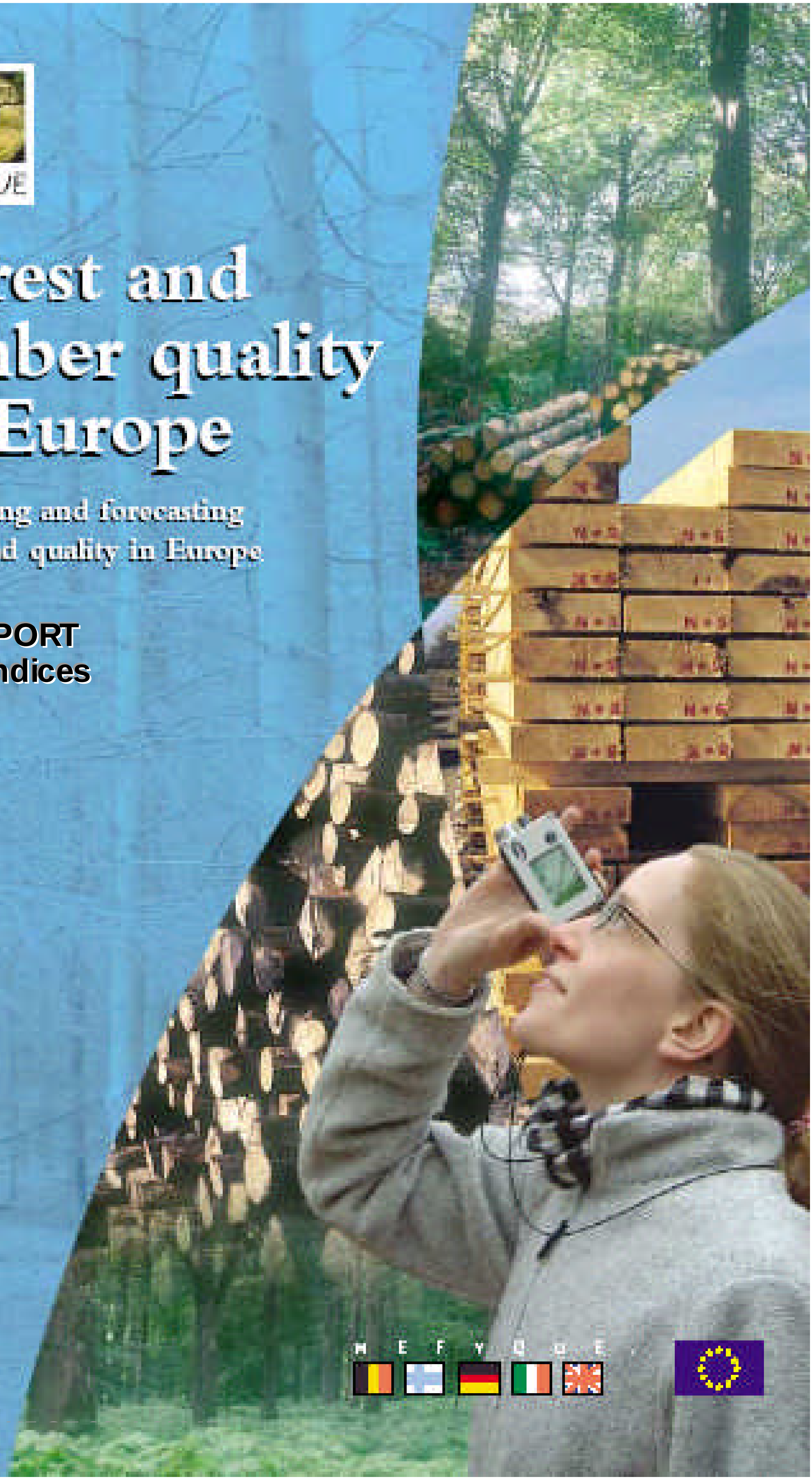
MEFYQUE

Forest and timber quality in Europe

Modelling and forecasting yield and quality in Europe

FINAL REPORT
Appendices



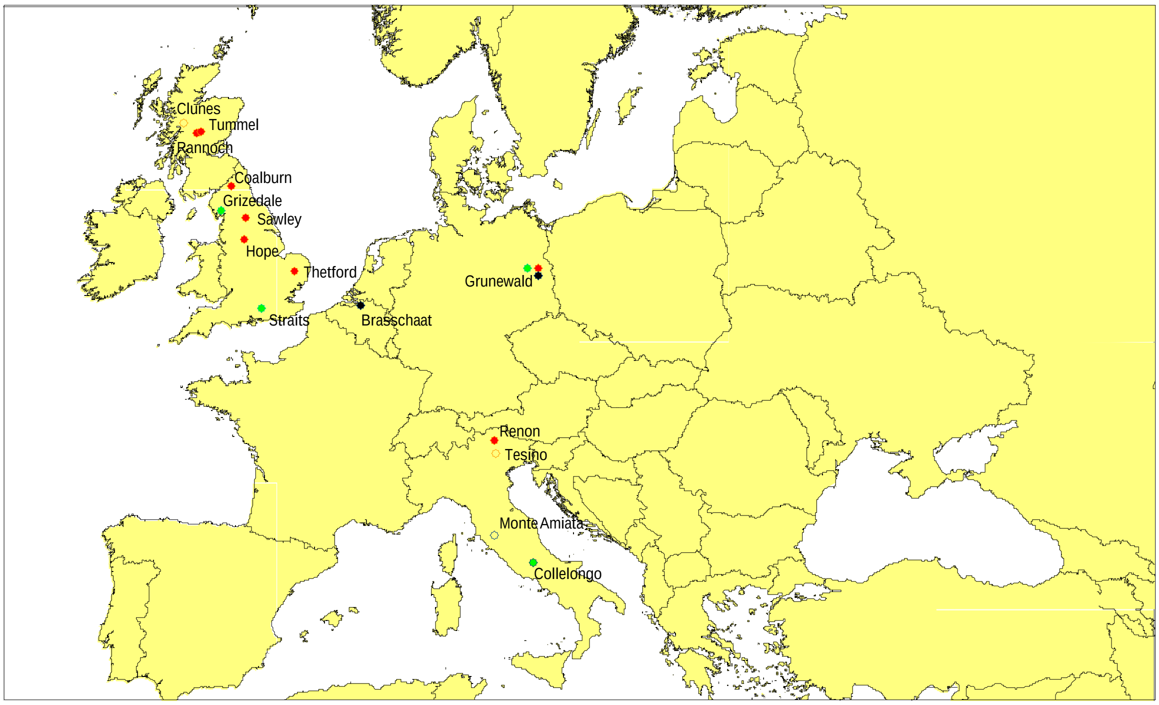
Final Report Appendices

Appendix 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	M.Lindner	European Forest Institute Torikatu 34, FIN-80100 Joensuu FINLAND	+358-(0)13-252.0240	+358-(0)13-124.393	Jari.Liski@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

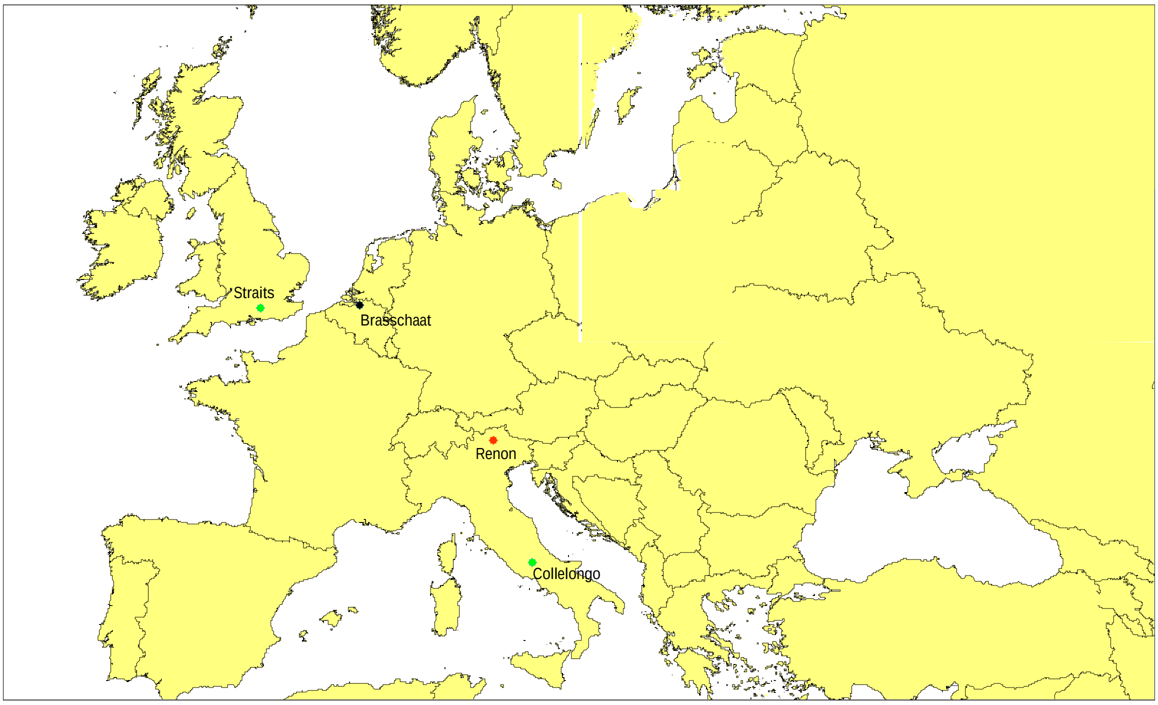
Appendix B. Location map of MEFYQUE primary sites

Appendix B. Location map of MEFYQUE primary sites



- Deciduous plot
- Evergreen plot
- Mixed plot
- Plot not yet established

Appendix C. Location map of MEFYQUE secondary sites.

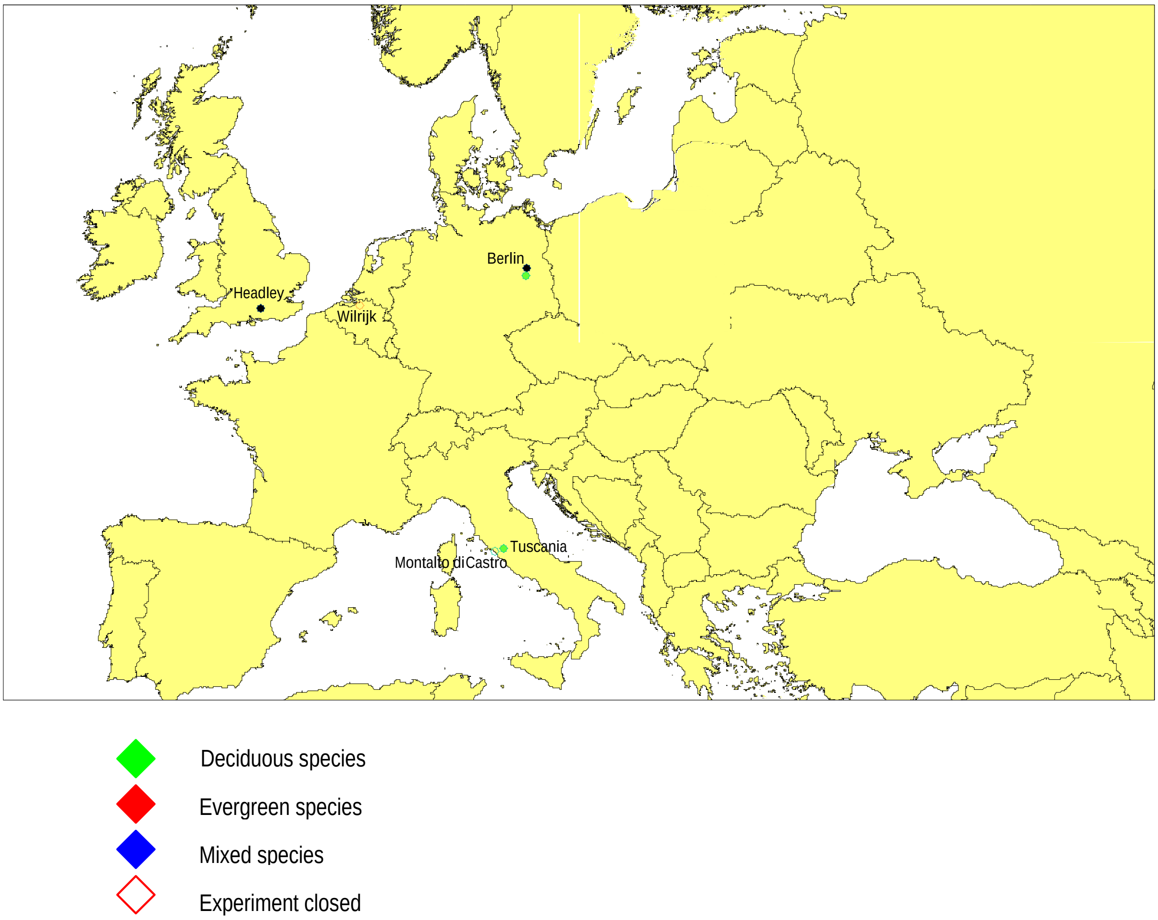


Deciduous stand

Evergreen stand

Mixed stand

Appendix D. Location map of MEFYQUE tertiary sites.


Berlin
Headley
Wilrijk
Tuscania
Montalto di Castro
Deciduous species
Evergreen species
Mixed species
Experiment closed

Appendix E. Sampling protocol**.**

Forest Research
An agency of the Forestry Commission

MEFYQUE PROJECT

SAMPLE PLOT PROTOCOL

Final version

30 January 2002

TABLE OF CONTENTS

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. Pre-establishment information. 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. Sources of information. 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. Sample plot numbers. Plots will be numbered according to the following system:

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

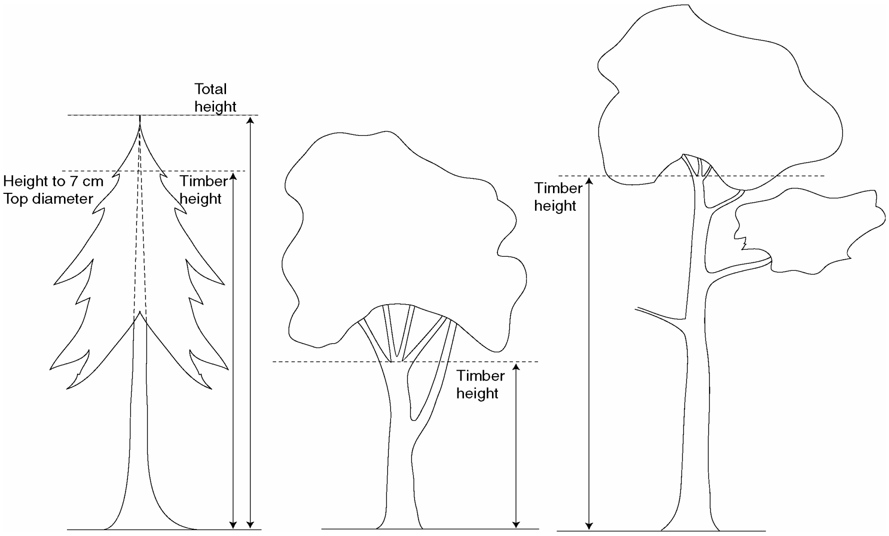
A girthing sheet should also be prepared, listing diameters in ascending order by 0.5 cm class onto a MEFYQUE Form No. 3. Each tree number is then listed against the appropriate diameter class.

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

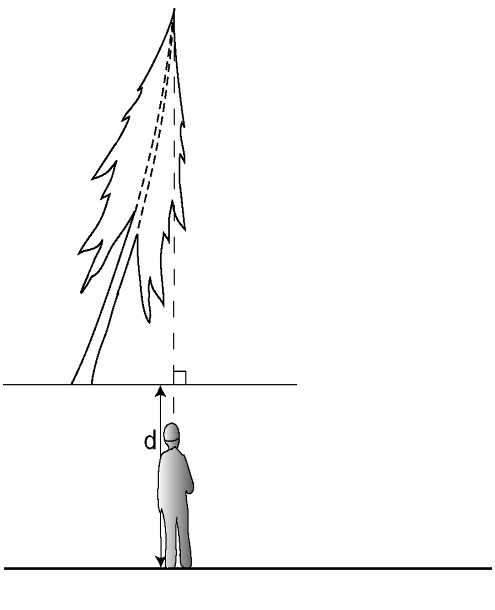
37. All heights will be measured using a hypsometer or clinometer (e.g. Vertex, Blume Leiss, Suunto). Total height is the vertical distance from the base of the tree to its tip, recorded to the nearest 0.1 metre. All height measurements on standing trees in sample plots will be recorded on MEFYQUE Form 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 2.8^{th}

44. Measuring timber height. 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).

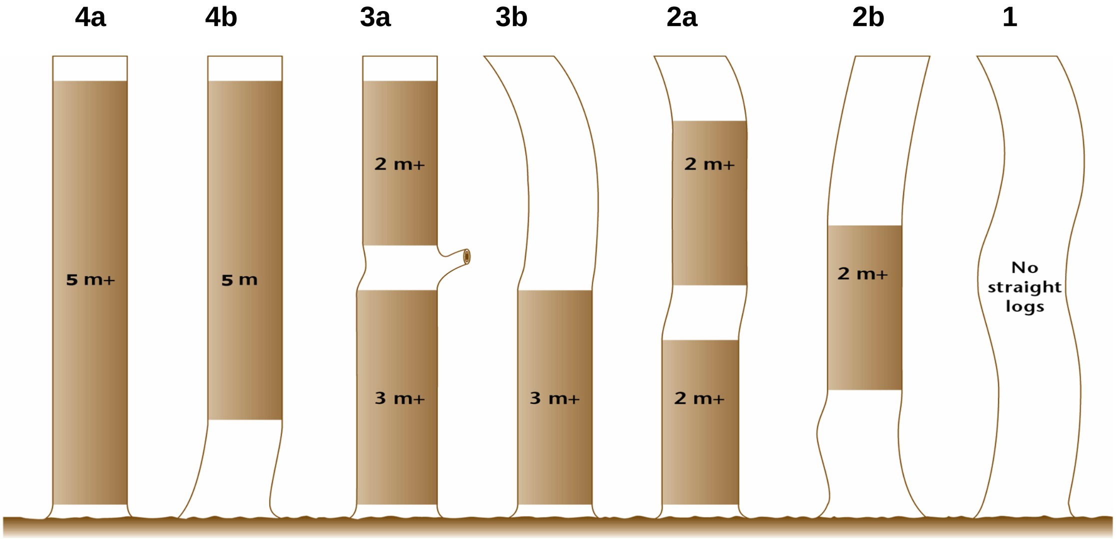
(5) STEM FORM

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.

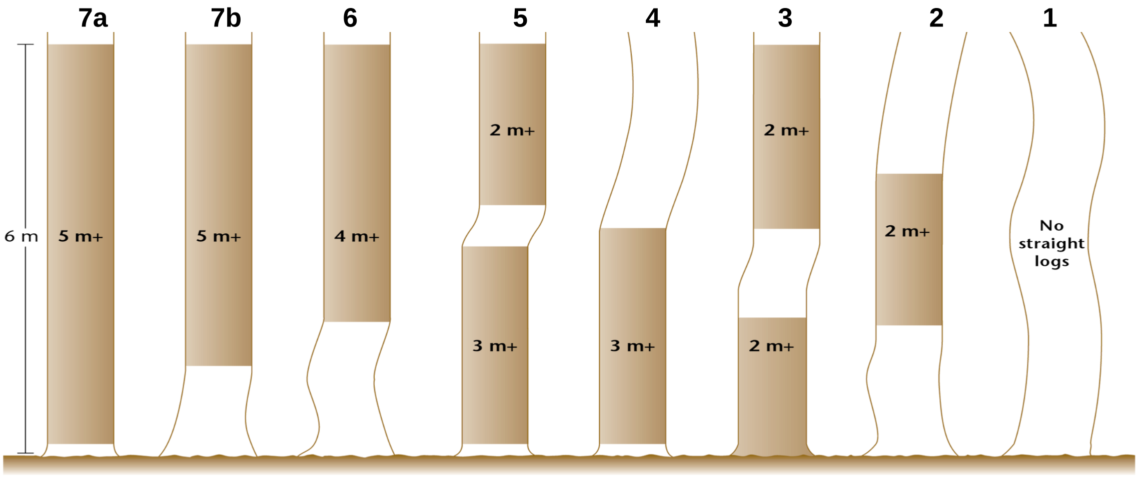
a. *Broadleaves*. For broadleaves a system with 4 classes will be adopted at tree level:

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.

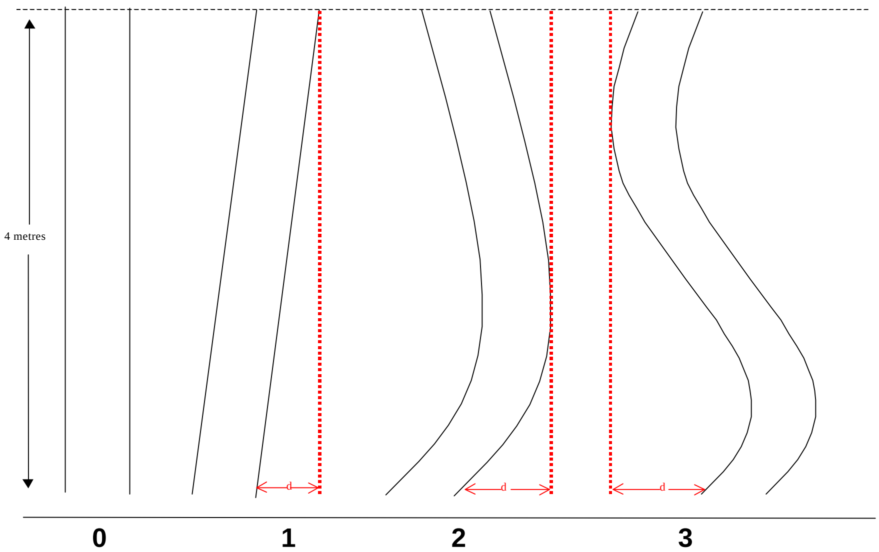


b. *Conifers*. For conifers a system with 7 classes will be adopted at tree level.

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 Defective	The majority of the stem is, or will be, of good millable quality however most of the 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.

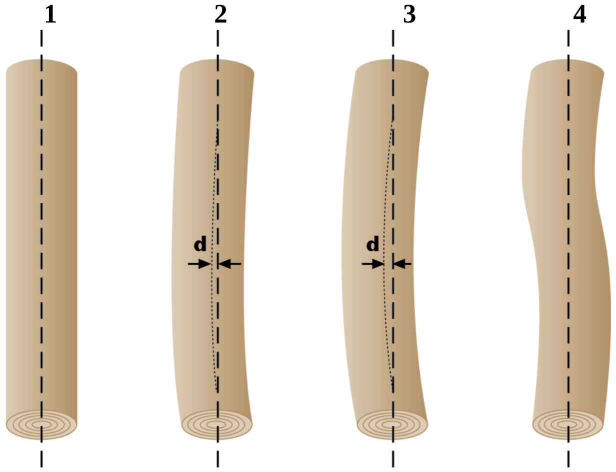
(5) Height of first whole dead branch.

(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.

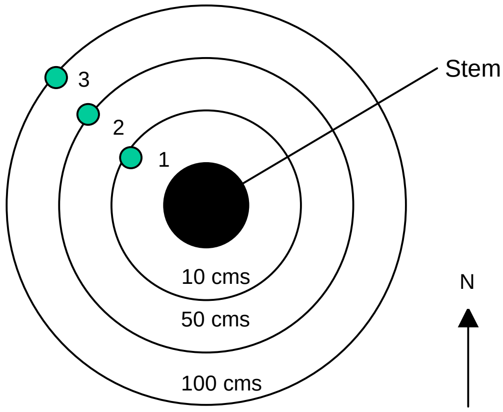
(c) Sampling should be done as hygienically as possible and contamination from pruners, secateurs, industrial gloves or hands should be avoided. Excess water should be shaken from the foliar sample if wet, and before placing in bags.

(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.

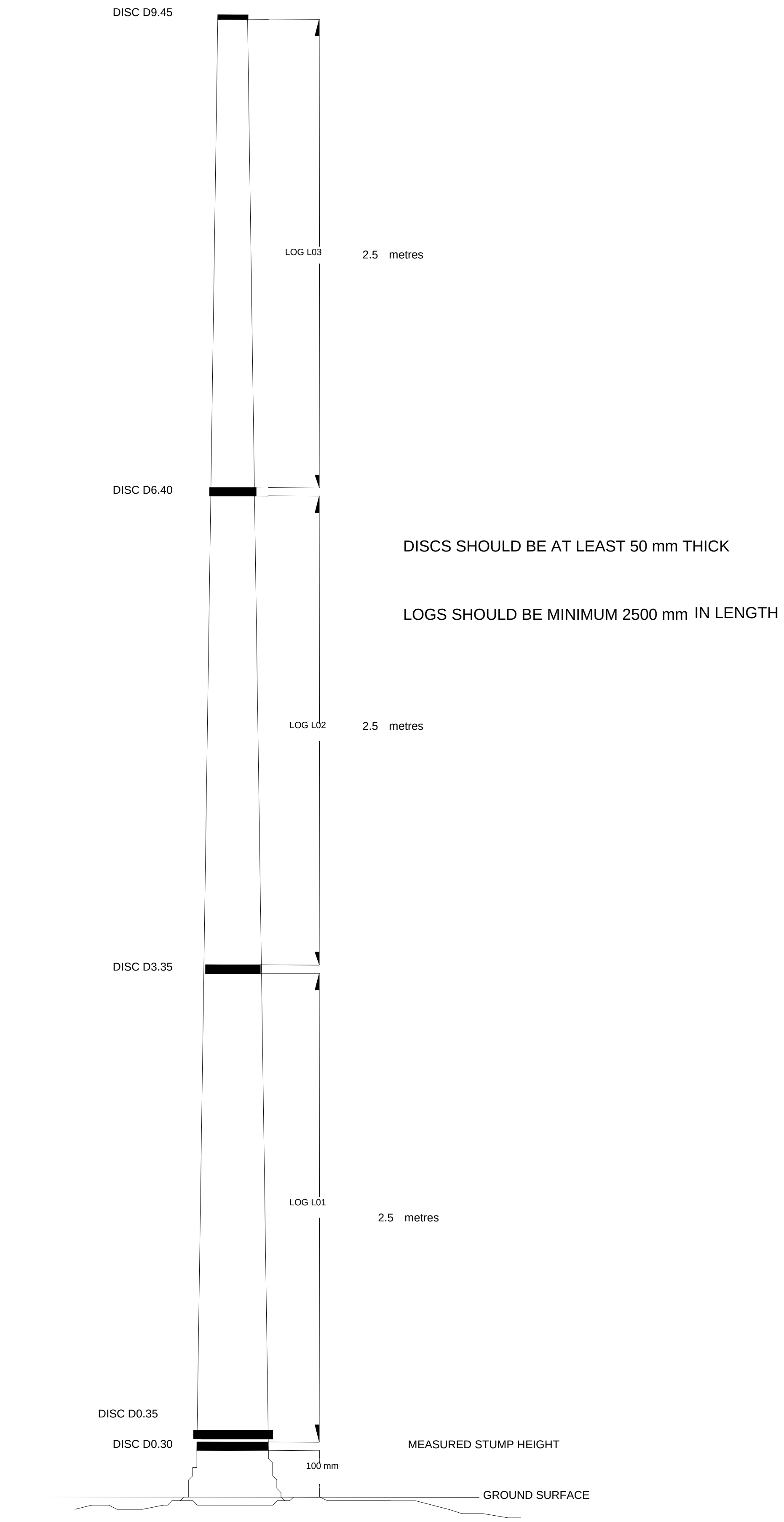
b. Hardwoods. Summer 2002.

