). The working paper described below outlines the main assumptions made, and the mathematics behind the description of the stem sections around a central reference datum line.

Assumptions:

§ Stems growth is in yearly sections (new height growth of each year).
§ Within the yearly growth section diameter and lean are constant
§ Lean is calculated yearly for each sector assuming a new sector will try to grow straight up even though lower sectors are leaning. Lean is a function of stem width and density, wind and openness of the canopy and crown size (derived for only one site)
§ Cross-section of the stem is ellipsoid and linked to lean (longest axis in the direction of the lean).
§ Although the stem is thus not 'smooth', it will not influence calculations and therefore no attempt to smooth between the sections is made.

Lean

The angle of each section and the 'trueheight' versus the section 'length' is stored together with the angle to the vertical (lean-angle, α) and the horizontal displacement (Δx) at the top of the section compared to a vertical stem, as well as the lean orientation (N-S)

Cross-section

The ratio of the longer to the shorter axis (a/b) is calculated in function of (to start with) lean.
Radii are not stored throughout since they are only important for the BRE output.
Since the volume must be more precise the ellipsoid needs to be at straight angles to the lean axis of the section (we must beware of creating volume out of nothing).

Logs

Logs are 2.5-m in length measured along the length of the stem. The ellipsoid cross-section is in the same direction as the section to avert errors in calculation of the volume.

Instead of having the sections as in the Figure 1, below, with the midpoints above each other, the volume in reality is spread out to get the same axis throughout the middle with overlaps offsetting gaps at the other side.

Figure 1. *Different datum points for each section fail to describe bend in the bole.*

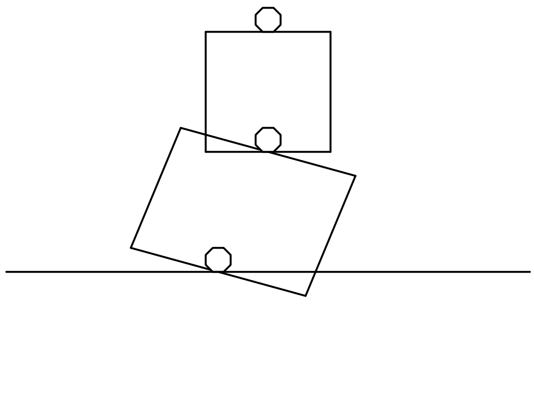
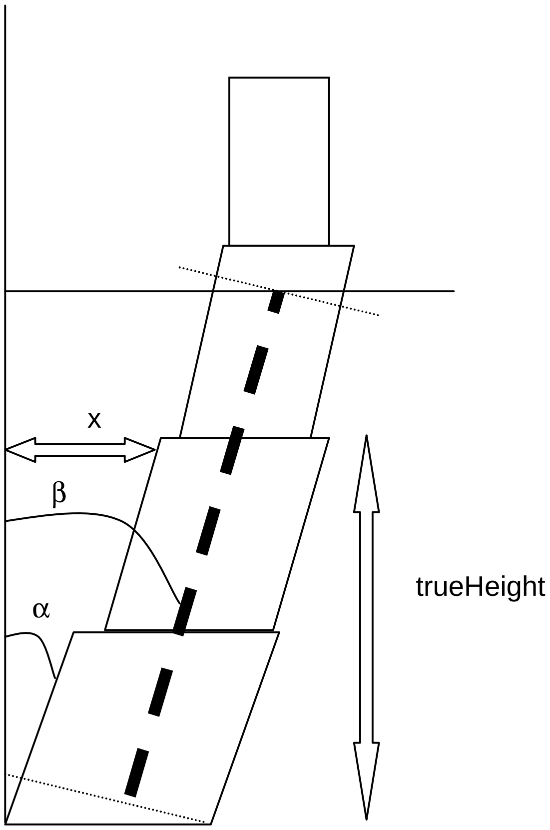


Figure 2. *Sections described about a common datum line.*



▬ ▬ : Axis used for the BRE calculations is from midpoint of bottom of log to midpoint of top of log.

The log-length is approximately 2.5-m (not equal to height of 2.5-m), since the 2.5-m is measured against the mean angle direction of the tree.

Calculations:

1. Calculate the height at which the tree is chopped (log length of 2.5-m)
   From total true height and total displacement, calculate stem lean as

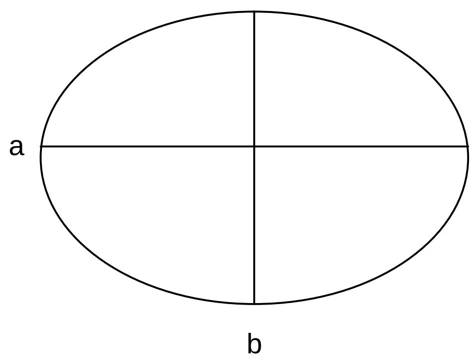
   $\cos(\beta)= \text{trueHeight}/\sqrt{(\text{xtot}^2+\text{trueHeight}^2)}$

2. Now the true height at which the logs are cut is every $2.5\text{m}\cdot\cos(\beta)$

3. But because of loss by cutting the tree at an angle to the soil surface, subtract the 'lost' height;

   Lostheight=diameter at soil$\cdot\sin(\beta)/2\cdot\cos(\beta)$. The volume of the stump is ignored.

Figure 3. *Major and minor axis of an ellipsoid*



Calculations for the cross-section

1. Ellipse with short axis b, long axis a (figure 3)
   Assume the model gives us a/b
   e is the distance to focal point from midpoint

   $\xi=e/a=\sqrt{(a^2-b^2/a)}$

   radius, r from ellipse in function of angle to long axis:

   $r = \sqrt{(b^2/(1-\xi^2\cos^2(\lambda)))}$

2. Change the point to which the radius is described: This point will move along the long axis (over a distance Δmidpoint), depending on the angle between the log axis and the section axis (δ). But also the cross-section is not at straight angles to the section, so the cross-section BRE needs described is at an angle to the ellipse that already calculated

3. First calculate the realHeight at which each 10-cm layer cuts through the middle axis of the section. i.e. realHeight at which the log-axis cuts through the slices;

   realHeight=$n\cdot 10cm\cdot\cos(\alpha)+h_0$, displacement of the log-axis is realHeight/$\cos(\alpha)$

   The displacement (distance to the vertical) of the midpoint of the sector at that height is;

   $\Delta x=(\Delta.\text{endsection}-\Delta.\text{ startsection})\cdot(h-h_{start}/h_{end}-h_{start})$

   This gives a triangle with Δh the difference in real height between where the section axis and the log-axis cut through the 10-cm layer. i.e. Δh is the difference between the displacements$\cdot\sin(\alpha)/\cos(\alpha)$.

4. From the realHeight of the section midpoint project the ellipsoid cross-section to the log-angle needed, still calculating from the midpoint. Assuming the start of the angles of the ellipse at 0 on the long axis and away from the lean-angle, then;

   $r'=r\cdot\cos(\delta)$

5. The reference point moves up the long axis of this new ellipsoid over a distance Δmidpoint.

6. We calculate Δmidpoint as follows, in the same triangle as in 3,
   $\Delta\text{midpoint}=\sqrt{((\Delta h^2+\text{ difference between the displacements})^2)}$

Figure 4. *Schematic diagram of disc data-point calculations, adjusting for the real length of the log/*