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

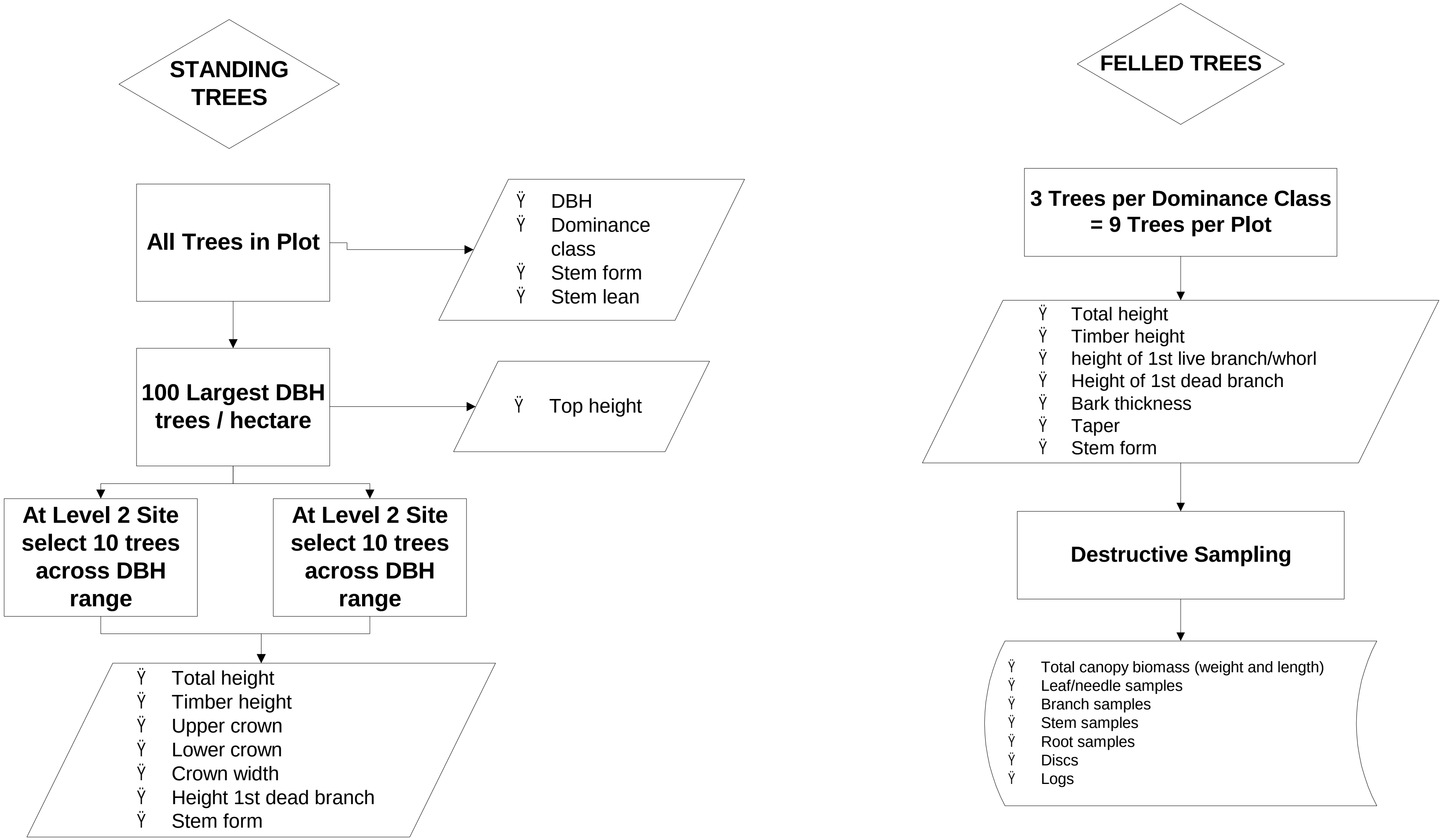
6. *Photographs*

Sample trees prior to felling.

7. *Biomass samples*

Samples bagged and correctly labelled.

Checklist flow diagrams

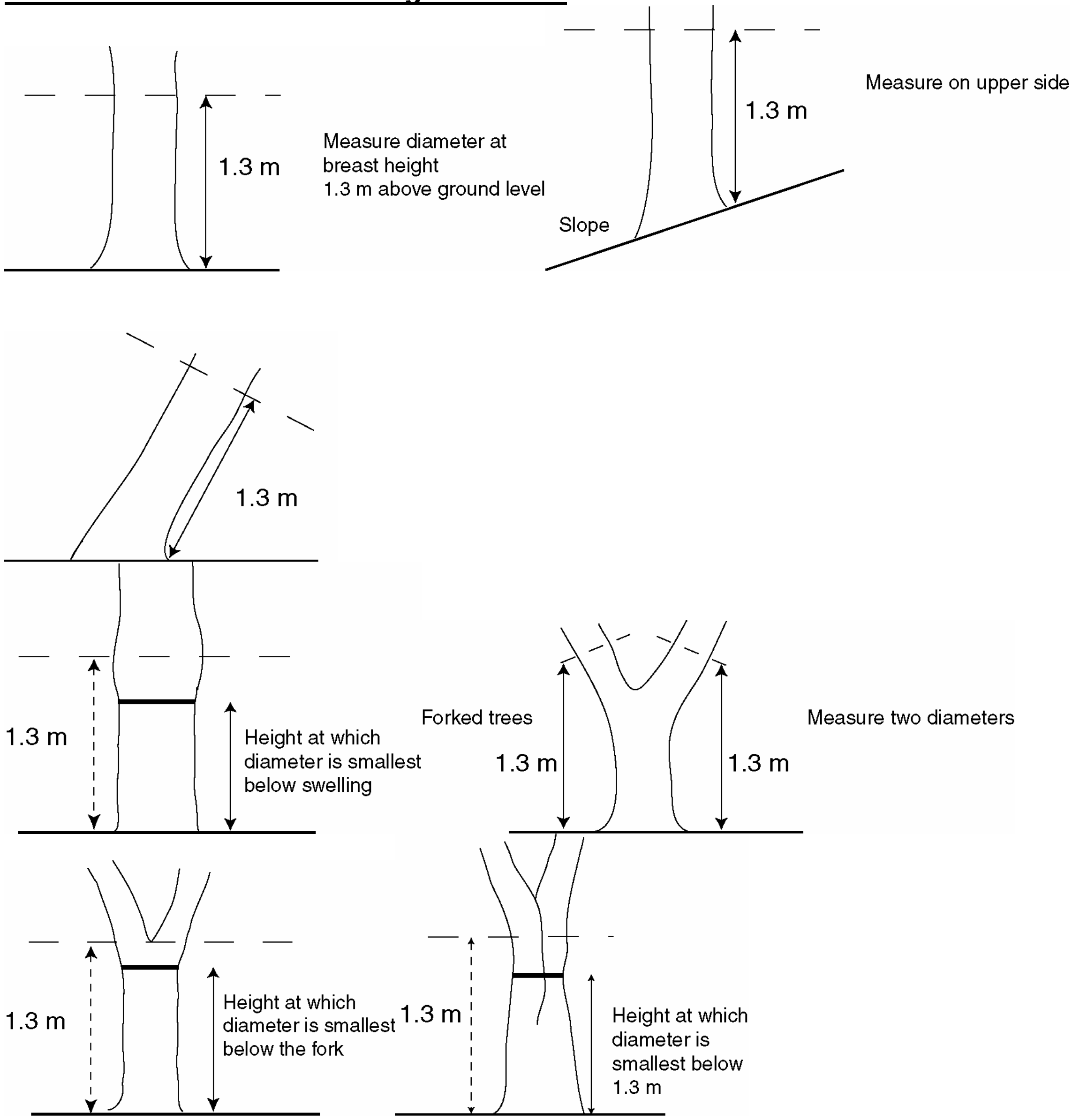


APPENDIX 1. Species Code Numbers.

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.



APPENDIX 3. Field Forms

Form MEFYQUE 1

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:					

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

Form MEFYQUE 4

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

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

Tree Number ……………….

<u>Crown component</u> **L / M / U*** (*delete) <u>Component length</u> ……..…**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**
Wt / whorl kg	**L/ D**	**Branch length (m)**	**Wt / whorl (kg)**	**L/ D**	**Branch length (m)**	**Wt / whorl (kg)**	**Wt / whorl (kg)**

Appendix F. Wood anatomy sampling protocol.

MEFYQUE PROJECT

WOOD ANATOMY AND BIOCHEMICAL PROTOCOL

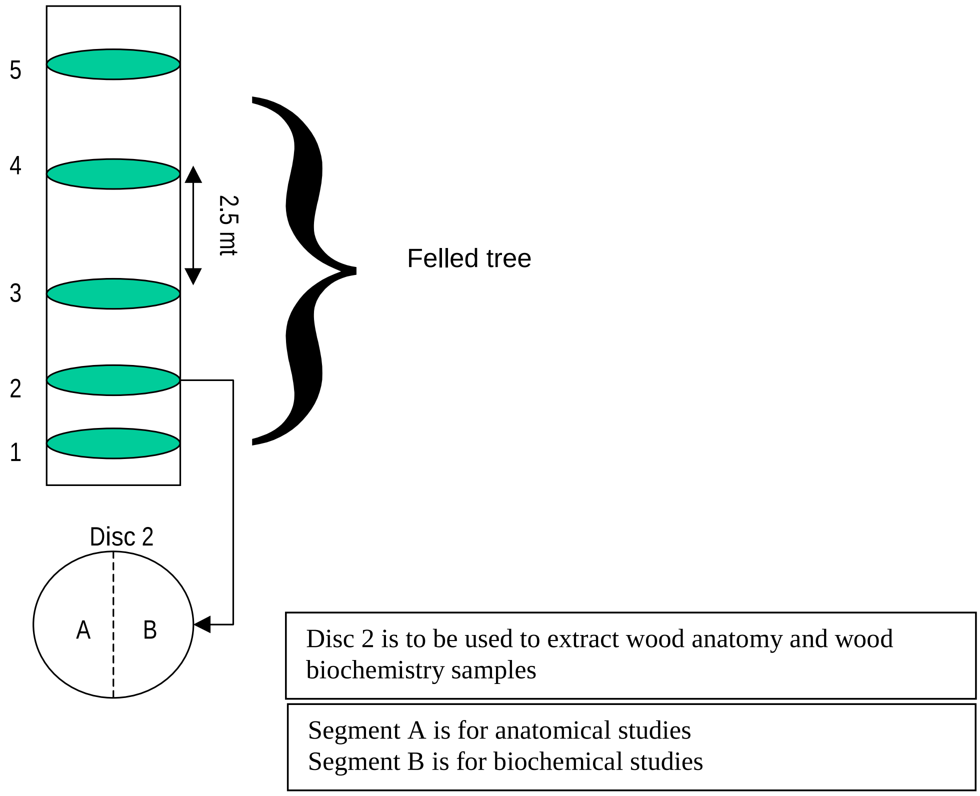
Dieter Overdieck and Daniel Ziche

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.

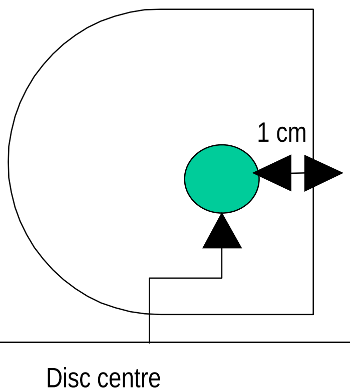


- The disk must be divided into two halves along the North-South axis. The western half-disk (marked as *A* in Figure 1) is for anatomical analyses. It must include all annual rings and the bark.

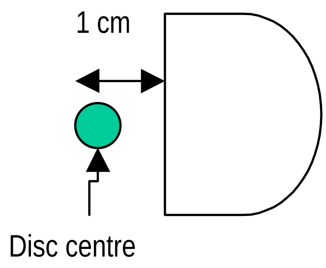
Either the whole disc or the two sub-samples are to be stored immediately in the field at 4 degrees Celsius (using cool box) and sent to TU-Berlin as quickly as possible. Rapid storage is required in particular for the biochemical studies sub-sample, as exposure to ambient conditions will rapidly degrade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



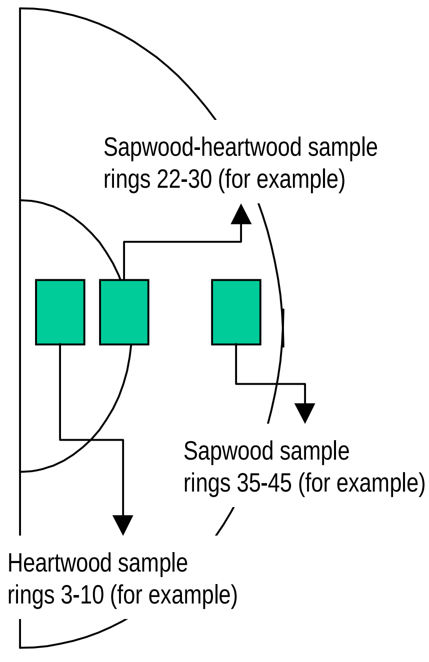
3. Characteristics of sub-sample for biochemical studies. The *B* portion of the disc is the balance of the disc left over after the sampling for wood anatomy material. (see Figure 3). The portion of the disc is to be cut 1 cm away from the centre of the disc, so that the youngest tree ring is available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

Parameter	***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	

[Note. 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

- Storage. Samples are stored in a dry and cool place.
- Cutting. Sections of 15µm thickness are obtained using a sliding microtome. Care is taken to ensure growth rings do not get out of sequence.
- Staining. 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. Measurement priority. 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 G. Wood technology sampling protocol.

MEFYQUE PROJECT

WOOD TECHNOLOGY PROTOCOL

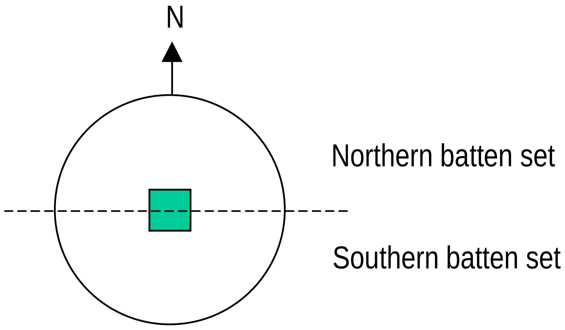
Joris van Acker and Keith Maun

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 H. 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.

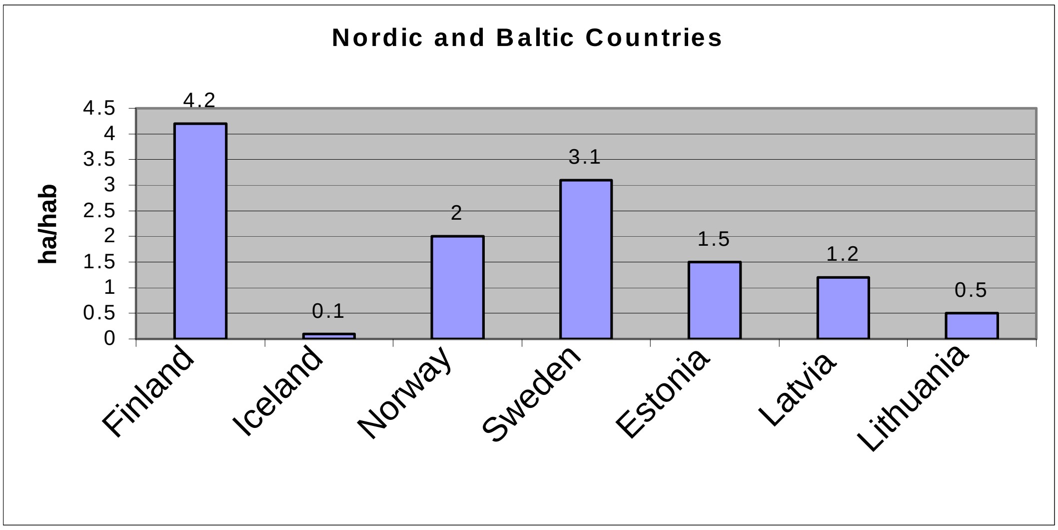


Figure 1: Hectares of forest per capita in Nordic and Baltic countries. (TBFRA 2000 database)

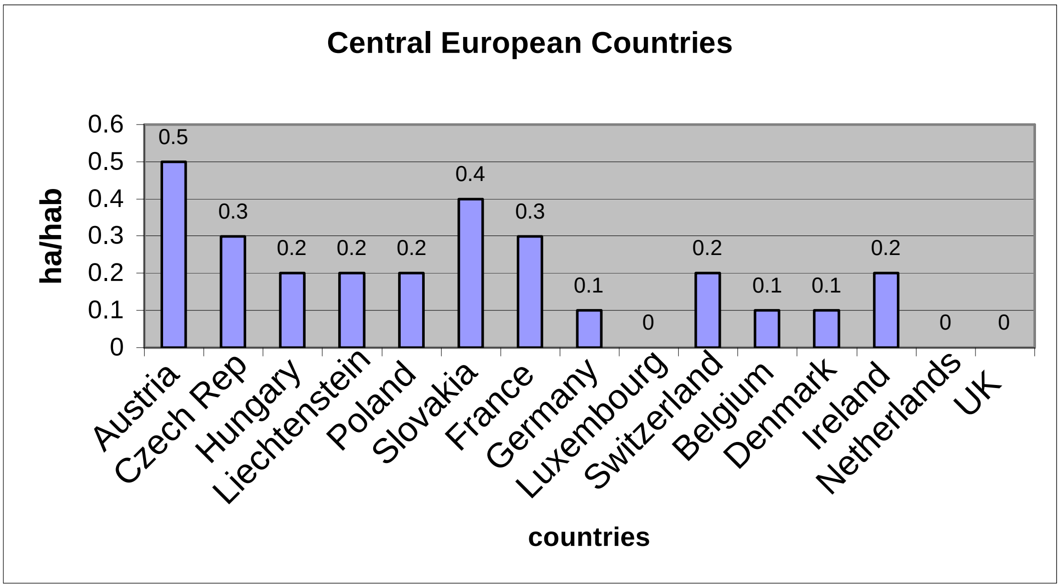


Figure 2: Hectares of forest per capita in Central European countries (TBFRA 2000 database)

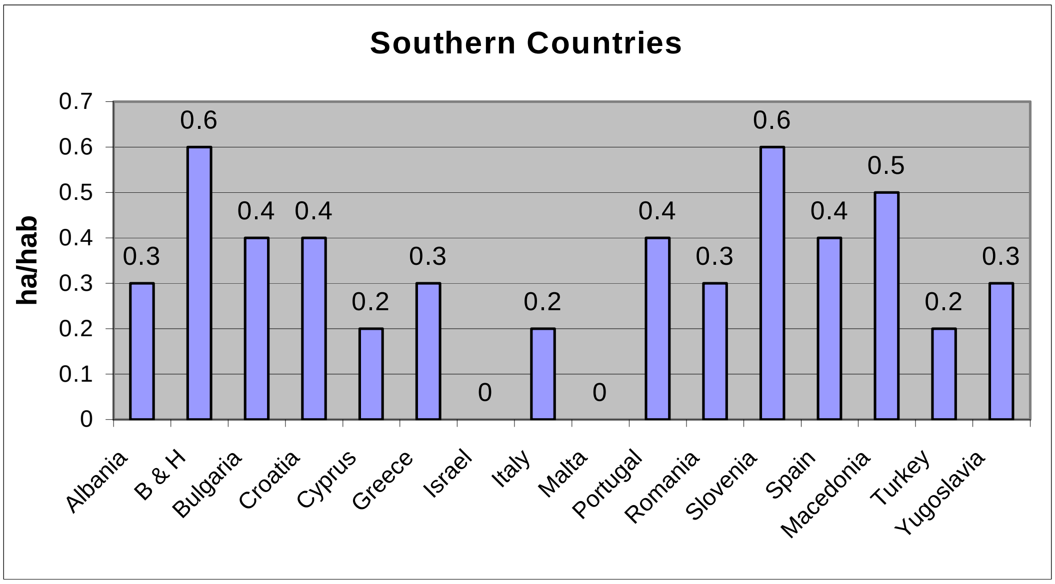


Figure 3: Hectares of forest per capita in Southern European countries. (TBFRA 2000 database)

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)

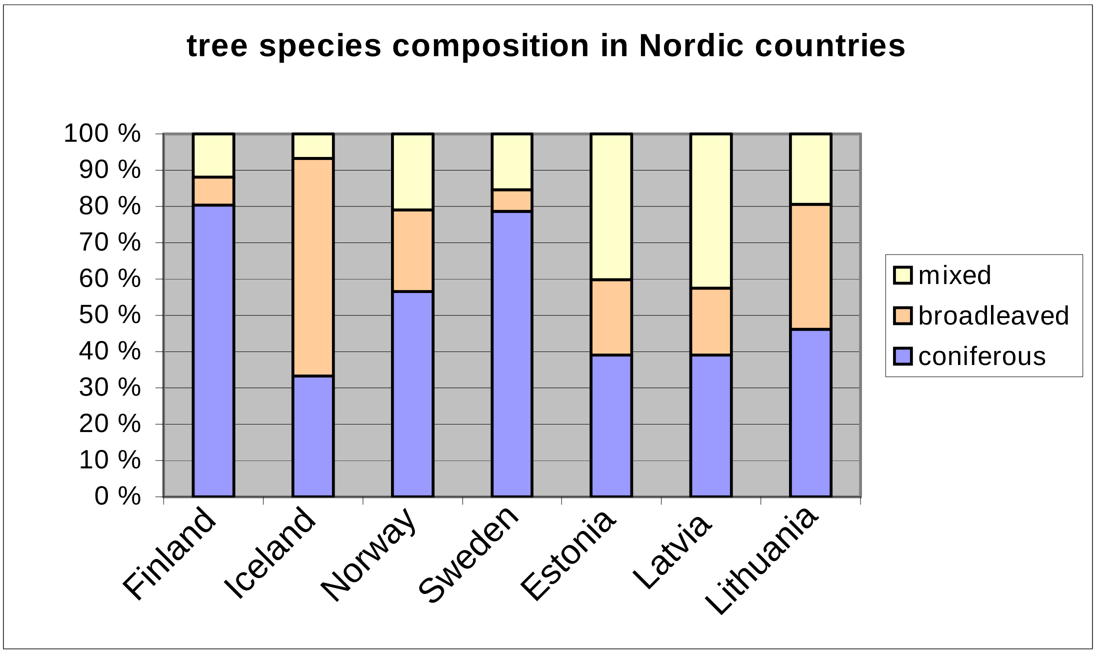


Figure 5: Tree species composition in Central European countries. (TBFRA 2000 database)

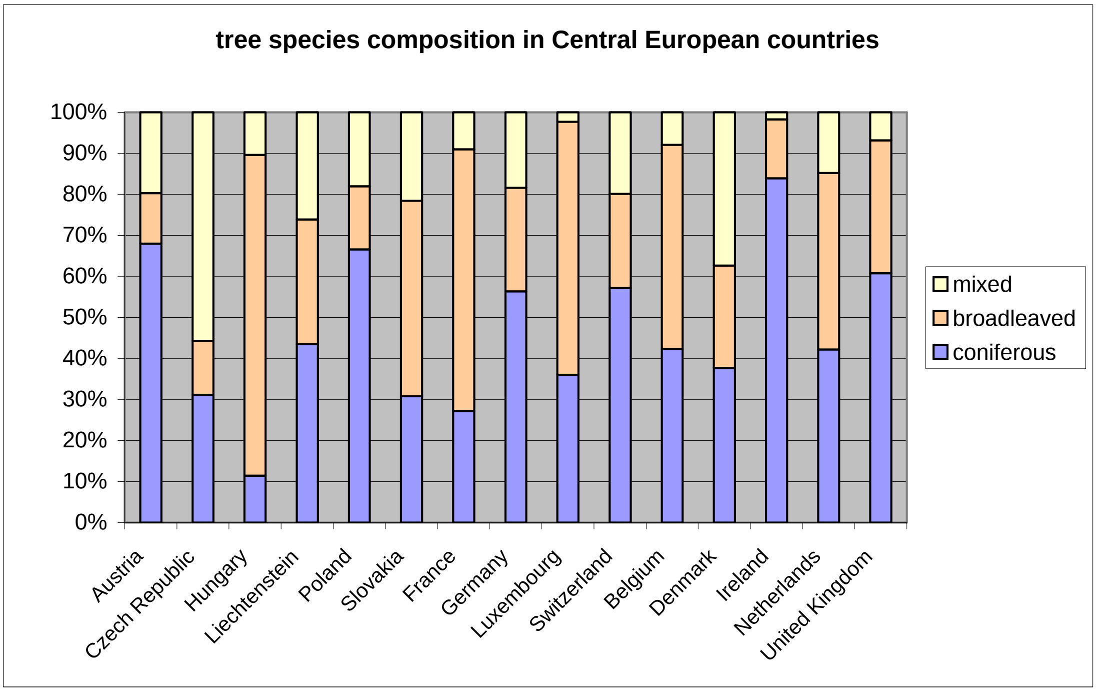
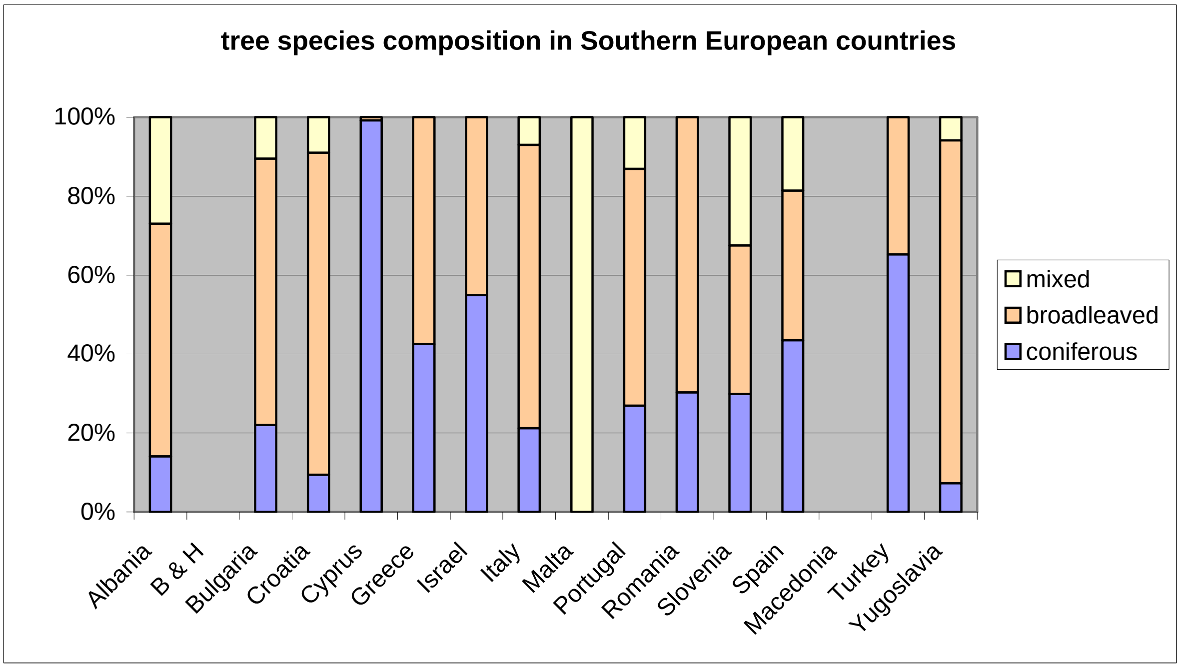


Figure 6: Tree species composition in Southern European countries. (TBFRA 2000 database)



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)

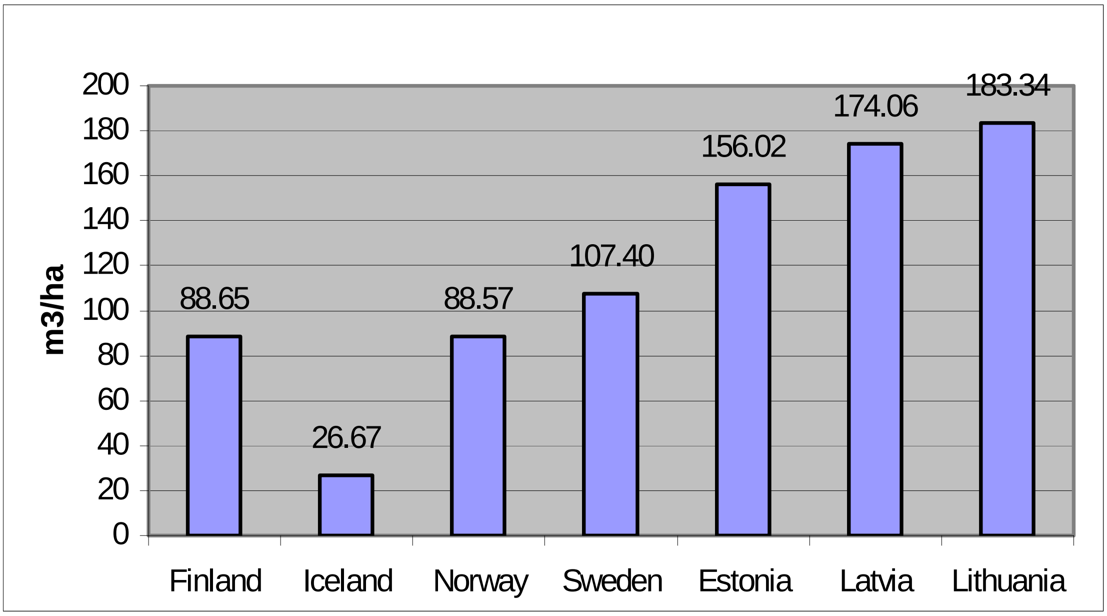


Figure 8: Growing stock in Central European national forests. (TBFRA 2000 database)

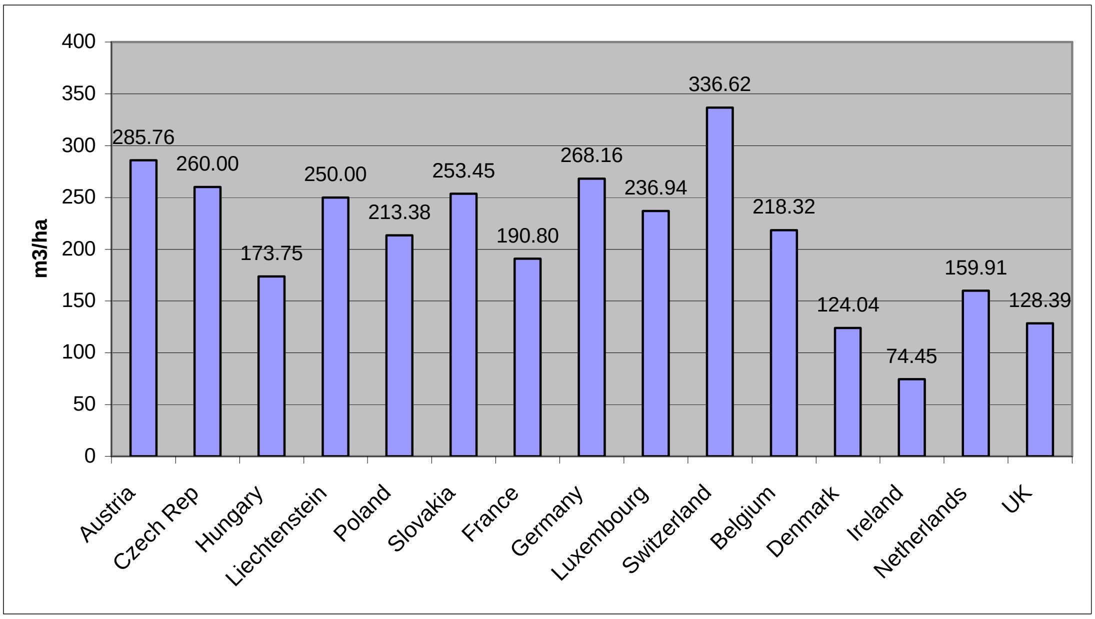
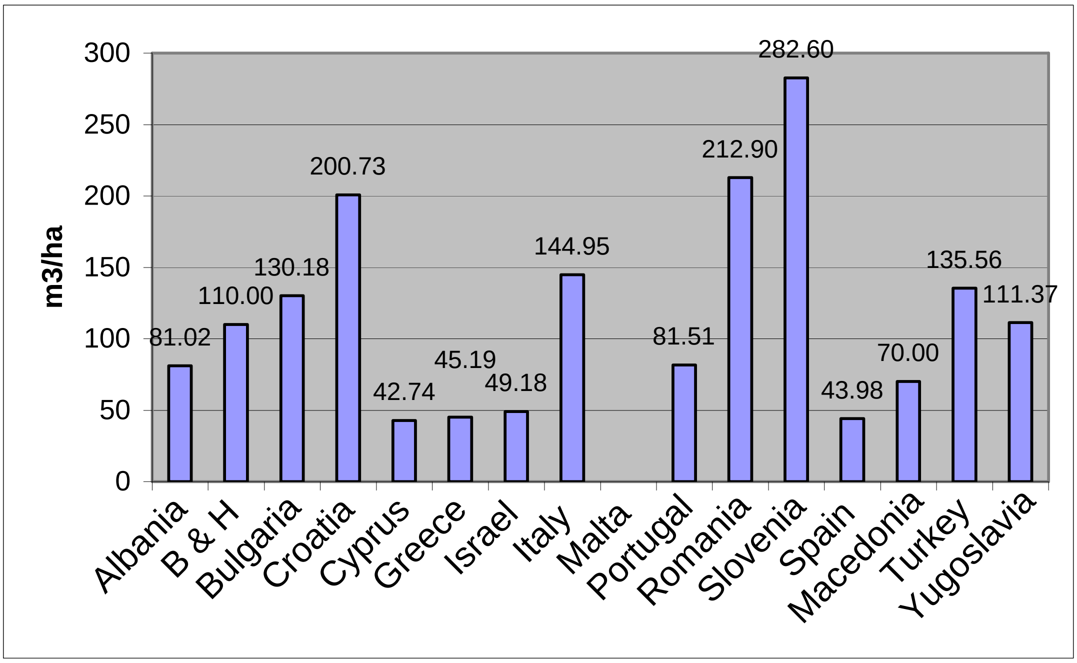


Figure 9: Growing stock in Southern European national forests. (TBFRA 2000 database)



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)

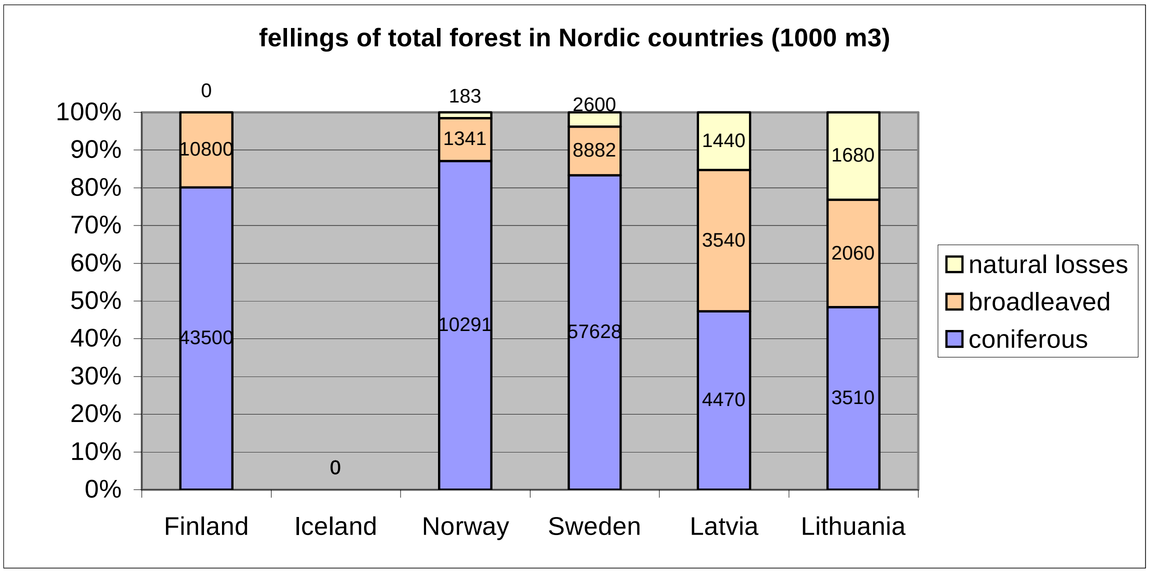


Figure 11: Fellings from total forest in Central European forest. (TBFRA 2000 database)

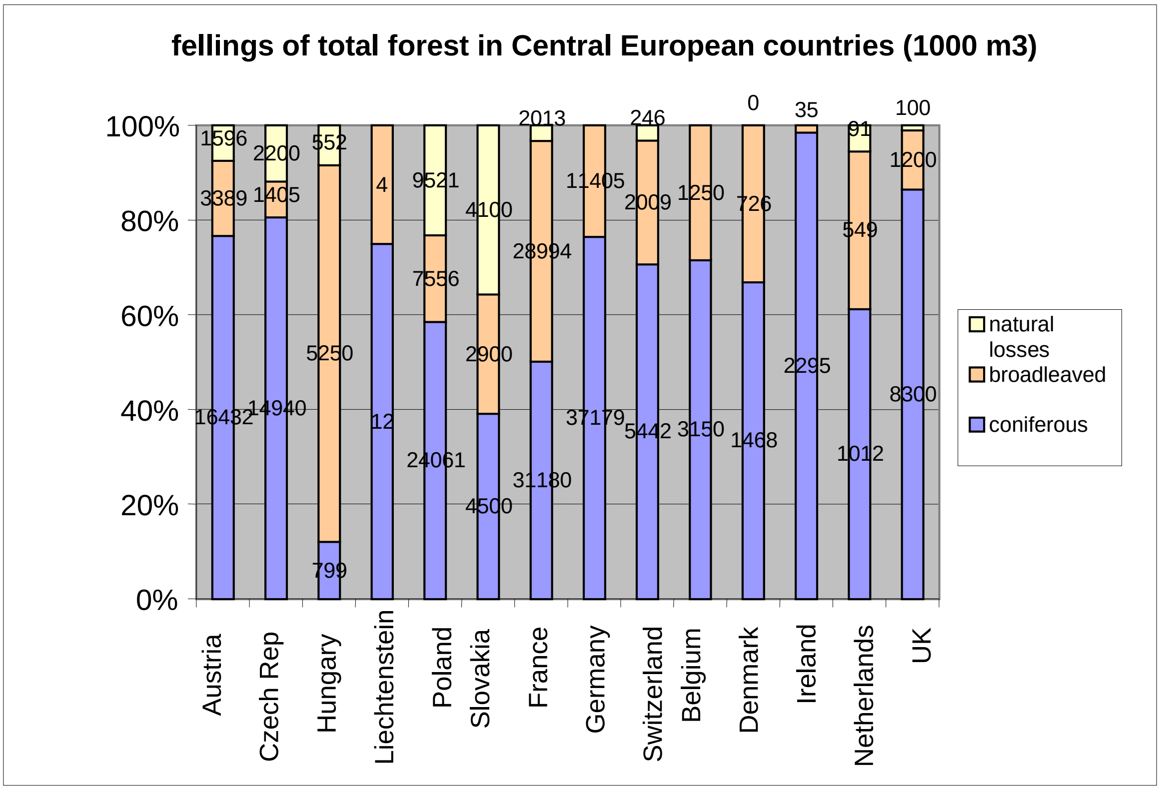


Figure 12: Fellings from total forest in Southern European countries. (TBFRA 2000 database)

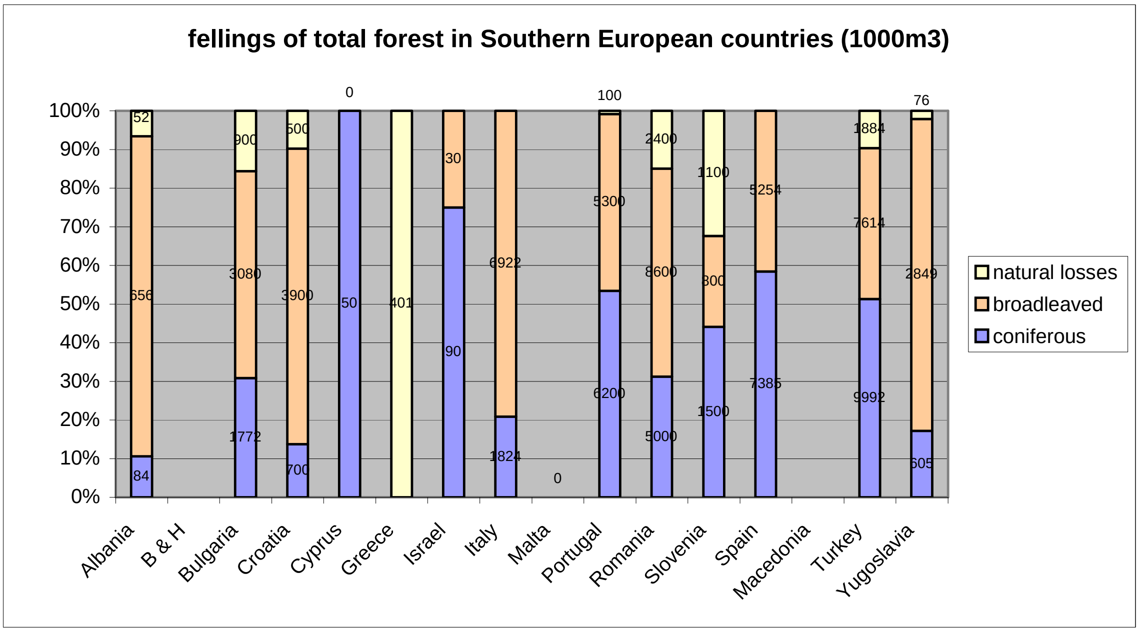


Figure 13: Harvest volume distributed to roundwood from final cuttings, thinnings and not classified (m3 o.b./ha). (Schwaiger and Zimmer, 2000).

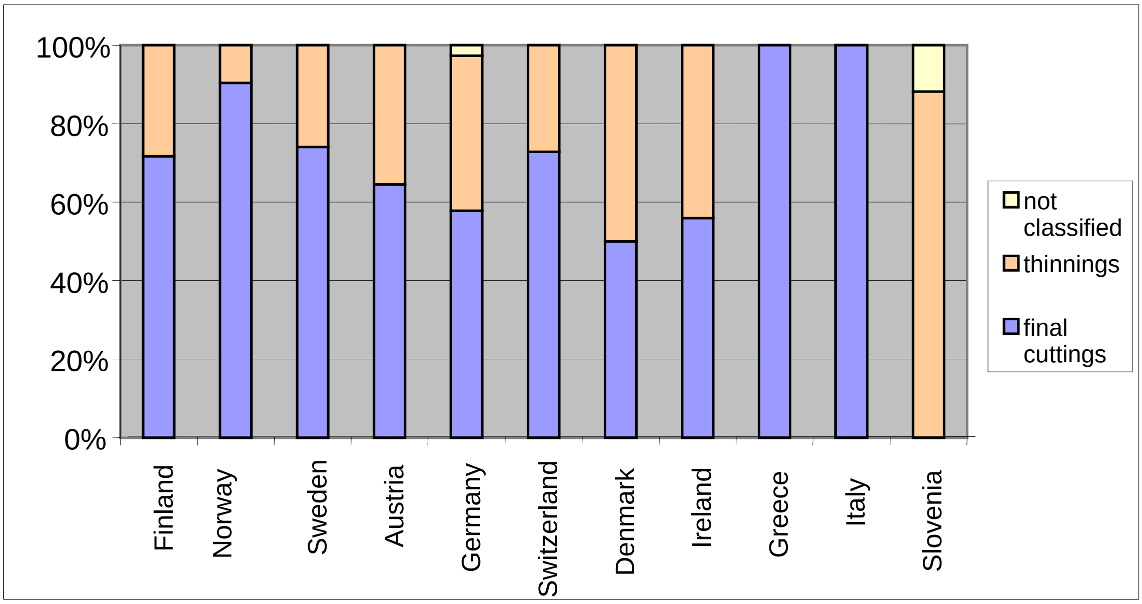


Figure 13 shows the amount of volume coming from different forestry methods in some of the European countries (table 5). Data is approximated, taken from Schwiger and Zimmer report. The most notable thing is that Slovenia processes nearly 90% of the harvested volume from thinnings. By the other side, 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 hauling in European countries, 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.

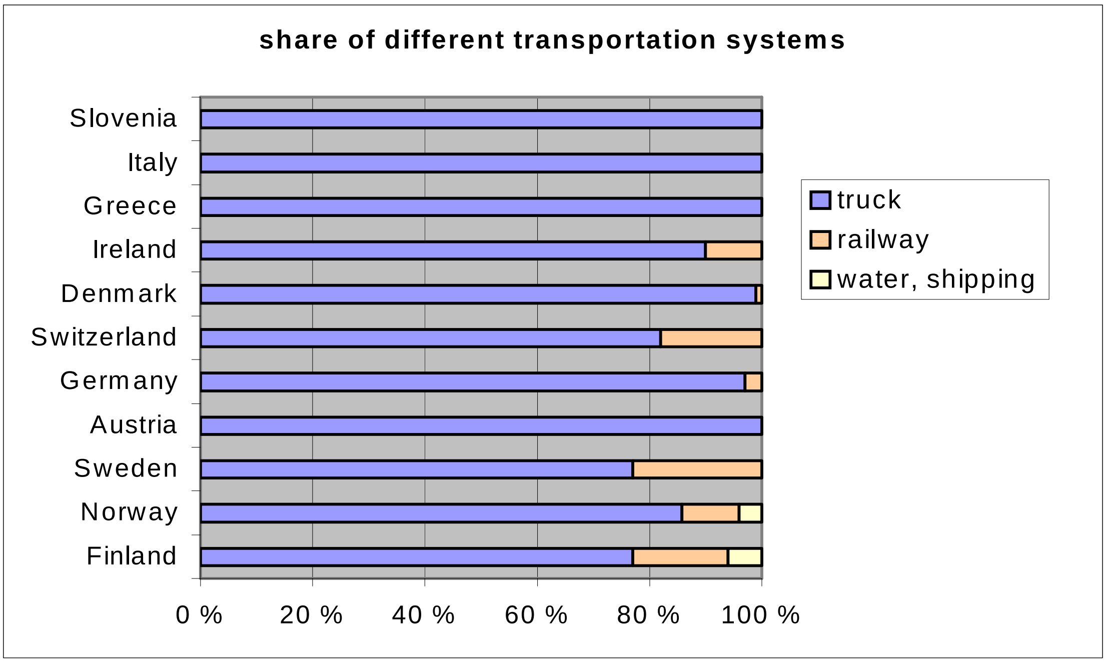
Table 6: Share of hauling processes. (%). (Schwaiger and Zimmer, 2000)

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
				S total emissions and S 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) Scarification: 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 I: Forest ETp

Forest Research
An agency of the Forestry Commission

A COUPLED SOIL-FOREST-ATMOSPHERE DYNAMIC MODEL FOR PREDICTING EVAPO-TRANSPIRATION (ETp) DEMANDS AT THE PLOT AND LANDSCAPE SCALES IN THE UK

by

Samuel P. Evans, Tim Randle and Paul Henshall

Disclaimer.

No responsibility for loss occasions to any person or organisation acting, or refraining from action, as a result of any material in this report can be accepted by the Forestry Commission.

A coupled soil-forest-atmosphere dynamic model for predicting evapo-transpiration (ETp) demands at the plot and landscape scales in the UK. – Final Report

Authors:

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

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 COUPLED SOIL-FOREST-ATMOSPHERE DYNAMIC MODEL FOR PREDICTING EVAPO-TRANSPIRATION (ETp) DEMANDS AT THE PLOT AND LANDSCAPE SCALES IN THE UK

A. INTRODUCTION

Overview.

Evapo-transpiration (ET) is the term used to describe the process of water movement and loss from the soil-plant systems to the atmosphere. Values of ET can be approximated in a number of ways. The most commonly used approach is through the use of predictive numerical equations that summarise the key physical, biophysical and biological processes involved in the movement of water from the soil and through a generic plant. A range of ET equations are available in the literature; it is widely accepted that the Penman-Monteith version provides a comprehensive description of the relevant processes involved. This equation allows the prediction of potential evapo-transpiration (ETp) for a generic plant system that can be refined to describe a specific plant where knowledge of the plant life cycle is known [actual ET (ETa)].

Within the conceptual framework of the Penman-Monteith (P-M) ETp equation, this project has developed a range of process-based modules that describe in greater detail each of the constituent components of the equation. The P-M equation can be broken down into 3 major components:

- the physical, describing relevant climate and soil processes;
- the biophysical, describing plant water uptake and water loss from the canopy surface;
- the biological, describing plant life cycle, water use and loss.

The purpose of developing a process-based version of the P-M equation is:

- to improve the spatial accuracy of ETp predictions, by accounting for local soil and climate conditions;
- to account for relevant biophysical (e.g. soil water availability and uptake, canopy interception) and biological processes (e.g. photosynthesis and stomatal conductance) to allow accurate species-level predictions to be made that account for the individual plant's life cycle as well as site conditions;
- to create feed forward-feedback effects (e.g. soil water content *vs.* stomatal conductance) between relevant modelling components.

Modelling assumptions. The modelling solution conforms to the following requirements:

- operates at the daily time step;
- uses a modularised approach to allow future component replacement/interchange as a means of exploiting future advancements in understanding.
- uses widely available data on site conditions (e.g. weather and soils);
- uses commonly available data on plant ecophysiological characteristics;
- is suitable for predicting ETp under future scenarios of environmental change e.g. climate change effects on weather and CO_2 effects on plant ecophysiology.

B. THE MODEL

The project has contributed to the development of a fully coupled, point-scale, daily time-step soil-vegetation-atmosphere transfer (SVAT) model that allows the prediction of water movement through the soil-plant-atmosphere continuum. The model simulates relevant terrestrial hydrology processes (interception, vertical and lateral soil water movement, runoff, soil and canopy evaporation, and N-sensitive photosynthesis-coupled transpiration) for a tree species of known size growing in a locally defined soil and climate. As an alternative to instrumental meteorological daily data, the model can be coupled with a weather generator that allows the downscaling of summary meteorological data and the generation of climate time series to the daily scale. The model structure is provided at Figure 2 and the system resistance model at Figure 1.

FIGURE 1 . SVAT model structure.

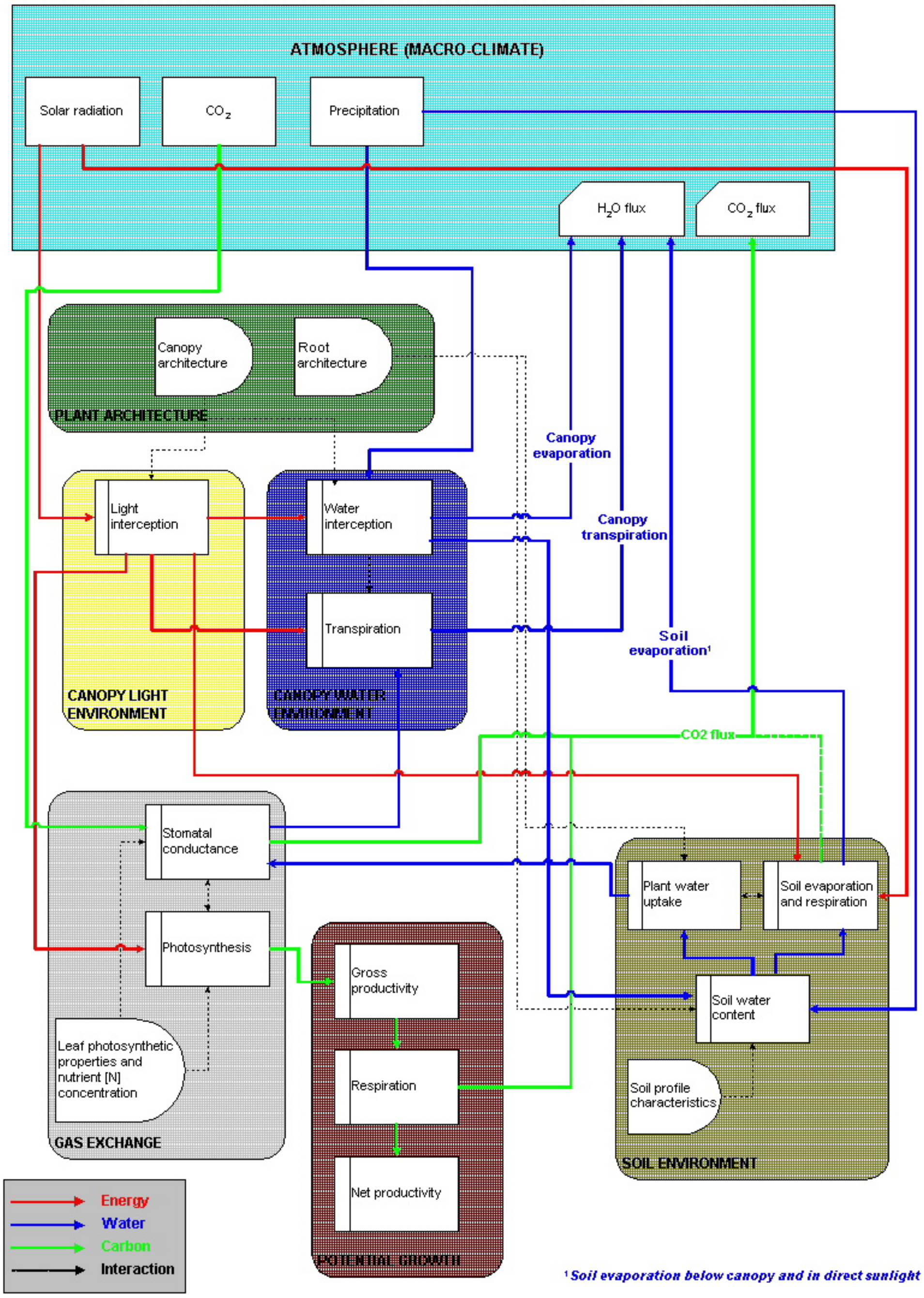
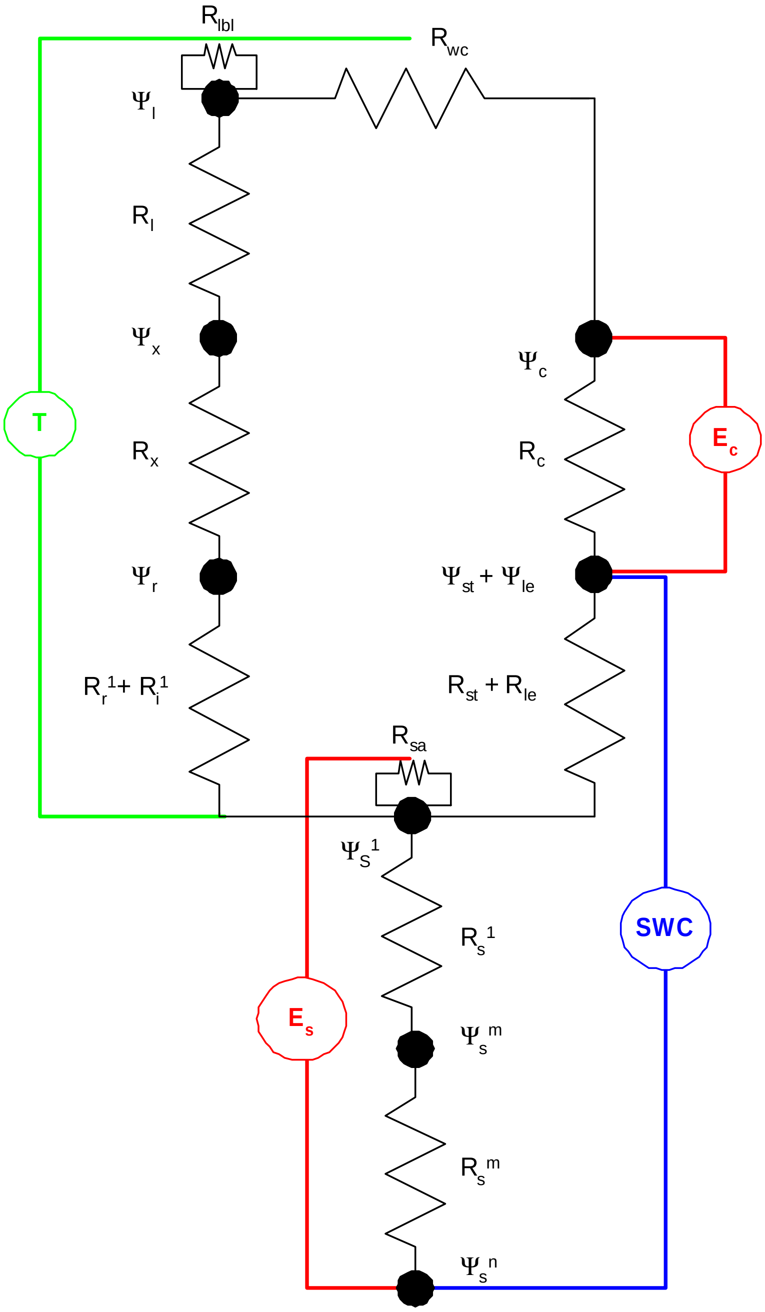


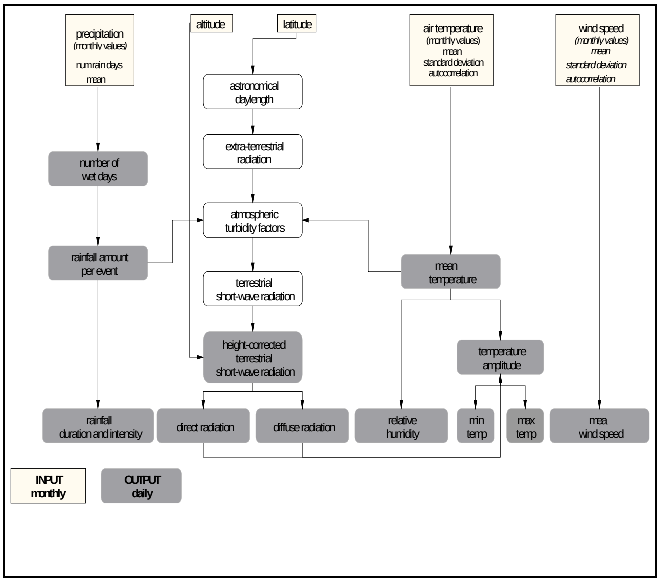
FIGURE 2. System resistance model.



(1). Macro-climate module

The module defines a stochastic-deterministic, site-scale model that downscales widely available monthly time-step input data to the daily scales. Instrumental monthly rainfall totals and wet day frequencies are input into a first-order two-state Markov chain to generate daily scale estimates of precipitation on a given rain day. A constrained random distribution around the observed mean, 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 is approximated using spherical geometry, corrected for latitude, slope and aspect. 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 3. 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. Model runs were presented in the last annual report. Module equations are provided at Appendix 1.

FIGURE 3. Weather generator model structure.



(2). Canopy light environment

The model employs a process-based light environment module that considers the heterogeneity of radiation in the canopy, as the necessary precursor to approximating the non-linear response of photosynthesis to irradiance. The model separates penetration of direct and diffuse radiation (net of albedo) though a canopy in which 2 classes of leaves (sunlight and shaded) are distributed in a multi-layer canopy model. This approach allows the explicit description of within-canopy profiles (on a *per* layer basis) of both environmental [1] and physiological variables [2] in response to radiation attenuation, through a canopy with uniform leaf distribution (spherical) as prescribed by Beer's law (Monsi & Saeki 1953) for each leaf class. By dynamically calculating the leaf areas of sunlight and shaded leaves, and their mean irradiance, mean layer assimilation, transpiration and conductance rates are obtained, adjusted for the photosynthetic capacity of each leaf class. Through integration, data are upscaled to approximate total canopy photosynthesis and gas exchange. In each layer sunlight leaves are assumed to receive both direct and diffuse radiation from the macro-climate model; shaded leaves receive diffuse light only, assuming no radiative energy transmittance through leaves. The within-canopy profiles of leaf nitrogen follows the predicted distribution of absorbed irradiance through each canopy layer, separately for sunlight and shaded leaves and assuming a uniform leaf angle distribution (spherical). Seasonal variation of N content in foliage is also represented. Given the separate descriptions of sun and shade leaves and within-canopy variation of photosynthesis, the module allows non-uniform vertical profiles of photosynthetic capacity to be developed. Module equations are provided at Appendix 2.

(3). Canopy water environment

The canopy water environment module approximates rainfall interception and wet canopy evaporation, based on understanding of the canopy structure, mean evaporation and rainfall

[1] e.g. wind profile, VPD
[2] e.g. leaf temperature

rates, assuming a single rainfall event per rainy day. After Gash et al. (1995), each rainfall event results in a period of canopy wetting up, when the daily cumulative rainfall is less than a prescribed canopy holding capacity (separate for leafy and leafless periods), a period of canopy saturation and a dying out period after rainfall ceases. Separate parameters define:

(i) the throughfall coefficient that determines the amount of rain falling directly on the soil surface without touching the canopy;

(ii) the canopy drip rate proportional to the amount of rainfall dripping onto the soil surface from a saturated canopy;

(iii)the stem storage rate, and

(iv) the proportion of rainfall diverted to stemflow and reaching the soil surface. Wet canopy evaporation is approximated using a simplified Penman-Monteith, in which the ground heat sink and the canopy transpiration terms are removed.

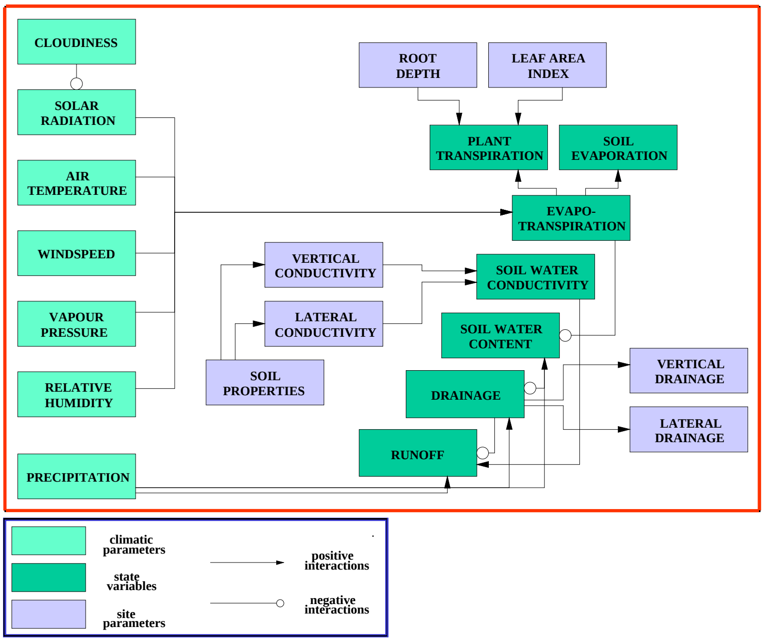
Wind speed is an important determinant of leaf energy budget, pertinent to both wet canopy evaporation and leaf/canopy transpiration, through the effects on the boundary layer conductance term. In this version of the model, a simple exponential decline of windspeed through the canopy is assumed, from a fixed value of windspeed taken at a measurement height above the canopy. Further work will be required to replace this function with a non-linear description that better approximates the effects of canopy structures on the distribution of sources and sinks for heat, mass and momentum.

Module equations are provided at Appendix 3.

(4). <u>Soil environment</u>

This module outlines a daily-time step, multi-horizon capacity model of soil-water balance which requires climate data, together with soil survey and laboratory-measured physical data as input. Temporal integration is restricted to the daily time-step in order to use widely available meteorological data. The structure of this module is outlined in Figure 4; symbols and equations are described in the Appendices. The model is designed to be applicable over a wide range of soil lower boundary conditions that commonly occur in most temperate high latitude countries such as the UK, ranging from free-draining to impermeable. The module simulates the formation of transient perched water tables and the generation of surface runoff. It is currently applied in two-dimensional form and, although it addresses vertical and lateral water movement in an explicit manner, not account for simultaneous vertical/lateral movement along slopes, nor does it consider the effect of excess soil water moving into the profile from spatially adjacent profiles. The predictive ability of the two-dimensional model has been tested against soil moisture data collected across a range of soil types under permanent grass in the UK and results have been published in Evans et al. (1998). Module outputs have compared with predictions made by MACRO (Jarvis, 1994), a mechanistic solute transport model that incorporates a physically-based preferential flow model in which total soil porosity is divided into two flow domains (macro-pores and micro-pores), each characterised by a flow rate. Soil water flow in the micro-pore domain is modelled using Richards' equation.

FIGURE 4. Soil water balance model structure



Root water uptake is calculated from transpiration demand, root distribution and soil water content using the 'sink function' described by Jarvis (1989). This approach assumes the ratio between actual and potential root water uptake varies in proportion with a dimensionless water stress index, or root adaptability factor, that adjusts the stress in one part of the root system by increasing uptake from other parts where conditions may be more favourable. After Feddes et al. (1974) root length distribution is assumed logarithmic with depth and root water uptake is distributed within the root depth according to the stress (determined by water availability) in each soil horizon.

Module equations are provided at Appendix 4.

Soil surface evaporation, an important component of water loss to the canopy, is calculated using an evaporation rate assuming a soil boundary layer conductance term. Total incident radiation on the soil surface (net of albedo) provides the net radiation balance, separately for the soil surface beneath the canopy and adjacent to the tree with no canopy interception. After Campbell (1985) the model accounts for the increase in effective soil resistance to evaporation that occurs during soil drying by using a matrix model calculating the soil moisture in both the liquid and gaseous phases within soil pores at various depths. Soil temperature is assumed to be equal to air.

Module equations are provided at Appendix 5.

(5). Gas exchange and potential growth

Leaf model. The leaf module combines the model for C_3 photosynthesis developed by Farquhar et al. (1980) and von Caemmerer & Farquhar (1981) that describes the regulation of ribulose 1.5-biphosphate carboxylase and electron transport in the leaf, with additions from Long (1991), McMurtrie & Wang (1993) and Friend (1995). In this module the modified C_3 photosynthesis model, widely used and tested across a range of species, is tightly coupled with the C_3 version of the Ball and Berry stomatal conductance model that, in turn, provides a robust phenomenological description of stomatal behaviour. This coupling is required in order to predict leaf response to varying environmental conditions, including atmospheric CO_2 concentrations.

The central axiom the Farquhar et al. C_3 model is that non-limiting photosynthesis is regulated to balance the capacity of limiting processes: at steady state Rubisco will consume RuBP at a rate equal to that of RuBP generation. In theoretical terms, and after Farquhar et al., the rate of RuBP use (R) equals the carboxylation rate (V_c), plus the rate of oxygenation (V_o), thus [$R = V_c+V_o$]. When limited by Rubisco, R can be described by [$R = W_c + V_o$] where W_c is the Rubisco-limited rate of carboxylation.

Gross rates of photosynthesis (assimilation) are a function of the compensation point in the absence of daylight respiration (Γ*), the inter-cellular concentration of CO_2 (C_i) at the site of reaction, limited by both the ribulose biphosphate [RuBP] carboxylase-oxygenase (Rubisco) activity (w_c), and the rate of RuBP regeneration through electron transport (w_j) [3]. Net (potential) photosynthesis accounts for mitochondrial (dark) respiration, as follows:

$$A_i = \left(1 - \frac{\Gamma *}{c_i}\right)\min\left\{w_c, w_j\right\} - R_D \quad \text{(eq. 1)}$$

Rubisco activity (W_c) is calculated using the potential maximum velocity of fully activated Rubisco that is inhibitor free (V_{cmax}), the oxygen concentration in the stroma (O_i), and the maximum potential rate of electron transport (J_{max}). RuBP regeneration is calculated using the inter-cellular CO_2 concentration (C_i), compensation point in the absence of daylight respiration (Γ*), and an actual (PAR adjusted) rate of electron transport (J). The effects of temperature on the kinetic properties of carboxylation and RuBP regeneration take into account changes in the CO_2 solubility and Rubisco affinity of $O_{2.}$; the kinetic constants of Rubisco are provided by McMurtrie & Wang (1993).

After Farquhar et al., leaf nitrogen content (linearly) influences two of the rate-limiting processes of the, namely the potential maximum velocity of fully activated Rubisco that is inhibitor free (V_{cmax}) and the maximum potential rate of electron transport (J_{max}). After Friend (1995), the module explicitly describes the role of nitrogen as a major influence on photosynthesis through influencing the Rubisco concentration in soluble leaf proteins involved in electron transport. Leaf nitrogen content also (linearly) influences mitochondrial (dark) respiration.

After Ball and Berry, C_i is determined within the leaf as a function of the interactions between CO_2 assimilation and stomatal conductance to CO_2, regulated by the leaf boundary layer and mesophyll cell surface resistances to CO_2 transfer. The same processes are assumed to apply for water vapour. As assimilation (demand) and conductance (supply) are inter-dependent, the values of C_i and assimilation are resolved by iteration, taking into account the leaf water potential and canopy temperature. Supply of CO_2 by diffusion through the leaf boundary layers, the stomata and the intercellular spaces is given by:

$$A_i = g_s(c_a - c_i) \quad \text{(eq. 2)}$$

in which g_s is the conductance accounting for boundary layer, stomatal and intercellular resistance to molecular diffusion and C_a is the CO_2 concentrations in free air; (C_a=C_s) where C_s is the CO_2 concentration at the leaf surface.

Foliage respiration is accounted for within the assimilation model. The balance of whole plant respiration during the leafy and non-leafy periods is approximated using a Q_{10} function, based

[3] In this version of the model the effect of potential phosphate limitation (W_p), resulting from the failure of triose phosphate utilisation (production of starches and sugars) to meet triose phosphate production in the Calvin cycle has not been used (Sharkey 1985).

on actual whole system respiration using eddy-covariance measurements of CO_2 fluxes data measured site. Respiration will be the object of further model developmental activity.

Module equations are provided at Appendix 6.

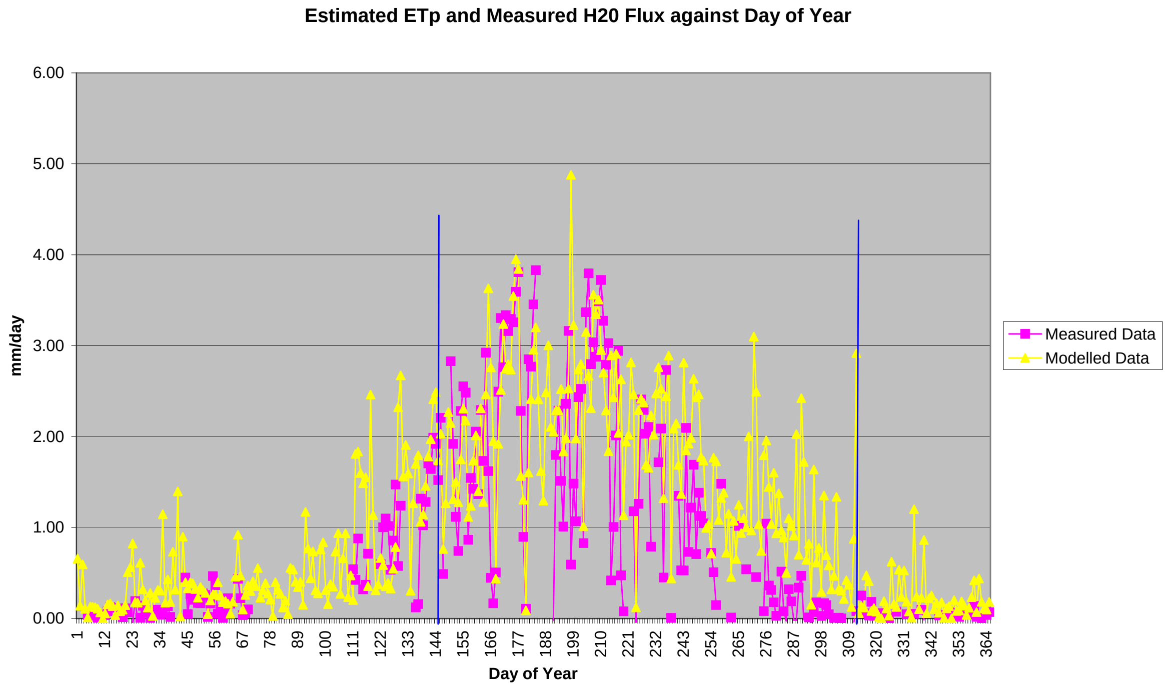
(6). Model testing

Testing of the integrated model's predictive ability has been carried out using eddy-covariance measurements of CO_2 and H_2O flux measured above a forest canopy, as these data provide dynamic whole-system responses environmental and physiological variability at sub-daily and daily scales. It is increasingly accepted (Kramer et al. 2002) that process-based SVAT models should be able to describe the carbon and water fluxes measured with an acceptable degree of accuracy at various temporal scales.

The model has been run uncoupled from the weather generator, and uses observed meteorological data as input. Input files have been parameterised using experimental data for oak collected at the Straits flux site, part of the CarboEuroflux network; physiological data are reported in the ECOCRAFT project database.

Figures 5-6 compare estimated ETp and NPP against the eddy-covariance measurements of H_2O flux and estimated GPP (eddy-covariance measurements of CO_2 flux) at the Headley site and at the daily time-step, respectively. Overall the model represents observed data well, with the exception of the latter part of the growing season (area bounded between blue lines) where it over-estimates wet canopy evaporation. The coefficients of determination indicate a reasonable fit between observed and simulated data (figures 7-8), particularly for GPP.

FIGURE 5. Estimated ETp and eddy-covariance measurements of H_2O flux at the Headley



site.

FIGURE 6. Comparison between estimated ETp and eddy-covariance measurements of H_2O flux at the Headley site

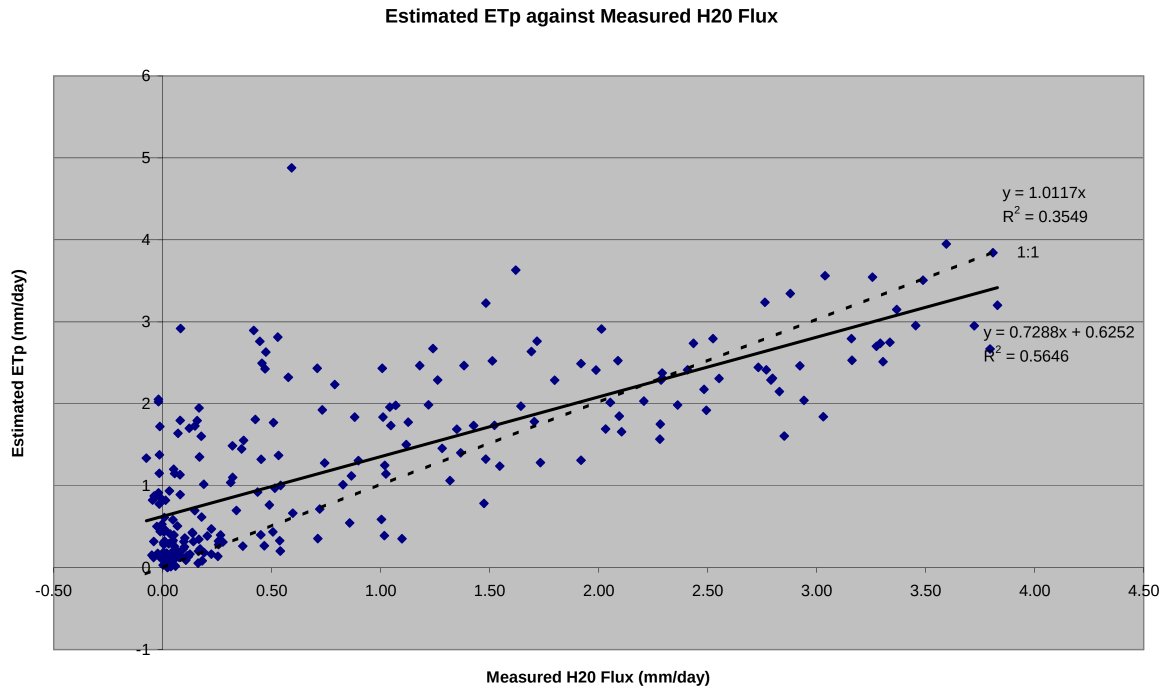


FIGURE 7. Estimated ETp and eddy-covariance measurements of H_2O flux at the Headley site.

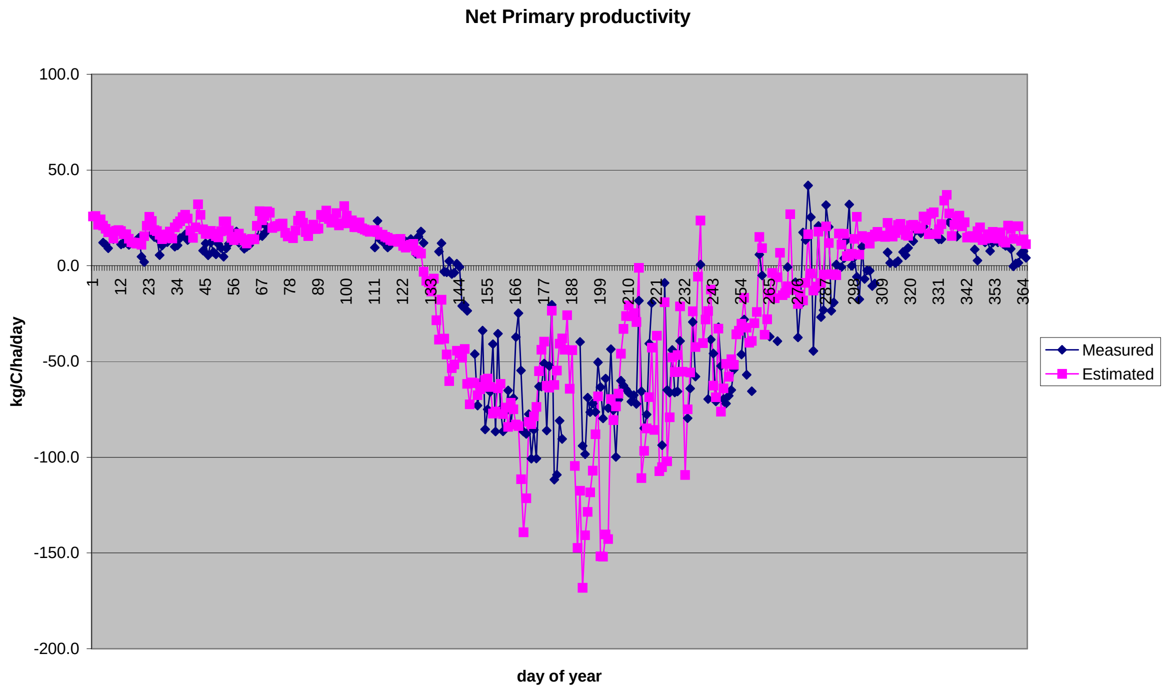
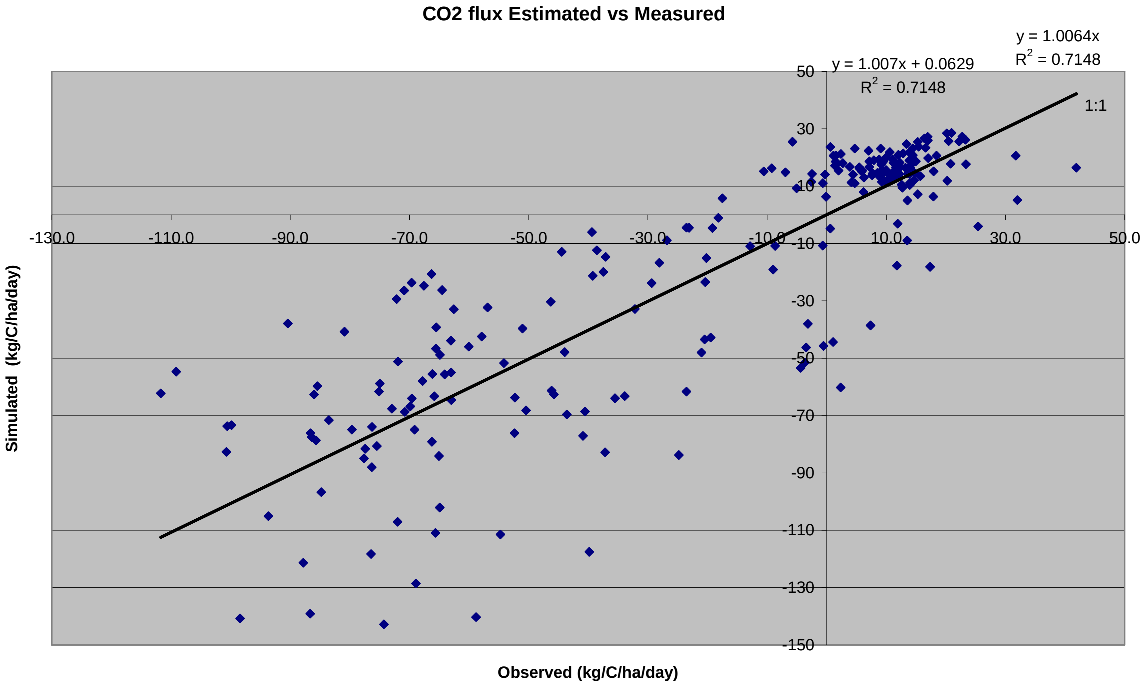


FIGURE 8. Estimated ETp and eddy-covariance measurements of H_2O flux at the Headley site. Note the overlap between the actual and 1:1 regression line.



References

Campbell, G.S., 1985. Soil Physics With BASIC: Transport models for soil-plant systems. *Developments in Soil Science* 14.

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

Farquhar, G.D., von Caemmerer, S. and Berry, J.A., 1980. A biochemical model of photosynthetic CO_2 assimilation in leaves of C_3 plants. *Planta* 149, 78-90.

Feddes, R.A. Bresler, E. and Neuman, S.P., 1974. Field test of a modified numerical model for water uptake by root systems. *Water Resources Research* 10, 1199-1206.

Friend, A.D., 1995. PGEN: an integrated model of leaf photosynthesis, transpiration, and conductance. *Ecological Modelling* 77, 233-255.

Gash, J.H.C., LLoyd, C.R. and Lachaud, G., 1995. Estimating sparse forest rainfall interception with an analytical model. Journal of Hydrology 170, 79-85.

Jarvis, N.J., 1989. A simple empirical model of root water uptake. *Journal of Hydrology* 107, 57-72.

Jarvis, N.J., 1994. The MACRO Model (Version 3.1): Technical Description and Sample Simulations. *Reports and Dissertations* 19. Swedish University of Agricultural Sciences, Uppsala.

Kramer , K. Leinonen, I., Bartelink, H.H, Berbigier, P., Borghetti, M., Bernhofer, C., Cienciala, E., Dolman, A.J., Froer, O., Gracia, C.A., Granier, A., Grünwald, T., Hari, P. Jans, W., Kellomäki, S., Loustau, D., Magnani, F., Markkanen, T., Matteucci, G., Mohren, G.M.J., Moors, E., Nissinen, A., Peltola, H., Sabaté, S. Sanchez, A., Sontag, M., Valentini, R. and Vesala, T., 2002. Evaluation of six process-based forest growth models using eddy-covariance measurements of CO_2 and H_2O fluxes at six forest sites in Europe. *Global Change Biology* 8, 213-230.

Long, S.P., 1991. Modification of the response of photosynthetic productivity to rising temperature by atmospheric CO2 concentrations: Has its importance been underestimated? *Plant, Cell and Environment* 14, 729-739.

McMurtrie, R. E. and Wang, Y., 1993. Mathematical models of the photosynthetic response of tree stands to rising CO2 concentrations and temperatures. *Plant Cell and Environment* 16, 1-13.

Monsei, M. and Saeki, T., 1953. Über den Lichtfaktor in den Pflanzengesellenschaften und SEine Bedeutung für die Stoffproduktion. Japanese Journal of Botany 14, 22-52.

Sharkey, T.D., 1985. O_2-insensitive photosynthesis in C_3 plants. *Plant Physiology* 78, 71-75.

von Caemmerer, S. and Farquhar, G.D., 1981. Some relationships between the biochemistry of photosynthesis and the gas exchange of leaves. *Planta* 153, 376-387.

APPENDICES

APPENDIX 1 –Weather Generator

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 - observed first-order autocorrelation of mean observed daily air temperature for each month [correlation $J:J^{-1}$] [default value = 0.65] [eq. A1.B1]

δW - first-order autocorrelation of mean daily wind speed for each month [correlation $J:J^{-1}$] [default value = 0.65] [eq. A1.B1]

As – aspect [radians] [eq. A1.I6.2]

L - latitude [radians]

Long – longitude [radians]

MJ - number of days per month [eq. A1.C1]

PE - mean observed precipitation for each rainfall event per month [millimetres] [eq. A1.C5.2]

RJ - number of rain days per month [eq. A1.C1]

Sl – slope [radians] [eq. A1.I6.2]

ST - standard deviation of the mean observed daily air temperature [degrees Celsius][eq. A1.B1]

SW - standard deviation of mean daily wind speed [m s^{-1}] [eq. A1.J1]

XT - mean observed daily air temperature [degrees Celsius] [eq. A1.J1]

XW - mean daily wind speed [m s^{-1}] [eq. A1.J1]

Constants

σ - Ångström turbidity factor [eq. A1.E3]

A - coefficient of maximum clear-sky transmittance characteristics [0.016] [eq. A1.B2]

C_{sky} - coefficient of maximum clear-sky transmittance with ΔT increase [2.4] [eq. A1.B2]

P_{range} - rainfall range[>5,10,15,20,25,50,75,100 mm converted to inches] [eqs. A1.C6.1, A1.C6.2]

S' - solar constant [1367.0 W m^{-2}] [eq. A1.D9]

Symbols

α - Ångström turbidity factor [eq. A1.E1]

b – gamma distribution parameter [eq A1.C5.2]

β - Ångström factor [eq. A1.E2]

c – equation of time parameter [eq. A1.D4.2]

C - cloudiness [eq. A1.F1]

$C1_0$ – intermediate parameter to approximate solar radiation on tilted surface [eq. A1.I4.1]

Cts_0 – intermediate parameter to approximate solar radiation on tilted surface [eq. A1.I4.2]

Ctz_0 – intermediate parameter to approximate solar radiation on tilted surface [eq. A1.I5]

Cts_i - intermediate parameter to approximate daily tilted:flat ratio of beam sun [eq. A1.I6.2]

Ctz_i - intermediate parameter to approximate daily tilted:flat ratio of beam sun [eq. A1.I6.3]

ΔT - air temperature amplitude [eq. A1.B2]

- standard lapse rate (K m^{-1}) (6.5 K $100m^{-1}$) [eq. A1.L1]

Dayl - daylength [eq. A1.D7]

Ds - solar declination [eq. A1.D1]

$(\frac{\bar{d}}{d})^2$ - actual distance between sun and the earth [eq. A1.D8]

•IP - sum of wet days in a given month with rainfall within a specified range [eq. A1.C6.1]

EqT – equation of time [eq. A1.D4.1]

ev - saturated vapour pressure at a given air temperature [eq. A1.F2]

FWD - fraction of wet days per month [eq. A1.C1]

g – acceleration due to gravity (9.81m s^{-1}) [eq. A1.L1]

GMT – Greenwich Mean Time [in hours] [eq. A1.D3]
H – height of sun [eq. A1.D6]

hs - solar sunrise/sunset angle [eq. A1.I3]

hs_i – intermediate parameter to approximate daily tilted:flat ratio of beam sun [eq. A1.I6.4]

0IP – wet/dry day [0 - dry day; 1 - wet day] [eq. A1.C4]

P_0 – standard sea level atmospheric pressure (1013mb) [eq. A1.L1]
P_{dur} - duration per rainfall event [eq. A1.C6.2]

$\overline{P}_{dur}$ - mean rainfall duration [eq. A1.C6.1]

PWD - transitional probability of a wet day followed by a dry day [eq. A1.C2]

PWW - transitional probability of a wet day followed by a wet day [eq. A1.C3]

R_{gas} – universal gas constant for air (287 J kg K^{-1}) [eq. A1.L1]
R - terrestrial radiation on a horizontal surface at an elevation of 274 m asl [eq. A1.G1]

Rh – relative humidity [eq. A1.K1]

R_{dif} - diffuse radiation [eq. A1.I6]

R_{dir} - direct [beam] radiation [eq. A1.I5]

R_{so} - extra-terrestrial radiation [eq. A1.D9]

SR – time of sunrise [eq. A1.D2]

S_{mp} – sunrise hour fraction [eq. A1.I2]

S_{r+1} - next hour after sunrise [eq. A1.I1]

ST – solar time [eq. A1.D3]

SE – solar elevation [eq. A1.D5]

T'_0 – standard sea level temperature (288K) [eq. A1.L1]
Td - diffuse transmission coefficient [eq. A1.H2]

Tfr – daily tilted:flat ratio of beam sun [eq. A1.I6.1]

T_{mean} - mean air temperature [eq. A1.B1]

TotJ – total number of days in the year [365,366] [eq. A1.D1]

Tt - total transmission proportion [dimensionless] [eq. A1.H1]

u[z] - wind speed [eq. A1.J1]

ANNEX A. GENERAL EQUATIONS

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

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

ANNEX B: AIR TEMPERATURE

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

$$T_J^{est} = XT_{mT}^{obs} + \bullet T_{mT}^{obs} \bullet (T_{J-1}^{est} - XT_{mT}^{obs}) + ST_{mT}^{obs} \bullet rn_{0_J} \bullet (1 - (\bullet T_{mT}^{obs})^2)^{0.5} \quad [A1.B1]$$

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

$$\bullet T_J^{est} = \left[\frac{nlog(1 - \frac{Tt_J^{est}}{\bullet})}{-A}\right]^{(\frac{1}{C_{sky}})} \quad [A1.B2]$$

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

$$Tmax_J^{est} = T_{mean_J}^{est} + (\frac{\bullet T_J^{est}}{2}) \quad [A1.B3]$$

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

$$Tmin_J^{est} = T_{mean_J}^{est} - (\frac{\bullet T_J^{est}}{2}) \quad [A1.B4]$$

ANNEX C. PRECIPITATION

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

$$FWD_{mT}^{obs} = (\frac{RJ_{mT}^{obs}}{MJ_{mT}^{obs}}) \quad [A1.C1]$$

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:

$$PWD_{mT}^{est} = 0.75 \bullet FWD_{mT}^{obs} \quad [A1.C2]$$

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

$$PWW_{mT}^{est} = 0.25 + PWD_{mT}^{est} \quad [A1.C3]$$

Markov chain parameters

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

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

>0 IP = 0 [dry day]

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

>0 IP = 0 [dry day] [A1.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:

$$P_{IP_J=1}^{Est} = 0 - b \bullet n\log[rn(0,1)] \quad \text{[A1.C5.1]}$$

where b is:

$$b = \frac{Pe_{mT}^{obs^2}}{1 + \frac{(rn(0,1) - 0.5)}{2}} \quad \text{[A1.C5.2]}$$

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

$$\overline{P}_{dur_{mT}}^{est} = \frac{\sum_{i=1}^{n} IP = 1_{mT}^{est}}{1.39 \bullet [(P_{range} + 0.1)^{-3.55}]} \quad \text{[A1.C6.1]}$$

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

$$P_{dur_J}^{est} = \overline{P}_{dur_{mT}}^{est} \bullet \left(\frac{P_J^{est}}{P_{range}}\right) \bullet 60 \quad \text{[A1.C6.2]}$$

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

$$P_{in_J}^{est} = \frac{\left(\frac{P_J^{est}}{P_{dur_J}^{est}}\right)}{60} \quad \text{[A1.C7]}$$

ANNEX 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:

$$Ds_t = 23.45 \bullet \frac{\bullet}{180} \bullet \sin\left(\frac{\bullet}{180} \bullet \left[\frac{(360 \bullet J)}{TotJ^{-1} - 80}\right]\right) \quad \text{[A1.D1]}$$

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

$$SR_J = 12 - \frac{Dayl_J}{2} \quad \text{[A1.D2]}$$

Solar time [in hours] is given by:

$$ST_J = GMT + EqT + \left[\frac{(180 \bullet Long)}{\bullet \bullet 15}\right] \quad \text{[A1.D3]}$$

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

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

[A1.D4.1]

where C is a variable [radians] given by:

$$C = (279.575 + 0.986 \bullet J) \bullet \frac{\bullet}{180} \quad \text{[A1.D4.2]}$$

Solar elevation [in radians] is given by:

$$SE = \operatorname{asin}[\cos(L) \bullet \cos(Ds_J) \bullet \cos(H) + \sin(L) \bullet \sin(Ds_J)] \quad \text{[A1.D5]}$$

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

$$H = 15 \bullet (ST_J - 12) \bullet \frac{\bullet}{180} \quad \text{[A1.D6]}$$

Daylength [in hours] is given by:

$$Dayl_J = \left\{\operatorname{acos} - \left[\frac{\sin(Lat) \bullet \sin(Ds_J) - \sin\left(0.833 \bullet \frac{\bullet}{180}\right)}{\cos(L) \bullet \cos(Ds_J)}\right] \bullet \frac{180}{\bullet}\right\} \bullet \frac{2}{15} \quad \text{[A1.D7]}$$

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

$$\left(\frac{\bar{d}}{d}\right)^2 = 1.00011 + 0.034221 * \cos\left(\frac{2 \bullet \bullet \bullet (J-1)}{365}\right) + 0.00128 * \sin\left(\frac{2 \bullet \bullet \bullet (J-1)}{365}\right) + 0.000719 * \cos\left(2 * \frac{2 \bullet \bullet \bullet (J-1)}{365}\right) + 0.000077 * \sin\left(*2 * \frac{2 \bullet \bullet \bullet (J-1)}{365}\right) \quad \text{[A1.D8]}$$

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

$$Rso_J^{est} = \frac{\left(\frac{\bar{d}}{d}\right)^2 \bullet S' \bullet Sin(SE) \bullet 2 \bullet Dayl_J}{\left[\bullet \bullet \sin\left(\frac{\bullet}{2}\right)\right] \bullet 3600} \quad \text{[A1.D9]}$$

ANNEX 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]:

$$a = 32.9835 - 64.884 \bullet [1 - 1.3614 \bullet \cos(L)] \bullet 4.1842 \bullet 100 \bullet 100 \quad \text{[A1.E1]}$$

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

$$\bullet = 0.715 - 0.3183 \bullet [1 - 1.3614 \bullet \cos(L)] \quad \text{[A1.E2]}$$

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

$$\bullet = 0.03259 \quad \text{[A1.E3]}$$

ANNEX 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:

$$C_J^{est} = 10 - 2.5 \bullet \left(\frac{ev_J^{est}}{P_J^{est}}\right)^{0.5} \quad \text{[A1.F1]}$$

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

$$ev_J^{est} = 6.1078 \bullet \exp\left[\frac{17.269 \bullet Tmean_J^{est}}{Tmean_J^{est} + 237.3}\right] \quad \text{[A1.F2]}$$

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

$$ev_J^{est} = \exp\frac{\left[\frac{[-6140.4]}{273 + Tmean_J^{est}} + 28.916\right]}{100} \quad \text{[A1.F3]}$$

ANNEX G. TOTAL SOLAR RADIATION AT THE EARTH'S SURFACE

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

$$R_J = Rso_J \bullet \left(b - s \bullet C_J^{est}\right) - a \qquad \text{[A1.G1]}$$

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

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

$$Tt_J = \frac{R_J}{Rso_J} \qquad \text{[A1.H1]}$$

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 $Td_J = 1 - 2.3 \bullet (Tt_J - 0.07)^2$

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 $Td_J = 0.23$ [A1.H2]

ANNEX 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:

$$S_{r+1_J} = \text{int}(SR_J + 1) \qquad \text{[A1.I1]}$$

The sunrise hour fraction is given by:

$$S_{mp_J} = SR_j + \frac{S_{r+1_J} - SR_j}{2} \qquad \text{[A1.I2]}$$

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

$$hs_J = \frac{15 \bullet (S_{mp_J} - 12) \bullet \bullet}{180} \qquad \text{[A1.I3]}$$

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

$$C1_0 = \sin(Ds_J) \bullet \left(\sin(L) \bullet \cos(Sl) - \cos(L) \bullet \sin(Sl) \bullet \cos(As)\right) \qquad \text{[A1.I4.1]}$$

$$\begin{aligned} Cts_0 = \big[&C1_0 + \left(\cos(Ds_J) \bullet \cos(hs) \bullet \cos(L) \bullet \cos(Sl) + \sin(L) \bullet \sin(Sl) \bullet \sin(As)\right) + \\ &\left(\cos(Ds_J) \bullet \sin(Sl) \bullet \sin(As) \bullet \sin(hs)\right)\big] \bullet (S_{r+1} - SR_J) \end{aligned} \qquad \text{[A1.I4.2]}$$

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

$$Ctz_0 = (\cos(L) \bullet \cos(Ds_J) \bullet \cos(hs) + \sin(L) \bullet \sin(Ds_J)) \bullet (S_{r+1} - SR_J) \qquad \text{[A1.I5]}$$

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

$$Tfr_J = \left(Cts_o + \sum_{i=1}^{11} Cts_i \right) \Big/ \left(Ctz_o + \sum_{i=1}^{11} Ctz_i \right) \qquad \text{[A1.I6.1]}$$

where:

$$Cts_i = C1_0 + (\cos(Ds_j) \bullet \cos(hs_i) \bullet \cos(L) \bullet \cos(Sl) + \sin(L) \bullet \sin(Sl) \bullet \cos(As)) + (\cos(Ds_j) \bullet \sin(Sl) \bullet \sin(As) \bullet \sin(hs_i)) \qquad \text{[A1.I6.2]}$$

and

$$Ctz_i = \cos(L) \bullet \cos(Ds_J) \bullet \cos(hs_i) + \sin(L) \bullet \sin(Ds_J) \qquad \text{[A1.I6.3]}$$

and

$$hs_i = 15 \bullet (t - 12) \bullet \frac{\bullet}{180} \qquad \text{With } t = 0.5, 1.5, 2.5...11.5 \text{ as } i = 1,2,3...11 \qquad \text{[A1.I6.4]}$$

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

$$Rdir_j = Tfr_J \bullet R_j \bullet (1 - Tt_j) \qquad \text{[A1.I5]}$$

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

$$Rdif_J = \cos^2\left(\frac{Sl}{2}\right) \bullet (R_J \bullet Tt_J) \qquad \text{[A1.I6]}$$

ANNEX J. WIND SPEED

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

$$u(z)_J^{est} = XW_{mT}^{obs} + \bullet W_{mT}^{obs} \bullet (W_{J-1}^{est} - XW_{mT}^{obs}) + SW_{mT}^{obs} \bullet rn_{1_J} \bullet (1 - (\bullet W_{mT}^{obs})^2)^{0.5} \qquad \text{[A1.J1]}$$

ANNEX K. RELATIVE HUMIDITY

Relative humidity [in %] is given by:

$$Rh_J^{est} = \left(\frac{E_J^{est}}{ev_J^{est}} \right) \bullet 100 \qquad \text{[A1.K1]}$$

Where:

$$E_J^{est} = \min(1, ev_J^{est} - 0.66 \bullet (Tdb_J^{est} - Twb_J^{est}) \qquad \text{[A1.K2]}$$

$$Tdb_J^{est} = (Twb_J^{est} + \partial T_J^{est}) \qquad \text{[A1.K3]}$$

$$\partial T_J^{est} = \max(0, rn_o \bullet Tsd_J^{est} + Tampwd_J^{est} \qquad \text{[A1.K4]}$$

$$Tsd_J^{est} = abs\left(\frac{Twb_J^{est}}{5}\right) \quad [A1.K5]$$

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

$$Tampwd_J^{est} = 0.0587 \bullet Twb_J^{est} + 0.3845 \quad [A1.K6]$$

$$Twb_J^{est} = 1.0695 \bullet Tmean_J^{est} - 1.2073 \quad [A1.K7]$$

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

$$Tampwd_J^{est} = 0.1351 \bullet Twb_J^{est} + 0.2891 \quad [A1.K8]$$

$$Twb_J^{est} = 0.9513 \bullet Tmean_J^{est} - 0.5788 \quad [A1.K9]$$

An UK site correction factor is given by:

$$Rh_J^{est} = min(100, \frac{Rh_J^{est}}{Rh_{corr}}) \quad [A1.K10]$$

Where:

$$Rh_{corr} = max(0.9172 - 0.0031 \bullet Tmean_J^{est^2} + 1.0.0377 + Tmean_J^{est} + 0.9172) \quad [A1.K11]$$

ANNEX L. ATMOSPHERIC PRESSURE

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

$$P_J^{est} = P_0\left(\frac{\left[T_0^{'} - d\,(alt - alt_0)\right]^{\frac{g}{dR_{gas}}}}{T_0^{'}}\right) \quad [A1.L1]$$

APPENDIX 2 – Light Interception

Irradiance equations follow (de Pury, D.G.G. and Farquhar, G.D., 1997).

Irradiance absorbed by a canopy per unit ground area.

$$I_c = (1 - r_{cb}) I_b(0).(1 - e^{-k_b L_c}).(1 - r_{cd}) I_d(0).(1 - e^{-k_d L_c}) \quad \text{(A2.1)}$$

I_c: Irradiance absorbed by canopy per unit ground area.(µmol.m^{-2}.s^{-1})

$I_c(0)$: Diffuse PAR per unit ground area at top of canopy. (µmol.m^{-2}.s^{-1})

$k_d{}'$ Radiation extinction coefficient of canopy for diffuse irradiance, adjusted for scatter.(-)

L_c Canopy Leaf Area Index. m^2.m^{-2}

ρ_{cb} Canopy reflection co-efficient for beam radiation.

ρ_{cd} Canopy reflection co-efficient for diffuse radiation.

Calculate sunlit leaf area index.

$$L_{sun} = \frac{(1 - e^{k_b' l_c})}{k_b'} \quad \text{(A2.2)}$$

L_{sun} Sunlit Leaf Area Index (m^2.m^{-2})

L_c Canopy Leaf Area Index. (m^2.m^{-2})

k_b' Radiation extinction coefficient of canopy for beam irradiance, adjusted for scatter. (-)

Irradiance absorbed by the sunlit canopy per unit ground area.

$$I_{cSun} = I_{clbSun} + I_{cldSun} + I_{clbsSun} \quad \text{(A2.3)}$$

I_{cSun} Irradiance absorbed by sunlit fraction of canopy. (µmol.m^{-2}.s^{-1})

I_{clbSun} Direct beam irradiance absorbed by sunlit leaves. (µmol.m^{-2}.s^{-1})

I_{cldSun} Diffuse irradiance absorbed by sunlit leaves. (µmol.m^{-2}.s^{-1})

I_{clbSun} Scattered beam irradiance absorbed by sunlit leaves. (µmol.m^{-2}.s^{-1})

Direct beam irradiance absorbed by sunlit leaves.

$$I_{clbSun} = I_b(0)(1 - s)(1 - e^{-k_b L_c}) \quad \text{(A2.4)}$$

I_{clbSun} : Direct beam irradiance absorbed by sunlit leaves.

$I_b(0)$: Beam PAR per unit ground area at top of canopy. (µmol.m^{-2}.s^{-1})

k_b Radiation extinction coefficient of canopy for beam irradiance.

σ Leaf scattering coefficient of PAR

L_c Canopy Leaf Area Index. (m^2.m^{-2})

Direct beam irradiance absorbed by sunlit leaves

$$I_{clbSun} = I_b\,(0)\,(1 - s\,)\,(1 - e^{(-k_b L_c)}) \qquad \text{(A2.5)}$$

I_{clbSun} Direct beam irradiance absorbed by sunlit leaves. (μmol.m^{-2}.s^{-1})

$I_b(0)$: Beam PAR per unit ground area at top of canopy. (μmol.m^{-2}.s^{-1})

k_b Radiation extinction coefficient of canopy for beam irradiance.

σ Leaf scattering coefficient of PAR

L_c Canopy Leaf Area Index. (m^2.m^{-2})

Diffuse Irradiance absorbed by sunlit canopy per unit ground area.

$$I_{cldSun} = \frac{I_d(0).\,(1 - \bullet_{cd})\,(1 - e^{-(k_d' + k_b)*L_c}).k_d'}{(k_d' + k_b)} \qquad \text{(A2.6)}$$

I_{cldSun} Diffuse irradiance absorbed by sunlit leaves. (μmol.m^{-2}.s^{-1})

$I_b(0)$: Beam PAR per unit ground area at top of canopy. (μmol.m^{-2}.s^{-1})

L_c Canopy Leaf Area Index. (m^2.m^{-2})

k_b Radiation extinction coefficient of canopy for beam irradiance.

k_d' Radiation extinction coefficient of canopy for diffuse irradiance, adjusted for scatter. (--)

ρ_{cd} Canopy reflection co-efficient for diffuse radiation.(--)

Scattered beam Irradiance absorbed by a canopy per unit ground area.

$$I_{lbs} = \frac{I_b(0)(1 - r_{cb})\,(1 - e^{-(k_b' + k_b)*L_c}) * k_b'}{(k_b' + k_b)} - \frac{(1 - s\,)\,(1 - e^{-2k_b L_c}\,)}{2} \qquad \text{(A2.7)}$$

I_{lbs} Irradiance - Photosynthetically Active Radiation(PAR) per unit ground area - scattered beam. (μmol.m^{-2}.s^{-1})

$I_b(0)$: beam PAR per unit ground area at top of canopy. (μmol.m^{-2}.s^{-1})

L_c Canopy Leaf Area Index. (m^2.m^{-2})

k_b Radiation extinction coefficient of canopy for beam irradiance.

k_b' Radiation extinction coefficient of canopy for beam irradiance, adjusted for scatter. (-)

σ Leaf scattering coefficient of PAR

ρ_{cb} Canopy reflection co-efficient for beam radiation.

Calculate the irradiance absorbed by the shaded canopy fraction.

$$I_{cSh} = I_c - I_{cSun} \qquad \text{(A2.8)}$$

I_{cSh} PAR Absorbed by the shaded canopy fraction. (μmol.m^{-2}.s^{-1})

I_c PAR Absorbed by the canopy. (μmol.m^{-2}.s^{-1})

I_{cSun} PAR Absorbed by the sunlit canopy fraction. (μmol.m^{-2}.s^{-1})

Calculate sunfleck penetration.

$$f_{sun}(L) = e^{-k_b L} \quad \text{(A2.9)}$$

$f_{sun}(L)$ Fraction of leaves that are sunlit.

k_b Radiation extinction coefficient of canopy for beam irradiance.

L Cumulative leaf area index from top of canopy (L=0 at top). ($m^2.m^{-2}$)

Calculate Irradiance, either beam, beam with scatter, or diffuse,

$$I_{lr} = (1 - r_c) k_{ec} I_b(0) e^{-k_{ec} L} \quad \text{(A2.10)}$$

I_{lr} Irradiance (PAR) -per unit ground area - either beam, beam-with-scatter, or diffuse.

$I_b(0)$: beam PAR per unit ground area at top of canopy. ($\mu mol.m^{-2}.s^{-1}$)

k_{ec} Radiation extinction coefficient of canopy - either for beam, beam adjusted for scatter, or diffuse adjusted for

scatter. ie. either k_b, k_b', or k_d'

L Cumulative leaf area index from top of canopy (L=0 at top). ($m^2.m^{-2}$)

ρ_{ec} Canopy reflection co-efficient for beam radiation. (different for beam and diffuse radiation). ρ_{cb} - beam, ρ_{cd} – diffuse.

Takes an extinction co-efficient, and modifies it for scatter.

$$k_{ec}' = k_{ec} \sqrt{(1 - s)} \quad \text{(A2.11)}$$

k_{ec}' Radiation extinction coefficient of canopy adjusted for scatter,

k_{ec} Radiation extinction coefficient of canopy

σ Leaf scattering coefficient of PAR

Calculate the leaf scattering co-efficient of PAR.

$$s = r + t \quad \text{(A2.12)}$$

σ Leaf scattering coefficient of PAR

ρ Leaf reflection coefficient for PAR

τ Leaf transmissivity to PAR

τ

Calculates the irradiance absorbed by shaded leaves

$$I_{lSh} = I_{ld}(L) + I_{bs}(L) \quad \text{(A2.13)}$$

I_{lSh} Irradiance PAR absorbed by shaded leaves. ($\mu mol.m^{-2}.s^{-1}$)

I_{ld} Irradiance PAR per unit ground area - diffuse. ($\mu mol.m^{-2}.s^{-1}$)

I_{lbs} Irradiance (PAR) per unit ground area - scattered beam. ($\mu mol.m^{-2}.s^{-1}$)

L Cumulative leaf area index from top of canopy (L=0 at top). ($m^2.m^{-2}$)

Calculates scattered beam irradiance.

$$I_{lbs} = I_b(0)((1-\rho_{cb})k_b' e^{-k_b' L} - (1-\sigma)k_b e^{-k_b L} \qquad \text{(A2.14)}$$

I_{lbs} Irradiance (PAR) per unit ground area - scattered beam. (µmol.m^{-2}.s^{-1})

$I_b(0)$: Beam PAR per unit ground area at top of canopy. (µmol.m^{-2}.s^{-1})

k_b Radiation extinction coefficient of canopy for beam irradiance.

k_b' Radiation extinction coefficient of canopy for beam irradiance, adjusted for scatter. (-)

L Cumulative leaf area index from top of canopy (L=0 at top). (m^2.m^{-2})

σ Description: Leaf scattering coefficient of PAR

ρ_{cb} Canopy reflection co-efficient for beam radiation.

Calculates the fraction of leaves in each leaf-angle class.

$$f_{l1,2} = \cos\alpha_{1_1} - \cos\alpha_{1_2} \qquad \text{(A2.15)}$$

$f_1$1,2 Fraction of leaves in this leaf-angle class.

$\alpha 1_1$ Upper leaf angle for this angle class.

$\alpha 1_2$ Lower leaf angle for this angle class.

Calculates the mean cosine of leaf angle for each class.

$$\overline{\cos}\,\alpha_{1_{1,2}} = 0.5(\cos\alpha_{1_1} + \cos\alpha_{1_2}) \qquad \text{(A2.16)}$$

$\overline{\cos}\,\alpha_{1_{1,2}}$ Mean of the cosine of leaf angle for this class.

α11 Upper leaf angle for this angle class.

α12 Lower leaf angle for this angle class.

Calculates beam irradiance absorbed by sunlit leaves.

$$I_{lbSun} = (1-\sigma)I_b(0)\frac{\overline{\cos\alpha}}{\sin\beta} \qquad \text{(A2.17)}$$

I_{lbSun} Beam irradiance absorbed by sunlit leaves. (µmol.m^{-2}.s^{-1})

α1 Angle of beam irradiance to leaf normal

σ Leaf scattering coefficient of PAR

$I_b(0)$: Beam PAR per unit ground area at top of canopy. (µmol.m^{-2}.s^{-1})

β Solar angle of elevation.

β

Calculates total irradiance absorbed by sunlit leaves.

$$I_{lSun} = I_{lbSun} + I_{lSh} \qquad \text{(A2.18)}$$

I_{lSun} Total irradiance absorbed by sunlit leaves. (μmol.m^{-2}.s^{-1})

I_{lbSun} Beam irradiance absorbed by sunlit leaves. (μmol.m^{-2}.s^{-1})

I_{lSh} Irradiance absorbed by shaded leaves. (μmol.m^{-2}.s^{-1})

Calculate total irradiance.

$$I_l = I_{lb} + I_{ld} \quad \text{(A2.19)}$$

I_1 Total irradiance. (μmol.m^{-2}.s^{-1})

I_{lb} Beam irradiance. (μmol.m^{-2}.s^{-1})

I_{ld} Diffuse irradiance. (μmol.m^{-2}.s^{-1})

Beam irradiance, uniform leaf angle distribution, canopy reflection co-efficient.

$$\text{CanopyReflectionBeam} = 1 - e^{\left(\frac{2\, r_h k_b}{1+k_b}\right)} \quad \text{(A2.20)}$$

k_b Radiation extinction coefficient of canopy for beam irradiance.

ρ_h Canopy reflection co-efficient

Beam irradiance, horizontal leaves, canopy reflection coefficient.

$$\text{CanopyReflectionBeamHorizontal} = \frac{1-\sqrt{1-s}}{1+\sqrt{1-s}} \quad \text{(A2.21)}$$

σ Leaf scattering coefficient of PAR

σ

Diffuse irradiance canopy reflection co-efficient. =0.36

Fraction of incoming radiation absorbed:

$$f_{abs} = \frac{I_c}{I_b(0) + I_d(0)}$$

where :

f_{abs} – fraction of incoming radiation absorbed by the canopy (-) (A2.22)

I_c – radiation absorbed by the canopy (Jm^{-2}day^{-1})

$I_b(0)$ – beam radiation at top of canopy (Jm^{-2}day^{-1})

$I_d(0)$ – diffuse radition at top of canopy (Jm^{-2}day^{-1})

Canopy beam extinction co-efficient:

$$k_b = \frac{k_{b,0}}{\sin(b)}$$

where : (A2.23)

k_b '– canopy extinction coefficient for beam irradiance(-)

$k_{b,0}$ – reference canopy extinction coefficient for beam irradiance(-), assume = 0.46

b – solar elevation (-)

Scaling radiation absorbed at midday to a daily radiation value:

$$R = R_{12} \int_{t=0}^{t=D} \sin\left(\frac{pt}{D}\right) dt$$

$$\therefore R = \frac{2DR_{12}}{p}$$

(A2.24)

where :

R – daily radiation (Jm $^{-2}$ day $^{-1}$)

R_{12} – radiation at solar noon (Wm $^{-2}$)

D – daylit time for theday (s)

APPENDIX 3 – Water balance

All equations follow (Gash, et al. 1995)

calculates the precipitation necessary to saturate the canopy ie holding capacity + evaporation while its raining

$$P_G' = MAX\{S_c, \frac{R * S_c}{E_{wet}} \ln(1 - \frac{E_c}{R})\} \qquad (A3.1)$$

P_G' Rainfall needed to saturate the canopy (mm)

R Average rate of rainfall in the day ($mm.hr^{-1}$)

S_c Holding capacity of the canopy (mm (rain)/ projected area)

E_{wet} Average Evaporation during rain ($mm.hr^{-1}$) (stand basis not projected area) Typical Penman-Montieth =

0.17mm/hr

Rainfall interception by a stands canopy

$$\text{If } PPT <= P_G' \quad I_{can,unsat} = PPT * p_{Cover}$$

$$\text{If } PPT > P_G' \quad I_{can,unsat} = 0.0 \qquad (A3.2)$$

$I_{can,unsat}$ Interception by canopy of samm rainfall incidents (mm)

PPT Rainfall ($mm.day^{-1}$)

P_G' Rainfall needed to saturate the canopy (mm)

p_{cover} Projected crown cover of stand ($m^2.m^{-2}$)

Evaporation from a canopy during its process of saturation ie raining and will saturate canopy

$$\text{If } PPT = 0.0 \text{ and } P_G' > PPT \quad I_{can,wet} = 0.0$$

$$\text{Else } I_{can,wet} = (P_G' - S_c) * p_{cover} \qquad (A3.3)$$

$I_{can,wet}$ Interception of rain for Evaporation during the period of wetting (mm)

PPT Rainfall ($mm.day^{-1}$)

P_G' Rainfall needed to saturate the canopy (mm)

S_c Holding capacity of the canopy (mm (rain)/ projected area)

p_{cover} Projected crown cover of stand ($m^2.m^{-2}$)

Interception/Evaporation from saturation to end of rain

$$\text{if } PPT <= P_G' \qquad I_{can,rain} = 0.0$$
$$\text{if } PPT > P_G' \qquad I_{can,rain} = Cover * E_c \frac{(PPT - P_G')}{R * Cover} \qquad \text{(A3.4)}$$

$I_{can, rain}$ Intercepted rain for evaporation during rain (mm)

PPT Rainfall ($mm.day^{-1}$)

P_G' Rainfall needed to saturate the canopy (mm)

E_c Average Evaporation during rain ($mm.hr^{-1}$) (stand basis not projected area)

Typical Penman montieth = 0.17mm/hr

Cover Projected crown cover of stand ($m^2.m^{-2}$)

R Rate of rainfall ($mm.hr^{-1}$)

Loss of water from canopy storage

$$\text{If } I_{can,rain} <= 0 \quad I_{can,post} = 0.0$$
$$\text{if } I_{can,rain} > 0 \quad I_{can,post} = S_c * p_{cover} \qquad \text{(A3.5)}$$

$I_{can,post}$ Intercepted rain evaporated after saturation (mm)

$I_{can, rain}$ Intercepted rain for evaporation during rain (mm)

S_c Holding capacity of the canopy (mm (rain)/ projected area)

p_{cover} Projected crown cover of stand ($m^2.m^{-2}$)

Interception & loss of water via the stem - assumed that small instances of rain are intercepted by the canopy

$$\text{If } PPT >= \frac{S_t}{P_t} \qquad I_{stem} = S_t$$
$$\text{If } PPT < \frac{S_t}{P_t} \text{ and } I_{can,rain} > 0 \qquad I_{stem} = PPT * P_t \qquad \text{(A3.6)}$$

I_{stem} Intercepted rain evaporated from stem (mm)

$I_{can, rain}$ Intercepted rain for evaporation during rain (mm)

S_t Holding capacity of the stem (trunk) (mm)

P_t proportion of rainfall diverted to stemflow (--)

PPT precipitation (mm)

ANNEX A. Evaporation equations for the system and canopy.

Rate of change of saturated vapour pressure with temperature:

$$\Delta V = \frac{4098.25 e_s}{(\bar{T} + 237.3)^2}$$

where : (A3.A1)

ΔV – rate of change of saturated vapour pressure with temperature ($mbarK^{-1}$)

e_s – saturated vapour pressure (mbar)

$\bar{T}$ – mean daily temperature (^0C)

Heat-sink ground function:

$$G = 0.033 R_{net}$$

where : (A3.A2)

G – ground heat - sink ($Jm^{-2}day^{-1}$)

R_{net} – net radiation ($Jm^{-2}day^{-1}$)

Latent heat of vapourisation:

$$l = 2500.78 - 2.3601T$$

where : (A3.A3)

l – latent heat of vapourisation ($kJkg^{-1}$)

T – air temperature (^0C)

Canopy aerodynamic resistance:

$$r_a = \frac{\ln\left(\frac{z_m - d}{z_{om}}\right)\ln\left(\frac{z_h - d}{z_{oh}}\right)}{k^2 u_z}$$

where :

r_a – aerodynamic resistance (sm^{-1})

z_m – height of wind measurements (m)

z_h – height of humdity measurements (m), assume = z_m

d – zero plane displacement height (m), assume = 0.75h

h – crop height (m)

z_{om} – roughness length governing momentum transfer (m), assume = 0.123h

z_{oh} – roughness length governing governing transfer of heat and vapour (m), assume = $0.1z_{om}$

k – Von Karman's constant (-), = 0.41

u_z – windspeed at height z_m (ms^{-1})

(A3.A4)

Psychrometric constant (relationship between vapour pressure deficit and wet bulb depression) function:

$$g_p = \frac{1.0035 P_{atm}}{0.62198 \lambda}$$

where :

g_p – psychrometric constant ($mbarK^{-1}$)

P_{atm} – barometric atmospheric pressure (mbar)

λ – latent heat of vapourisation ($kJkg^{-1}$)

(A3.A5)

Emissivity of a clear sky:

$$e_{atm} = -0.02 + 0.261 * e^{-0.000777T^2}$$

where :

e_{atm} – Emissivity of the clear sky atmosphere ($W\,^oC^{-1}day^{-1}$)

T - Air temperature (^oC)

(A3.A6)

Emissivity of the total sky atmosphere, including below cloud:

$$e_{sky} = e_{atm} + C(1 - e_{atm})\left(1 - \frac{4 * \Delta T_C}{T + 273.15}\right)$$

where :

e_{sky} – emissivity of the total sky atmosphere, including below cloud ($W\,^0C^{-1}day^{-1}$) (A3.A7)

e_{atm} – emissivity of the clear sky atmosphere ($W\,^0C^{-1}day^{-1}$)

C – cloud cover ratio (-)

ΔT_C – difference in cloud base temperature and air temperature (K), assume = 2

T – air temperature (^0C)

Net longwave radiation:

$$R_{lw,net} = e_{surf}\, s\, (273.13 + T)^4 \times 1.28\left[\left(\frac{e_a}{273.13 + T}\right)^{\frac{1}{7}} - 1\right]$$

where : (A3.A8)

$R_{lw,net}$ – net longwave radiation (Wm^{-2})

e_{surf} – surface emissivity (-), assume = 0.97

s – Steffan - Boltzmann constant ($Wm^{-2}K^{-4}$), assume = 5.67×10^{-8}

T – air temperature (^0C)

e_a – actual (unsaturated) vapour pressure (mbar)

Net radiation:

$$R_{net} = R_{lw,net,day}(1 - C) + (R_{sw,abs} + R_{sw,tran})$$

where :

R_{net} – net daily radiation ($Jm^{-2}day^{-1}$)

$R_{lw,net,day}$ – net daily longwave radiation ($Jm^{-2}day^{-1}$) (A3.A9)

C – cloud cover ratio (-)

$R_{sw,abs}$ – shortwave radiation absorbed by the crop ($Jm^{-2}day^{-1}$)

$R_{sw,tran}$ – shortwave radiation transmitted by the crop ($Jm^{-2}day^{-1}$)

Air density function:

$$r_a = \frac{101.325 - 0.01055A}{0.27\left[\dfrac{273.13 + T}{1 - 0.378\left(\dfrac{e_a}{101.325 - 0.01055A}\right)}\right]} \qquad \text{(A3.A10)}$$

where :

r_a – air density (kg.m^{-3})

A – altitude (m)

T - air temperature(^{o}C)

Evaporation from a wet canopy:

$$E_{wet} = 3600D_{hr}\,\frac{\Delta V\left(\dfrac{R_n}{3600D_{hr}} - \dfrac{G}{3600D_{hr}}\right)^{*} f_{abs} + r_a c_p\left(\dfrac{e_s - e_a}{r_a}\right)}{l \times 10^{3}(\Delta V + g_p)}$$

where :

E_{wet} – Evaporation from a wet canopy (mm.day^{-1})

D_{hr} – daylit time for the day (hr)

ΔV – the rate of change of saturated vapour pressure with temeperature (mbarK^{-1})

R_n – net daily radiation (Jm^{-2}day^{-1})

G – ground heat - sink (Jm^{-2}day^{-1})

f_{abs} – fraction of incoming radiation absorbed by the canopy (-)

r_a – air density (kg.m^{-3})

c_p – specific heat capacity of air (Jkg^{-1}K^{-1}), assume = 1005.01

e_s – saturated vapour pressure (mbar)

e_a – actual vapour pressure (mbar)

r_a – aerodynamic (boundary layer) resistance of the canopy to water diffusion (sm^{-1})

l – latent heat of vapourisation (kJ.kg^{-1}) (A3.A11)

g_p – psychrometric constant (mbar.K^{-1})

Total evapotranspiration:

$$E_{total} = (1 - p_{dry}) \cdot E_{wet} \cdot p_{cover} + p_{dry} \cdot E_{transp} \cdot p_{cover} + E_{shade} \cdot p_{cover} + E_{bare} \cdot (1 - p_{cover})$$

where:

p_{dry} – proportion of the daylight time that is dry.(-)

E_{wet} – wet canopy evaporation $(mm \cdot day^{-1})$ (A3.A12)

p_{cover} – projected canopy cover (-)

E_{transp} – transpiration from a dry canopy $(mm \cdot day^{-1})$

E_{shade} – evaporation from soil shaded by the canopy $(mm \cdot day^{-1})$

E_{bare} – evaporation from the bare soil $(mm \cdot day^{-1})$

Evaporation during rain:

$$E_{rain} = \frac{E_{wet}}{D_{hr}}$$

where: (A3.A13)

E_{rain} – rate of evaporation from the canopy during rain $(mm \cdot hr^{-1})$

E_{wet} – potential wet canopy evaporation $(mm \cdot day^{-1})$

D_{hr} – Daylight time for the day (hr)

Proportion of the day that is dry:

$$p_{dry} = 1 - \frac{I_{ppt,canopy}}{E_{wet}}$$

where: (A3.A14)

p_{dry} – proportion of the day that the canopy is dry (-)

$I_{ppt,canopy}$ – precipitation intercepted by the canopy $(mm \cdot day^{-1})$

E_{wet} – potential wet canopy evaporation $(mm \cdot day^{-1})$

Quantity of precipition that reaches the soil:

$$I_{ppt,soil} = (1 - p_{cover})P_{IP} + p_{cover}(P_{IP} - I_{ppt,canopy})$$

where :

$I_{ppt,soil}$ – rain that reaches the soil $(mm \cdot day)$ (A3.A15)

p_{cover} – projected canopy cover (-)

P_{IP} – precipitation for the day $(mm \cdot day^{-1})$

$I_{ppt,canopy}$ – precipitation intercepted by the canopy $(mm \cdot day^{-1})$

Projected cover:

$$p_{cover} = \min(L_c, C_{max})$$

where : (A3.A16)

p_{cover} – projected cover of the canopy (-)

L_c – canopy leaf area idex $(m^2 m^{-2})$

C_{max} – maximum canopy cover (-), INPUT

APPENDIX 4 - Soil water

ANNEX A. VOLUMETRIC WATER CONTENT FOR EACH HORIZON

Volumetric water content at total porosity is given by

$$OTP^{z} = T_p^{\,n} \bullet LD^{n} \tag{A4.A1}$$

Volumetric water content at field capacity is given by

$$OFC^{n} = PFC^{n} \bullet LD^{n} \tag{A4.A2}$$

Volumetric water content at wilting point is given by

$$OWP^{n} = PWP^{n} \bullet LD^{n} \tag{A4.A3}$$

Volumetric water content at 30% wilting point is given by

$$Oair^{n} = PWP^{n} \bullet LD^{n} \bullet 0.3 \tag{A4.A4}$$

Volumetric air capacity at 0.05 bar suction is given by

$$C_a^{\,n} = \left(T^{n} - PFC^{n}\right) \bullet 100 \tag{A4.A5}$$

Total water content at total porosity is given by

$$WQS^{n} = PWQS^{n} \bullet LD^{n} \tag{A4.A6}$$

ANNEX B. PEDO-TRANSFER FUNCTIONS FOR CALCULATING SATURATED SUB-VERTICAL AND SUB-LATERAL HYDRAULIC CONDUCTIVITY

Pedo-transfer functions (PTFs) were developed from field datasets in England and Wales to calculate sub-vertical and sub-lateral saturated hydraulic conductivity (Hollis and Wood, 1989) and have been enhanced in the present paper to adjust for stoniness and organic matter content. The equations outlined below can be run using laboratory measured water retention data; for applications outside England and Wales, equations should be replaced either with appropriate values, or water retention data values approximated using existing PTFs.

Retained volume of soil water is given by

$$q_m(x) = \frac{\left(\frac{q_v(x)}{100}\right)}{D_{bt}} \tag{A4.B1}$$

where (*x*) is the suction pressure at 0, 0.1, 0.4, 2 and 15 bar, respectively.

Volumetric total pore space, corrected for organic matter and stoniness, is given by

$$T = \left[\left(1 - \left(\frac{D_{bt}}{D_p}\right)\right) \bullet (1 - S) \bullet \left[(1 - OM) + OM\right]\right] \bullet 100 \text{ with } D_p = 2.65 \tag{A4.B2}$$

Sub-vertical saturated conductivity is given by

if C < 16 and $[(Z + 2 \bullet C) < 31]$ *if C_a < 7.5* $Ks_V = (0.4535 \bullet T^{1.03423})$ (A4.B3a)

> 7.5 $Ks_V = [8.03578 - (6.7707 \bullet T) + (0.833 \bullet T^2)]$

if C > 16 and $[(Z + 2 \bullet C) > 31]$ *if C_a < 4* $Ks_V = [0.14143 \bullet e^{(T \bullet 0.46944)}]$ (A4.B3b)

> 4 $Ks_V = [5.8521 - (5.4125 \bullet T) + (1.05138 \bullet T^2)]$

Sub-lateral conductivity is given by

if C < 16 and $[(Z + 2 \bullet C) < 31]$ *if C_a < 7.5* $Ks_L = (0.4535 \bullet T^{1.03423})$ (A4.B4a)

> 7.5 $Ks_L = [8.03578 - (6.7707 \bullet T) + (0.833 \bullet T^2)]$

if C > 16 and $[(Z + 2 \bullet C) > 31]$ *if C_a < 5.5* $Ks_L = [0.14143 \bullet e^{(T \bullet 0.46944)}]$ (A4.B4b)

if C_a > 5.5 $Ks_L = [3.155 - (4.639 \bullet T) + (0.8143 \bullet T^2)]$

Air capacity is given by

$$C_a = T - q_V^{0.05}$$ (A4.B5a)

ANNEX C. UNSATURATED HYDRAULIC CONDUCTIVITY

Soil water retention at different pressure heads in the soil matrix is described using the simplified version of the Brooks-Corey expression (1964) introduced by Campbell (1974), in which the residual water content is assumed zero, and given by

$$\frac{K(q)}{K_s} = \left(\frac{h_b}{h}\right)^{-l}$$ (A4.C1)

Values of (*b*) and ( ) can be derived from PTFs or from non-linear interpolation of measured data, as carried out for this simulation experiment.

ANNEX D. DRAINAGE

When *FC* > q < *T,* excess volumetric water (*Ex*) is available for drainage (*D*) is given by

$$Ex_t = q_t - PFC_n$$ (D1)

Drainage occurs at the sub-vertical hydraulic conductivity rate (Ks_v) as given by

$$\min\{Ks_V^z, Ks_V^{z+1}\}$$ (A4.D2)

Drainage (*D*), both sub-vertical (D_V) and sub-lateral (D_L) occurring at the sub-vertical (K_{SV}) and sub-lateral saturated (K_{SL}) hydraulic conductivity rates, adjusted to the water content at the previous integration respectively, develops under a range of boundary conditions:

Condition A: free drainage both within the profile and at the lower boundary is given by

if $Ex_t < Ks_V$ $\qquad D_{V_t} = Ex_t$ *and* $D_{L_t} = 0$ (A4.D3a)

if $Ex_t - Ks_V < Ks_L$ $\qquad D_{V_t} = Ks_V$ *and* $D_{L_v} = Ex_t - Ks_L$ (A4.D3b)

if $Ex_t - Ks_V > Ks_L$ $\qquad D_{V_t} = Ks_V$ *and* $D_{L_t} = Ks_V$ (A4.D3c)

Under this condition a temporary perched water table is formed and carries over into the next day.

Condition B: temporary restricted drainage from one horizon (*z*), due to the formation of a perched water table in a lower horizon (*z+1*) restricts the potential drainable volume (DP), is given by

if $PFC^{z+1} > q_t^{z+1} < T^{z+1}$ $\qquad DP_t^{z+1} = T^{z+1} - q_t^{z+1}$ (A4.D4)

if $DP_t^{z+1} < D_{V_t}^z$ *and if* $(Ex_t^z - DP_t^{z+1}) < Ks_L^z$ $\qquad D_{V_t}^z = DP_t^{z+1}$ (A4.D5a)

$$D_{L_t}^z = Ex_t^z - DP_t^{z+1} \quad \text{(A4.D5b)}$$

Under this condition a temporary perched water table can be formed which drains both vertically and laterally in the same day.

$$(Ex_t^z - DP_t^{z+1}) > Ks_L^z \qquad D_{V_t}^z = DP_t^{z+1} \quad \text{(A4.D6a)}$$

$$D_{L_t}^z = Ks_L^z \quad \text{(A4.D6b)}$$

Under this condition a temporary perched water table can be formed which drains both vertically and laterally, and is carries over into the next day.

Condition C: restrictions in drainage from one horizon (*z*) due to a lower saturated layer (*z+1*) is given by

if $q_t^{z+1} > T^{z+1}$ $\qquad DP_t^{z+1} = 0$ (A4.D7)

if $DP_t^{z+1} < x$ *and if* $Ex_t^z < Ks_L^z$ $\qquad D_{V_t}^z = 0$ (A4.D8a)

$$D_{L_t}^z = Ex_t^z \quad \text{(A4.D8b)}$$

Under this condition a temporary perched water table can be formed which only drains laterally in the same day.

$$Ex_t^z > Ks_L^z \qquad D_{V_t}^z = 0 \quad \text{(A4.D9a)}$$

$$D_{L_t}^z = Ks_L^z \quad \text{(A4.D9b)}$$

Under this condition a temporary perched water table can be formed which only drains laterally and is carried over into the next iteration.

Condition D: restrictions to drainage from one horizon as a function of the water content of an adjacent downstream horizon are given by

$$\textit{if}\ (q_{t-1}^{z+1} - D_{V_t}^{z}) < T^{z+1} \qquad D_{L_t}^{z} = T^{z} - q_{t-1}^{z} \tag{A4.D10a}$$

$$\textit{if}\ (q_{t-1}^{z+1} - D_{V_t}^{z}) > T^{z+1} \qquad D_{L_t}^{z} = 0 \tag{A4.D10b}$$

ANNEX E. SOIL WATER BALANCE

Volumetric soil water content of the topsoil is given by

$$q_t^{z} = \left[\left(q_{t-1}^{z} - D_{V_{t-1}}^{z} - D_{L_{t-1}}^{z}\right) + P_t - \left(E_t + Tp_t\right)\right] \tag{A4.E1}$$

Volumetric soil water content of all lower horizons is given by

$$q_t^{z+1} = \left[\left(q_{t-1}^{z+1} - D_{V_{t-1}}^{z+1} - D_{L_{t-1}}^{z+1}\right) + D_{V_t}^{z}\right] - \left(E_t + Tp_t\right) \tag{A4.E2}$$

Minimum air-dry soil water content is given by

$$\textit{if}\ q_t < q_{air}\ \textit{then}\ q_t = q_{air} \tag{A4.E3}$$

ANNEX F. SURFACE RUNOFF

Surface runoff (*R*) from topsoil is given by

$$\text{if}\ \left(q_t^{z} > T^{z}\right) \qquad R_t = q_t^{z} - T^{z} \tag{A4.F1a}$$

$$\text{if}\ \left(P_t > Ks_V^{z}\right) \qquad R_t = q_t^{z} - P^{z} \tag{A4.F1b}$$

ANNEX G. SOIL MATRIC POTENTIAL

Soil matric potential is given by

$$Mpot_t^{z} = \frac{\left(\dfrac{q_t^{z}}{WQS^{z}}\right)^{(1/l)}}{h_b} \tag{A4.G1}$$

ANNEX H. Evaporation from the soil

Evaporation from the bare soil:

$$E_{bare} = 3600D_{hr} \frac{\Delta V\left(\frac{R_n}{3600D_{hr}} - \frac{G}{3600D_{hr}}\right) + r_a c_p \left(\frac{e_s - e_a}{r_{a,s}}\right)}{l \times 10^3 \left[\Delta V + g_p * \left(1 + \frac{r_{s,s}}{r_{a,s}}\right)\right]}$$

where :

E_{bare} – Evaporation from a bare soil ($mm.day^{-1}$)

D_{hr} – daylit time for the day (hr)

ΔV – the rate of change of saturated vapour pressure with temeperature ($mbarK^{-1}$)

R_n – net daily radiation ($Jm^{-2}day^{-1}$)

G – ground heat - sink ($Jm^{-2}day^{-1}$)

r_a – air density ($kg.m^{-3}$)

c_p – specific heat capacity of air ($Jkg^{-1}K^{-1}$), assume = 1005.01

e_s – saturated vapour pressure (mbar)

e_a – actual vapour pressure (mbar)

$r_{a,s}$ – aerodynamic (boundary layer) resistance of the soil to water diffusion (sm^{-1}), assume = 2

$r_{s,s}$ – resistance of the soil surface to water diffusion (sm^{-1}), assume = 100 (A4.H1)

l – latent heat of vapourisation ($kJ.kg^{-1}$)

g_p – psychrometric constant ($mbar.K^{-1}$)

Evaporation from the shaded soil:

$$E_{shade} = 3600D_{hr} \frac{\Delta V(1 - f_{abs)}\left(\frac{R_n}{3600D_{hr}} - \frac{G}{3600D_{hr}}\right) + r_a c_p \left(\frac{e_s - e_a}{r_2 + r_a}\right)}{l \times 10^3 (\Delta V + g_p)}$$

where :

E_{shade} – Evaporation from the shaded soil ($mm.day^{-1}$)

D_{hr} – daylit time for the day (hr)

ΔV – the rate of change of saturated vapour pressure with temeperature ($mbarK^{-1}$)

f_{abs} – fraction of incoming radiation absorbed by the canopy (-)

R_n – net daily radiation ($Jm^{-2}day^{-1}$)

G – ground heat - sink ($Jm^{-2}day^{-1}$)

r_a – air density ($kg.m^{-3}$)

c_p – specific heat capacity of air ($Jkg^{-1}K^{-1}$), assume = 1005.01

e_s – saturated vapour pressure (mbar)

e_a – actual vapour pressure (mbar)

r_2 – aerodynamic resistance between the soil surface and the sink for momentum in the canopy (sm^{-1})

r_a – aerodynamic (boundary layer) resistance of the canopy to water diffusion (sm^{-1})

l – latent heat of vapourisation ($kJ.kg^{-1}$) (A4.H2)

g_p – psychrometric constant ($mbar.K^{-1}$)

Exchange coefficient:

$$K(h) = \frac{k^2 (h-d) u_z}{\ln\left(\frac{z_m - d}{z_{om}}\right)}$$

where:

$K(h)$ – exchange coefficient at height h ($m^2 s^{-1}$) (A4.H3)

k – Von Karman's constant (-)

h – crop height (m)

d – zero plane displacement height (m), assume $= 0.75h$

u_z – wind speed at height z_m (ms^{-1})

z_m – height of wind speed measurements (m)

z_{om} – roughness length governing momentum transfer of the crop (m), assume $= 0.123h$

Aerodynamic resistance between the soil surface and the canopy:

$$r_2 = \frac{h \cdot e^{\alpha_f}}{\alpha_f K(h)} \left(e^{\frac{-\alpha_f z'_{om}}{h}} - e^{\frac{-\alpha(d+z_{om})}{h}} \right)$$

where:

r_2 – aerodynamic resistance between the soil surface and the canopy (sm^{-1})

h – crop height (m) (A4.H4)

α_f – attenuation factor (-), assume = 2

$K(h)$ – exchange coefficient ($m^2 s^{-1}$)

z'_{om} – roughness length of the soil surface (m), assume = 0.003

d – zero plane displacement height (m), assume = $0.75h$

z_{om} – roughness length governing momentum transfer of the crop (m), assume = $0.123h$

APPENDIX 5 Soil characteristics

Soil geometry (node depths):

$$D_i = 0 \qquad ;0 \le i \le 1$$
$$D_{i+1} = D_i + D_z * i^2 \qquad ;1 < i \le N_{nodes}$$
$$D_z = \frac{LD}{S_c}$$
$$S_c = \sum_{i=0}^{i=N_{node}} S_{c,i}$$
$$S_{c,i} = 0 \qquad ;i = 0$$
$$S_{c,i} = S_{c,i-1} + i^2 \qquad ;0 < i \le N_{nodes}$$

where:
D_i – depth of node i (m)
N_{nodes} – number of soil nodes (-)
D_z – intermediate calculation (m)
LD – soil depth (m), INPUT
S_c – intermediate calculation (-)
i – node (-) (A5.1)

Node liquid flux:

$$F_{L,i} = \frac{(f_{l,i} - f_{u,i})}{D_{i+1} - D_i} - g \bullet \bar{k}_i$$

where:
$F_{L,i}$ – node liquid water flux
$f_{l,i}$ – lower node value of intermediate f (A5.2)
$f_{u,i}$ – upper node value of intermediate f
D_i – node depth (m)
g – gravitational acceleration (ms^{-1}) - assume = 9.81
$\bar{k}_i$ – intermediate value
i – node number

$$\left.\frac{dj}{dp}\right|_{l,i} = \frac{k_l}{D_{i+1} - D_i} + g\left.\frac{dk}{dp}\right|_{l,i}$$

where :

$\left.\frac{dj}{dp}\right|_{l,i}$ – derivative of vapour flux at the lowest node point

$k_{u,i}$ – intermediate value for upper node (A5.3)

D_i – depth of node

g – gravitational acceleration (ms^{-1}), assume = 9.81

$\left.\frac{dk}{dp}\right|_{l,i}$ – intermediate derivative

i – node number

$$\left.\frac{dj}{dp}\right|_{u,i} = \frac{k_{u,i}}{D_{i+1} - D_i} + g\left.\frac{dk}{dp}\right|_{u,i}$$

where :

$\left.\frac{dj}{dp}\right|_{u,i}$ – derivative of vapour flux at the highest node point

$k_{u,i}$ – intermediate value for upper node (A5.4)

D_i – depth of node

g – gravitational acceleration (ms^{-1}), assume = 9.81

$\left.\frac{dk}{dp}\right|_{u,i}$ – intermediate derivative

i – node number

$$
\begin{aligned}
&\mathrm{IF}(p_{w,i+1} < p_{ae,i})\\
&\quad k_{l,i} = k_{s,i}\left(\frac{p_{ae,i}}{p_{w,i+1}}\right)^{b_{uc,i}}\\
&\quad f_{l,i} = k_{l,i}\left(\frac{p_{w,i+1}}{1-b_{uc,i}}\right) \qquad\qquad \text{(A5.5)}\\
&\mathrm{ELSE}\\
&\quad k_{l,i} = k_{s,i}\\
&\quad f_{l,i} = k_{s,i}\left(\frac{p_{ae,i}\,b_{uc,i}}{1-b_{uc,i}} + p_{w,i+1}\right)
\end{aligned}
$$

$$\begin{aligned}
&\mathrm{IF}(p_{w,i} < p_{ae,i})\\
&\quad k_{u,i} = k_{s,i}\left(\frac{p_{ae,i}}{p_{w,i}}\right)^{b_{uc,i}}\\
&\quad f_{u,i} = k_{u,i}\left(\frac{p_{w,i}}{1-b_{uc,i}}\right)\\
&\mathrm{ELSE}\\
&\quad k_{u,i} = k_{s,i}\\
&\quad f_{u,i} = k_{s,i}\left(\frac{p_{ae,i}\,b_{uc,i}}{1-b_{uc,i}} + p_{w,i}\right)
\end{aligned} \qquad \text{(A5.6)}$$

$$\begin{aligned}
&\mathrm{IF}(\left|p_i - p_{i+1}\right| < 0.1)\\
&\quad \bar{k}_i = \frac{(k_{u,i} + k_{l,i})}{2}\\
&\quad \frac{dk}{dp}_{u,i} = -b_{uc,i}\frac{k_{u,i}}{p_{w,i}}\\
&\quad \frac{dk}{dp}_{,il} = -b_{uc,i}\frac{k_{l,i}}{p_{w,i+1}}\\
&\mathrm{ELSE}\\
&\quad \bar{k}_i = \frac{f_{u,i} - f_{l,i}}{p_{w,i} - p_{w,i+1}}\\
&\quad \frac{dk}{dp}_{u,i} = \frac{\bar{k}_i - k_{u,i}}{p_{w,i+1} - p_{w,i}}\\
&\quad \frac{dk}{dp}_{l,i} = \frac{k_{l,i} - \bar{k}_i}{p_{w,i+1} - p_{w,i}}
\end{aligned}$$

(A5.7)

where:

$p_{w,i}$ – node water potential
$p_{ae,I}$ – node air entry water potential
$b_{uc,I}$ – node slope of unsaturated conductivity

Node vapour flux:

$$F_{V,i} = k_{v,i}(h_{i+1} - h_i)$$
$$k_{v,i} = 0.66 V_{diff} V_{conc} P_i$$
$$P_i = q_{sat,i} - \frac{q_{su,i} - q_{sl,i}}{2}$$

where :
h_i – node humidity
V_{diff} – vapour diffusity , assume = 0.000024
V_{conc} – vapour concentration $(kg \cdot m^{-3})$, assume = 0.017
p_i – node porosity
$q_{sat,i}$ – saturated water content for the node
$q_{su,i}$ – upper node water content at start of time step
$q_{lu,i}$ – lower node water content at start of time step
(A5.8)

Derivative of vapour flux for upper node:

$$\frac{djv}{dp}_{u,i} = \frac{k_{v,i} M_w h_i}{R_m T_i}$$

where :
$\frac{djv}{dp}_{u,i}$ – vapour flux derivative for upper node
h_i – node humidity
M_w – molecular mass of water $(kg \cdot mol^{-1}) = 0.018$
R_m – universal gas constant $(J \cdot mol^{-1} \cdot K^{-1})$, assume = 8.314
T_i – temperature of the node (K)
i – node number
(A5.9)

Derivative of vapour flux for lower node:

$$\left.\frac{djv}{dp}\right|_{l,i} = \frac{k_{v,i} M_w h_i}{R_m T_i}$$

where :

$\left.\frac{djv}{dp}\right|_{l,i}$ – vapour flux derivative for lower node

h_i – node humidity (A5.10)

M_w – molecular mass of water $(kg \cdot mol^{-1}) = 0.018$

R_m – universal gas constant $(J \cdot mol^{-1} \cdot K^{-1})$, assume $= 8.314$

T_i – temperature of the node (K)

i – node number

Node humidity:

$$h_i = e^{\frac{M_w p_{w,i}}{R_m \cdot T_i}}$$

where :

h_i – node humidity

M_w – molecular mass of water $(kg \cdot mol^{-1}) = 0.018$ (A5.11)

$p_{w,i}$ – node water potential

R_m – universal gas constant $(J \cdot mol^{-1} \cdot K^{-1})$, assume $= 8.314$

T_i – temperature of the node (K)

i – node number

Node water content:

$$\begin{aligned}
&\mathrm{IF}(p_{w,i} < p_{ae,i})\\
&\quad q_{u,i} = q_{sat,i} + \left(\frac{p_{ae,i}}{p_{w,i}}\right)^{b_{1,i}}\\
&\quad b_{1,i} = \frac{1}{b_i}\\
&\quad \frac{dw}{dp}_{u,i} = \frac{-q_i b_{1,i}}{p_{w,i}}\\
&\mathrm{ELSE}\\
&\quad q_{u,i} = q_{sat,u,i}\\
&\quad \frac{dw}{dp}_{u,i} = 0.0001
\end{aligned}$$

where:

i – node number

$b_{1,i}$ – reciprical of soil b value

$\frac{dw}{dp}_{u,i}$ – upper water content derivative

$q_{u,i}$ – upper water content at end of time step

$p_{ae,i}$ – node air entry water potential

$p_{w,i}$ – node water potential (A5.11)

$$\mathrm{IF}(p_{w,i+1} < p_{ae,i+1})$$

$$q_{l,i} = q_{sat,i+1} + \left(\frac{p_{ae,i+1}}{p_{w,i+1}}\right)^{b_{1,i+1}}$$

$$b_{1,i+1} = \frac{1}{b_{i+1}}$$

$$\frac{dw}{dp}_{l,i} = \frac{-q_i b_{1,i+1}}{p_{w,i+1}}$$

ELSE

$$q_{l,i} = q_{sat,i+1}$$

$$\frac{dw}{dp}_{l,i} = 0.0001$$

where:

i – node number

$b_{1,i}$ – reciprical of soil b value

$\frac{dw}{dp}_{l,i}$ – lower water content derivative

$q_{l,i}$ – lower water content at end of time step

$p_{ae,i}$ – node air entry water potential

$p_{w,i}$ – node water potential (A5.12)

To find evaporation, solve the following, such that the mass balance error (E_S) < a maximum allowable value (0.000001):

Calculate humidity for the first node.

Calculate the node vapour flux for node 0:

$$k_{v,,i=0} = \frac{E_0}{1-h_f}$$

where: (A5.13)

E_0 – potential (Penman) evaporation (mm), per time step

h_f – fractional relative humidity (-)

$$F_{v,i=0} = k_{v,i=0}(h_{i=1}, -h_f)$$

(A5.14)

$$\frac{djv}{dp}_{u,i=0} = 0 \qquad (A5.15)$$

$$\left.\frac{djv}{dp}\right|_{l,i=0} = \frac{k_{v,i=0} M_w h_{i=1}}{R_m T_{i=1}} \tag{A5.16}$$

$$\left.\frac{dj}{dp}\right|_{l,i=0} = 0 \tag{A5.17}$$

$$\left.\frac{dj}{dp}\right|_{u,i=0} = 0 \tag{A5.18}$$

For each node, I, where i>0 and i<= number of nodes:

Calculate the node humidity for the next node.
Calculate the vapour and liquid fluxes and their derivatives for node i.
Calculate the upper and lower node soil water-contents

$$C_{wl,i} = \frac{V_{soil,i} \left.\frac{dw}{dp}\right|_{l,i}}{2t_s} \tag{A5.19}$$

$$C_{wl,i} = \frac{V_{soil,i} \left.\frac{dw}{dp}\right|_{u,i}}{2t_s}$$

where:
$C_{wl,i}$ – lower node water capacity (A5.20)
$C_{ul,i}$ – upper node water capacity
$V_{soil,i}$ – volume of soil at the node
t_s – model time-step (s)

$$a_i = -\left.\frac{dj}{du}\right|_{u,i-1} - \left.\frac{djv}{du}\right|_{u,i-1} \tag{A5.21}$$

$$c_i = -\left.\frac{dj}{dp}\right|_{l,i} - \left.\frac{djv}{dp}\right|_{l,i} \tag{A5.22}$$

$$b_{x,i} = \left.\frac{dj}{dp}\right|_{l,i-1} + \left.\frac{dj}{dp}\right|_{u,i} + \left.\frac{djv}{dp}\right|_{l,i-1} + \left.\frac{djv}{dp}\right|_{u,i} + C_{ul,i} + C_{wl,i-l} \tag{A5.23}$$

$$f_i = F_{L,i-1} + F_{V,i-1} - F_{L,i} = F_{V,i} + \frac{V_{soil,i}\left(q_{u,i} - q_{su,i} + q_{l,i-1} - q_{sl,i-1}\right)}{2t_s} \qquad \text{(A5.24)}$$

IF ($p_{surface}$ < 0)

$$f_{i=1} = 0$$
$$c_{i=1} = 0 \quad \text{(A5.25)}$$

$p_{surface}$ – water potential at the upper boundary, INPUT

$$E_s = \sum |f_i| \quad \text{(A5.30)}$$

prepare values for next iteration:

For all nodes from i = 1 to i = N_{nodes} - 1:

$$c_i = \frac{c_i}{b_{x,i}} \quad \text{(A5.31)}$$

$$f_i = \frac{f_i}{b_{x,i}} \quad \text{(A5.32)}$$

$$b_{x,i+1} = b_{x,i+1} - a_{i+1}c_i \quad \text{(A5.33)}$$

$$f_{i+1} = f_{i+1} - a_{i+1}f_i \quad \text{(A5.34)}$$

Calculate new node water potentials:

$$dp_{i=N_{nodes}} = \frac{f_{i=N_{nodes}}}{b_{x,i=N_{nodes}}} \quad \text{(A5.35)}$$

$$p_{w,i=N_{nodes}} = p_{w,i=N_{nodes}} - dp_{i=M_{nodes}} \quad \text{(A5.36)}$$

dp_i = change in node water potential for node i.

For all nodes from i = N_{nodes} – 1 down to i = 1

$$dp_i = f_i - c_i dp_{i+1}$$
$$l_{t,i} = 0.8|p_{w,i}|$$
$$a_{bv,i} = |dp_i|$$
$$\text{IF}(a_{bv,i} > l_{t,i}) \quad \text{(A5.37)}$$
$$dp_i = l_{t,i}\frac{dp_i}{a_{bv,i}}$$
$$p_{w,i} = p_{w,i} - dp_i$$

when iteration is complete (i.e. E_s < 0.00001), set the start upper water content to the end upper water content, for the upper and lower nodes.

$$E_{soil} = F_{v,i=0} \tag{A5.38}$$

E_{soil} – soil evaporation for the time step

APPENDIX 6 - Photosynthesis

Convert radiation from total radiation to photosynthetically active radiation:

$$R_{PAR} = \frac{R_{tot}\, p_{PAR}}{100}$$

where:

R_{PAR} – photosynthetically active radiation (Wm^{-2})

R_{tot} – total solar radiation (Wm^{-2})

p_{PAR} – percentage of incoming radiation that is in the photosynthetically active range (%), assume = 45

(A6.1)

Convert photosynthetically active radiation (*Wm^{-2}*) to photosynthetic photon flux density (*$umol.m^{-2}$*)

$$R_{PPFD} = R_{PAR}\, p_{PPFD}$$

where: (A6.2)

R_{PPFD} – radiation as a photosynthetic photon flux density $mmol \cdot m^{-2}$)

R_{PAR} – photosynthetically active radiation (Wm^{-2})

p_{PPFD} – conversion factor for W to umol PAR ($mmol \cdot W^{-1}$), assume = 4.5

Canopy leaf nitrogen, per m^2 leaf:

$$N_c = (N_0 - N_b)\frac{(1 - e^{-k_n})}{k_n} + N_b$$

where:

N_c – Canopy nitrogen content per m^2 leaf area ($mmol \cdot m^{-2}$) (A6.3)

N_0 – Leaf nitrogen content at the top of the canopy ($mmol \cdot m^{-2}$)

N_b - Leaf nitrogen content not associated with photosynthesis ($mmol \cdot m^{-2}$)

k_n - leaf nitrogen allocation coefficient (-), INPUT, De Pury (1995) gives a value of 0.713

Mitochondrial (dark) respiration:

$$R_d = 1.658 \times 10^6 e^{\frac{-54836}{8.3144(T_{leaf}+273.15)}} N_{leaf} \times 10^6$$

where:

R_d – mitochondrial (dark) respiraition ($\mu mol \cdot m^{-2} s^{-1}$)

T_{leaf} – leaf temperature (^0C)

N_{leaf} – leaf nitrogen content per m^2 of leaf ($kg \cdot m^{-2}$)

(A6.4)

Intercellular oxygen concentration:

$$O_i = 210\left(\frac{0.047 - 0.0013087T_{leaf} + 0.000025603T_{leaf}^2 - 0.00000021441T_{leaf}^3}{0.026934}\right)$$

where:

O_i – intercellular oxygen concentration ($mmol \cdot mol^{-1}$)

T_{leaf} – leaf temperature (^0C)

(A6.5)

Based on Von Caemmerer, Evans, Hudson & Andrews, (Planta 1994) and on Ecocraft photosynthesis (D. De Pury).

NB there is an approx. equivalence that 1 bar=1 mol/mol at 1atm

Rubisco to oxygen:

$$k_o = 248e^{\frac{36000(T_{leaf}+273-298)}{298R_m(T_{leaf}+273)}}$$

where: (A6.6)

k_o – rubisco to O_2 coefficient ($mmol \cdot mol^{-1}$)

T_{leaf} – leaf temperature (^0C)

Rubisco to carbon-dioxide:

$$k_c = 404e^{\frac{59400(T_{leaf}+273-298)}{298R_m(T_{leaf}+273)}}$$

where : (A6.7)

k_c – rubisco to CO_2 coefficient ($mmol \cdot mol^{-1}$)

T_{leaf} – leaf temperature (^oC)

Effective Michaelis-Menten constant of Rubisco:

$$k_m = k_c\left(1+\frac{O_i}{k_o}\right)$$

where :

k_m – effective Michaelis - Menten constant of rubisco ($mmol \cdot m^{-2} \cdot s^{-1}$)

k_c – Michaelis - Menten constant of rubisco for CO_2 ($mmol \cdot m^{-2} \cdot s^{-1}$)

O_i – Intercellular oxygen concentration ($mmol \cdot m^{-2} \cdot s^{-1}$)

k_o – Michaelis - Mentent constant of rubisco for O_2 ($mmol \cdot m^{-2} \cdot s^{-1}$)

(A6.8)

Leaf Rubisco catalytic site content:

$$e_t = \frac{8 \bullet 6.25 \bullet 0.22N_{leaf}}{550} \times 10^6$$

where :

e_t – leaf rubisco catalytic site content ($mmol \cdot m^{-2} s^{-1}$)

N_{leaf} – leaf nitrogen content ($kg \cdot m^{-2}$)

(A6.9)

Maximum rate of carboxylation by Rubisco at 25 °C:

$$V_{cmax,25} = 1.584e_t$$

where :

$V_{cmax,25}$ – maximum rate of carboxylation by rubisco at 25^{o}C ($mmol \cdot m^{-2} \cdot s^{-1}$)

e_t – leaf rubisco catalytic site content ($mmol \cdot m^{-2} \cdot s^{-1}$)

(A6.10)

Maximum rate of carboxylation by Rubisco:

$$V_{cmax} = V_{cmax,25}(1 + 0.0505(T_{leaf} - 25) - 0.000284(T_{leaf} - 25)^2 - 0.000309(T_{leaf} - 25)^3)$$

where :

V_{cmax} – maximum rate of carboxylation by rubisco ($mmol \cdot m^{-2} \cdot s^{-1}$)

$V_{cmax,25}$ – maximum rate of carboxylation by rubisco at 25^oC ($mmol \cdot m^{-2} \cdot s^{-1}$)

T_{leaf} – leaf temperature (^oC)

(A6.11)

Fraction of the canopy that is sunlit:

$$f_{sun} = \frac{1 - e^{-k'_b L_c}}{k'_b L_c}$$

where :

f_{sun} – fraction of the canopy that is sunlit (-)

L_c – leaf area index of the canopy ($m^2 m^{-2}$)

k'_b –beam radiation canopy extinction coefficient (-)

(A6.12)

Sunlit canopy carboxylation by Rubisco

$$V_{cmax,sun} = f_{sun} V_{cmax}$$

where :

$V_{c\,max,sun}$ – sunlit canopy carboxylation by rubisco ($mmol \cdot m^{-2} \cdot s^{-1}$)

f_{sun} – fraction of the canopy that is sunlit (-)

V_{cmax} – maximum rate of carboxylation by rubisco ($mmol \cdot m^{-2} \cdot s^{-1}$)

(A6.13)

Shaded canopy carboxylation by Rubisco per unit leaf area:

$$V_{cmax,shade} = (1 - f_{sun})V_{cmax}$$

where :

$V_{cmax,shade}$ – shaded canopy carboxylation by rubisco ($mmol \cdot m^{-2}s^{-1}$)

f_{sun} – fraction of the canopy that is sunlit (-)

V_{cmax} – maximum rate of carboxylation by rubisco ($mmol \cdot m^{-2}s^{-1}$)

(A6.14)

Maximum rate of potential electron transport per unit leaf area at 25 °C:

$$J_{max,25} = 2.1 \cdot V_{cmax,25}$$

where :

$J_{max,25}$ – maximum rate of electron transport rate at 25° C ($mmol \cdot m^{-2} \cdot s^{-1}$)

$V_{cmax,25}$ – maximum rate of carboxylation by rubisco at 25° C ($mmol \cdot m^{-2} \cdot s^{-1}$)

(A6.15)

Maximum rate of potential electron transport per unit leaf area:

$$J_{max} = J_{max,25} \cdot e^{\frac{(T_K - 298)E_a}{298 R_m \cdot T_k}} \left(\frac{1 + e^{\frac{298S - H}{298R}}}{1 + e^{\frac{S \cdot T_K - H}{R_m T_K}}} \right)$$

where :

J_{max} – maximum rate of electron transport rate ($mmol \cdot m^{-2} \cdot s^{-1}$) (A6.16)

$J_{max,25}$ – maximum rate of electron transport rate at 25° C ($mmol \cdot m^{-2} \cdot s^{-1}$)

T_K – leaf temperature in kelvin (K)

E_a – activation energy of electron transport ($J \cdot mol^{-1}$)

R_m – universal gas constant ($J \cdot mol^{-1} \cdot K^{-1}$), assume = 8.314

S – electron transport temperature response parameter ($J \cdot K^{-1} \cdot mol^{-1}$), INPUT

H – curvature parameter of J_{max} ($J \cdot mol^{-1}$)

Irradiance dependence of electron transport:

$$q_I J^2 - (I_{le} + J_{max})J + I_{le} J_{max} = 0$$

where :

q_1–curvature of leaf response of electron transport to irradiance (-) (A6.17)

J – rate of electron transport rate per unit leaf area ($mmol \cdot m^{-2} \cdot s^{-1}$)

I_{le} – PAR effectively absorbed by PSII per unit leaf area ($mmol \cdot m^{-2} \cdot s^{-1}$)

J_{max} – potential rate of electron transport rate per unit leaf area ($mmol \cdot m^{-2} \cdot s^{-1}$)

PAR effectively absorbed by PSII:

$$I_{le} = \frac{I_l}{2}(1 - f)$$

where: (A6.18)

I_{le} – PAR effectively absorbed by PSII per unit leaf area ($mmol \cdot m^{-2} \cdot s^{-1}$)

I_l – total absorbed PAR per unit leaf area ($mmol \cdot m^{-2} \cdot s^{-1}$)

f – spectral correction factor (-), INPUT, assume = 0.15

CO_2 compensation point of photosynthesis in the absence of respiration:

$$\Gamma^* = \Gamma^*_{25} + 1.88(T_l - 25) + 0.036(T_l - 25)^2$$

where: (A6.19)

Γ^* – CO_2 compensation point in the absence of respiration ($mmol \cdot mol^{-1}$)

Γ^*_{25} – CO_2 compensation point in the absence of respiration at $25^0 C$ ($mmol \cdot mol^{-1}$)

T_l – leaf temperature (^0C)

Numerically solve the following equations to give a value for photosynthetic rate and stomatal conductance, by altering the value for stomatal conductance:

Rearranged Ball-Berry equation:

$$A_n = \frac{(g_c - g_0)Ca}{g_1 h_f}$$

where:

A_n – net photosynthesis calculate by the Ball - Berry - Woodrow method ($mmol \cdot m^{-2} \cdot s^{-1}$)

g_c – stomatal conductance of CO_2, value changed to find solution ($mol \cdot m^{-2} \cdot s^{-1}$) (A6.20)

C_a – atmospheric carbon concentration ($umol \cdot mol^{-1}$), ≈ 370

g_0 – minimum stomatal conductance ($mol \cdot m^{-2} \cdot s^{-1}$), INPUT

g_1 – slope of the ball - berry equation (-), INPUT

h_f – fractional relative humidity (-)

RubP limited photosynthesis:

$$\frac{4}{g_c}A_{j,n}{}^2+\left(\frac{(4*R_d-J)}{g_c}-8\Gamma^*-4C_a\right)A_{j,n}+\left[J(C_a-\Gamma^*)-4R_d(C_a+2\Gamma^*)\right]=0$$

where :

$A_{j,n}$ – RubP limted value of net photosynthesis ($\mu mol \cdot mol^{-1}s^{-1}$)

R_d – mitochonrial (dark) respiration (A6.21)

J – rate of electron transport rate per unit leaf area ($\mu mol \cdot m^{-2} \cdot s^{-1}$)

g_c – stomatal conductance for CO_2 ($mol \cdot m^{-2} \cdot s^{-1}$)

Γ^* – CO_2 compensation point in the absence of respiration ($\mu mol \cdot mol^{-1}$)

C_a – Atmospheric carbon concentration ($umol \cdot mol^{-1}$), INPUT ≈ 370

Rubisco limited photosynthesis:

$$\frac{1}{g_c}A_{c,n}{}^2+\left(\frac{R_d-V_{cmax}}{g_c}-C_a-k_m\right)A_{c,n}+\left[V_{cmax}(C_a-\Gamma^*)-R_d(C_a+k_m)\right]=0$$

where :

$A_{c,n}$ – Rubisco limted value of net photosynthesis ($\mu mol \cdot mol^{-1}s^{-1}$)

R_d – mitochonrial (dark) respiration (A6.22)

$V_{c\,max}$ – maximum rate of carboxylation by rubisco ($\mu mol \cdot m^{-2} \cdot s^{-1}$)

g_c – stomatal conductance for CO_2 ($mol \cdot m^{-2} \cdot s^{-1}$)

Γ^* – CO_2 compensation point in the absence of respiration ($\mu mol \cdot mol^{-1}$)

C_a – Atmospheric carbon concentration ($umol \cdot mol^{-1}$), INPUT ≈ 370

k_m – effective Michaelis - Menten constant ($mol \cdot m^{-2} \cdot s^{-1}$)

Net photosynthesis by Farquhar method:

$$A_n = \min(A_{c,n}, A_{j,n})$$

where : (A6.23)

A_n – Net photosynthesis ($\mu mol \cdot mol^{-1}s^{-1}$)

$A_{c,n}$ – Rubisco limted value of net photosynthesis ($\mu mol \cdot mol^{-1}s^{-1}$)

$A_{j,n}$ – RubP limted value of net photosynthesis ($\mu mol \cdot mol^{-1}s^{-1}$)

ANNEX A. Transpiration

Transpiration calculation:

$$E_{transp} = 3600D_{hr} \frac{\Delta V\left(\frac{R_n}{3600D_{hr}} - \frac{G}{3600D_{hr}}\right) + r_a c_p \left(\frac{e_s - e_a}{r_a}\right)}{l \times 10^3 \left[\Delta V + g_p * \left(1 + \frac{r_s}{r_a}\right)\right]}$$

where :

E_{transp} – Transpiration from the plants (mm.day^{-1})

D_{hr} – daylit time for the day (hr)

ΔV – the rate of change of saturated vapour pressure with temeperature (mbarK^{-1})

R_n – net daily radiation (Jm^{-2}day^{-1})

G – ground heat - sink (Jm^{-2}day^{-1})

r_a – air density (kg.m^{-3})

c_p – specific heat capacity of air (Jkg^{-1}K^{-1}), assume = 1005.01

e_s – saturated vapour pressure (mbar)

e_a – actual vapour pressure (mbar)

r_a – aerodynamic (boundary layer) resistance of the canopy to water diffusion (sm^{-1})

r_s – resistance of the canopy surface to water diffusion (sm^{-1}) (A6.A1)

l – latent heat of vapourisation (kJ.kg^{-1})

g_p – psychrometric constant (mbar.K^{-1})

Appendix J: Example Process model inputs

Example of parameterisation for Mefyque-Lite for *Pinus Sylvestris* and *Populus alba* and Brasschat Stand data.

Gaby Deckmyn

Input for the Species *Pinus sylvestris*

Allocation

maxNeedleAge years	2
interWhorlMin, (minimal distance between whorls) m	0.2
interWhorlMax, m	0.5
leafAngle	1.1
widthHeightRatio, ratio of crownwidth to height of a dominant tree	0.71
relocateCarbon, C reused when leaves fall, 0-1	0.00003
RSratio	0.19
SLA, m2/kgC	10.55
leafDim, characteristic leaf dimension in m, for needle is diameter	0.002
numBranchesWhorl, number of branches in a whorl	6
branchLengthEfficiency, ratio of distance to crown outside and branch length	0.9

Photosynthesis

lightCompens, umol	23
CO2compens25, Pa	3.69
Cair, Pa	36
rootABAsynthesis, µmol ABA MPa-1 m-2 s-1, after Dewar	16
ABAsequestration mol m-2s-1	0.0001
photosyntheticCapacitytoLeafN, 0-2	0.6
leafABAsynthesis, µmol ABA MPa-1 m-2 s-1, after Dewar	8
kn, parameter for N distribution	0.713
leafNnonPhotosynthetical, N not used for photosynthesis, mmol m^{-2}	200
LeafNmax, maxNcontent for the species, kg m^{-2}	0.00245
dirrefl (leaf reflectance of direct light) 0-1	0.25
difrefl 0-1	0.2

Respiration

stemResp, constructionresp per unit growth kgC/kgC	0.123
leafResp	0.323
Frresp	0.323
Crresp	0.123
StQ10, stemQ10,	2
BrQ10, branch	2

CrQ10, coarse root	2
FrQ10, fine root	2
leafQ10	2
StBase, base respiration, kgC kgC-1 day-1	0.00048
FrBase	0.008
BrBase	0.00048
CrBase	0.00048
LeafRBase	0.008

Transpiration

transMax, maximal transpiration rate, kg H2O m-³s-1	0.00003
pressureGradient, max gradient in pressure from root to leaf, Pa	2000000
pipeEffic, efficiency of pipes in conducting water, %	29
evapFraction, fraction of intercepted rain on leaves evaporating, 0-1	0.1
numDaysStorageUse, days after budburst that stored carbon is used	15
numDaysLeafFall, duration of autumn leaf fall, days	30
startLeaffall, 1st day of leaffall for deciduous or day after which no needle growth	300
FRturnoverRate, yearly turnover of fine roots, %	150
NumBranchesWhorl	6
BranchLengthEfficiency	0.9

Woodquality

StPipeVolPerc	91
BrPipeVolPerc	90
StFibreVolPerc	2.5
BrFibreVolPerc	3
watPotLateWood, soil potential threshold for latewood formation, Pa	-500000
stPipeRadius	0.000007
brPipeRadius	0.0000065
winterEmbolition, percentage of pipes losing functionality over winter	15
cellWallWidth, m	0.0000035
PARENCHstoreCap, ratio stored to construction C	1.2
heartwoodAge, years	25
embolitionChance, daily chance of embolition	0.0009

fibreDensity	495
elasticity, Youngs modulus, Pa	0.0000006
branchFall, average age for a dead branch to fall	4
branchOvergrown, average age for an dead branch to overgrow	4
LWthreshold, piperadius below which wood = latewood, m	0.00001
start of Latewood formation, day of year (latest)	200
pipeParamA	2.5
pipeParamB	15

Input for the Species *Populus alba*

Allocation

maxNeedleAge years	0
interWhorlMin, (minimal distance between whorls) m	0.053
interWhorlMax, m	0.058
leafAngle	0.3
widthHeightRatio, ratio of crownwidth to height of a dominant tree	0.33
relocateCarbon, C reused when leaves fall, 0-1	0.00003
RSratio	0.23
SLA, m2/kgC	20.4
leafLength, m	0.05
numBranchesWhorl, number of branches in a whorl	1
branchLengthEfficiency, ratio of distance to crown outside and branch length	3.0

Photosynthesis

lightCompens, umol	31.5
CO2compens25, Pa	5.03
Cair, Pa	36
rootABAsynthesis, µmol ABA MPa-1 m-2 s-1, after Dewar (default 4)	4
ABAsequestration mol m-2s-1	0.0001
photosyntheticCapacitytoLeafN, 0-2	1.9
leafABAsynthesis, µmol ABA MPa-1 m-2 s-1, after Dewar (default 1)	1
kn, parameter for N distribution	0.713
leafNnonPhotosynthetical, N not used for photosynthesis, mmol m^{-2}	130
LeafNmax, maxNcontent for the species, kg m^{-2}	0.0028
dirrefl (leaf reflectance of direct light) 0-1	0.036

difrefl 0-1	0.036

Respiration

stemResp, constructionresp per unit growth kgC/kgC	0.123
leafResp	0.123
Frresp	0.123
Crresp	0.123
StQ10, stemQ10,	2
BrQ10, branch	2
CrQ10, coarse root	2
FrQ10, fine root	2
leafQ10	2
StBase, base respiration, kgC kgC-1 day-1	0.00018
FrBase	0.003
BrBase	0.00018
CrBase	0.00018
LeafRBase	0.003

Transpiration

transMax, maximal transpiration rate, kg H2O m^{-3}s-1	0.00004
pressureGradient, max gradient in pressure from root to leaf, Pa	2000000
pipeEffic, efficiency of pipes in conducting water, %	85
evapFraction, fraction of intercepted rain on leaves evaporating, 0-1	0.1
numDaysStorageUse, days after budburst that stored carbon is used	15
numDaysLeafFall, duration of autumn leaf fall, days	45
startLeaffall, 1st day of leaffall for deciduous or day after which no needle growth	300
FRturnoverRate, yearly turnover of fine roots, %	140
NumBranchesWhorl	1
BranchLengthEfficiency	3.0

Woodquality

StPipeVolPerc	64
BrPipeVolPerc	64
StFibreVolPerc	20
BrFibreVolPerc	20
watPotLateWood, soil potential threshold for latewood formation, Pa	-500000

stPipeRadius	0.000046
brPipeRadius	0.000045
winterEmbolition, percentage of pipes losing functionality over winter	5
cellWallWidth, m	0.0000035
PARENCHstoreCap, ratio stored to construction C	5
heartwoodAge, years	25
embolitionChance, daily chance of embolition	0.0003
fibreDensity	760
elasticity, Youngs modulus, Pa	0.0000006
branchFall, average age for a dead branch to fall	4
branchOvergrown, average age for an dead branch to overgrow	4
LWthreshold, piperadius below which wood = latewood, m	0.00002
start of Latewood formation, day of year (latest)	200
pipeParamA	2.5
pipeParamB	100

10.1.1 Stand data for Brasschaat

run	*Braspaper1*
numLayer, number of equal layers simulated, max 60	20
numYears, max 10	10
numTrees, max 3	3
dailyClimate available? from daily data=1, from monthly averages=0	0
layerHeight, m	1.5
number of Trees 1, ha-1	250
number of trees 2, ha-1	200
number of trees 3, ha-1	18
coniferous (1=true, 0 is false)	1
profileTreeNum, of which tree to save a stemdensity profile	3
profileHeight, at which height to create the profile	1.25
sunAngle, average sunangle (will soon be replaced by calculated value)	1.4
wind, average wind, if no wind data are available	1
slope, slope of the stand	0.05
latitude	51.7

thinningyears, up to 5 years in which to thin end of that year, year2=first simulated year	8 0 0 0 0
newcomposition , trees per ha of each tree category after the first thinning	201 160 14
newcomposition , trees per ha of each tree category after the second thinning	0 0 0
newcomposition , trees per ha of each tree category after the third thinning	0 0 0
newcomposition , trees per ha of each tree category after the fourth thinning	0 0 0
newcomposition , trees per ha of each tree categorie after the fifth thinning	0 0 0
initialheartwood, % heartwood in initial trees (tabs between the trees)	30 35 45

Description of initial trees

Tree1

Topaxis, topaxis of crown, m	5
CrownDepth, m	7.1
Start live crown, m	11.4
Crown radius, m	1.68
stem biomasss, kgC	75.6
Coarse root biomass, kgC	13.4
Fine root biomass, kgC	3.12
Needle or leaf Biomass, kgC	3.22
stemRadius,m	0.20
age at start simulation	70

°°°°°°°°*NOTE*°°°°°°°°°°°

For the branches, different whorls need to be initialised, Data input is tab-delimited for as many whorls (max 10) as you want. Don't put live branches below the start of the live crown!
If wood quality does not need to be determined, 1 whorl will work as well!

branch biomass (1 branch), kgC

0.4	0.3	0.3	0.3	0.2	0.2	0.2	0.2	0	0

branch length,m

1.5	1.3	1.2	1.2	1.2	1.2	1.2	1	0	0

branch radius, m

0.005	0.004	0.004	0.003	0.004	0.002	0.002	0.002	0.0	0.0

live(1) or year of death

1987	1989	1990	1	1	1	1	1	0	0

number of fallen branches

2	0	0	0	0	0	0	0	0	0

number of overgrown branches

1	0	0	0	0	0	0	0	0	0

year of appearance

1979	1980	1982	1985	1987	1988	1989	1990	0	0

height, m

19	18	12	15	17	9	9.9	19	0	0

Tree 2

Topaxis, m	6
CrownDepth, m	8.25
Start live crown, m	10.05
Crown radius, m	2.01
stem biomasss, kgC	205.2
Coarse root biomass	27
Fine root biomass	5.4
Needle or leaf Biomass	5.4
StemRadius	0.32
age at start simulation	70

branch biomass (1 branch), kgC									
0.5	0.4	0.4	0.3	0.2	0.2	0.2	0.2	0	0
branch length,m									
1.6	1.4	1.3	1.2	1.2	1.2	1.2	1	0	0
branch radius, m									
0.005	0.004	0.004	0.003	0.004	0.002	0.002	0.002	0	0
live(1) or year of death									
1987	1989	1990	1	1	1	1	1	0	0
number of fallen branches									
2	0	0	0	0	0	0	0	0	0
number of overgrown branches									
1	0	0	0	0	0	0	0	0	0
year of appearance									
1979	1980	1982	1985	1987	1988	1989	1990	0	0
Height, m									
7	8	9	11	12	13	14	15	0	0

Tree3

Topaxis	7
CrownDepth	8.29
Start live crown	10.61
Crown radius	2.1
stem biomasss in kgC	403
Coarse root biomass	22.04
Fine root biomass	8.76
Needle/leaf Biomass	8.76
StemRadius	0.43
age at start simulation	70

branch biomass (1 branch), kgC									
0.6	0.5	0.5	0.5	0.3	0.3	0.2	0.2	0	0
branch length,m									
1.7	1.5	1.4	1.4	1.4	1.3	1.2	1	0	0
branch radius, m									
0.005	0.004	0.004	0.003	0.004	0.002	0.002	0.002	0	0
live(1) or year of death									
1987	1989	1990	1	1	1	1	1	0	0
number of fallen branches									
2	0	0	0	0	0	0	0	0	0
number of overgrown branches									
1	0	0	0	0	0	0	0	0	0
year of appearance									
1979	1980	1982	1985	1987	1988	1989	1990	0	0
Height, m									
7	8	9	11	12	13	14	15	0	0

Soil data for Brasschaat

soilWaterContent, kg m-³ 300

maxWaterContent, kg m-³ 400

Composition in methabolisable, cell and lignine of the tree compartments (0-1), tab delimited

branchComposition(met-cell-lig)	0.05	0.8	0.15
Leaf Composition	0.5	0.4	0.1
Fine root composition	0.4	0.4	0.2
Coarse root composition	0.05	0.75	0.2
Stem composition	0.05	0.8	0.15

inNfert, daily N fertilisation, kg day-1 0.0

inNatmos, daily N from atmospheric input 0.0000164

NamoNitRatio, ammonium to nitrate ratio of N input 0.5

fClay, soil fraction clay, 0-1 (assuming 3 fractions(clay, sand, s?), to a total of 1=inorganic soil) 0.067

fSand 0.839

Tornley p53-55, T dependency is described with generic function allowing different shapes
Mft, describes total sensitivity of the function, default=1 1

Tzero, min T below which there are no processes, °C 0

Tpzero, max T above which there are no processes 45

Qft, describes the shape of the function, 1=quadratic(larger range), 2=cubic(default), 3=quarctic(narrow) 2

Tref, ref T at which the process rates were measured (here the decay rates, °C) 25

rootingDepth, m	2
CtoNmet, of the litter	20
fCbioTuSOMsandy, fraction of dead micro-organisms going into uSOM (instead of pSOM) in sandy soil	0.7
fCbioTuSOMClay, idem in clay	0.3
cBioClay, rate constant for partitioning dead to uSOM and pSOM	3
fCbioSoilMet, fraction of dead micro going to Met pool, default 0.95	0.75
optimalCN, kgC/kgN, Thornley p86	25
pH	3.9
q_decayLig, constant describing dependence of cel and lig decay on total lig content	3.0
AmoMaxLig, max amo that will stop all lignin degradation, kg Amo m^{-2}	0.01
Cnfungi	45
Cnbact	35
Cnmych	40
k_surfCel20	0.3
k_surfLig20	0.1
k_surfMet20	0.7
k_soilCel20	0.6
k_soilMet20	0.7
k_SoilLig20	0.05
k_coarseMet20	0.6
k_coarseCel20	0.1
k_coarseLig20	0.01
k_smallMet20	0.3
k_smallCel20	0.1
k_smallLig20	0.01
k_uSOM20	0.1
k_pSOM20	0.1
k_sSOM20	0.1
fungiDeathRate20	0.01
bactDeathRate20	0.01
mychDeathRate20	0.01
yieldCmet	8

yieldCcel	2
yieldClig	0.1
yieldCuSOM	0.9
yieldCpSOM	0.5
yieldCsSOM	0.1
yieldCplant	8
yieldCsol	8
fungiGrowth20	0.2
bactGrowth20	0.2
mychGrowth20	0.2

reqEsurvfungi is a kind of maintenance respiration, so put it to 10%, but E yield is up to 8!

ReqEsurvFungi	30
ReqEsurvBact	45
ReqEsurvMych	30
ReqEgrowthFungi	100
ReqEgrowthBact	100
ReqEgrowthMych	100

From Thornley, parameters for Nfixation by bact

KNfixBact	0.000050
JNfixBact	0.001
KCsolNfix	0.0005

Initialisation of the pools

CuSOM, unprotected soil organic matter, kgC m^{-2}	0.577
CpSOM, protected	5.712
CsSOM, stabilised	5.111
NsSOM, stabilised N content	0.45
CsurfMet, methabolisable surface litter,kgC m^{-2}	0.01
CsurfCel, cellulose	0.395
CsurfLig, lignin	0.595
CsoilMet, idem for soil litter pools (from dead roots)	0.2
CsoilCel	0.695
CsoilLig	0.795
CcoarseMet	0.25
CcoarseCel	0.55

CcoarseLig	0.2
CsmallCel	0.55
CsmallLig	0.2
CsmallMet	0.25
CfineCel	0.55
CfineMet	0.25
CfineLig	0.2
NuSOM	0.075
NpSOM	0.739
Namo	0.0036
Nnit	0.0009
Cmyc	0.070
Cbact	0.025
Cfungi	0.045
CsoilFauna, initial C in earthworms etc.	0.05

Appendix K: Technical Annex

QUALITY OF LIFE AND MANAGEMENT OF LIVING RESOURCES

FORECASTING THE DYNAMIC RESPONSE OF TIMBER QUALITY TO MANAGEMENT AND ENVIRONMENTAL CHANGE: AN INTEGRATED APPROACH

MEFYQUE

Proposal QLRT-2000-00345

KEY ACTION 5: Sustainable agriculture, fisheries and forestry and integrated development of rural areas including mountain areas

RTD Action 5.3: Sustainable and multipurpose utilisation of forest resources; the integrated forestry-wood chain

Priority 5.3.1: Multifunctional management of forests

Priority 5.3.2: Strategies for the sustainable and multipurpose utilisation of forest resources; the forestry-wood chain

Final Version
26 October 2000

TABLE OF CONTENTS

1. OBJECTIVES AND EXPECTED ACHIEVEMENTS

The overall objective of the project is to increase understanding of the relationships between site conditions and growth, yield and timber quality for current and future scenarios of atmospheric change. This objective will be achieved by developing a prototype modelling system operating at an appropriate forestry management scale (the forest stand) to forecast timber growth, yield, quality and marketability suitable for application in the EU. The system will also predict and quantify reversible and irreversible energy fluxes to and from the forest, including those due to fossil fuel consumption. Such a forecasting system must account for the reshaping of European forestry through policies aimed at the optimisation of sustainable management, the provision of renewable resources and the protection of the global and local environment, in particular the role of forestry in the carbon cycle. Thus, a fully integrated approach to pre- and post-production activities is required to develop a tool suitable for use both by the timber industry and national/governmental policy decision-makers.

THE PRINCIPAL DELIVERABLE OF THE PROJECT IS AN INTEGRATED MODELLING SYSTEM THAT WILL ASSIST FOREST MANAGERS, THE TIMBER INDUSTRY AND POLICY MAKERS TO DECIDE WHETHER MANAGEMENT OF FORESTS SHOULD BE PRIMARILY FOR PRODUCTION, CONSERVATION OR AMENITY OUTPUTS, WITHIN THE CONTEXT OF MULTI-PURPOSE FOREST MANAGEMENT.

In order to achieve this overall objective the project has the following specific objectives:

1. to increase understanding of the relationship between tree growth, timber quality, site conditions and stand management using a network of traditional mensuration sample plots and supplementary information on structure, quality, environment and physiology;

2. to increase understanding of the influence of climate and atmospheric composition (climate change) on timber quality through manipulative experiments and the analysis of wood properties for material grown under ambient and enhanced CO_2 concentrations. This will be obtained through a combination of the analysis of existing plant material from previous experiments and new material from specific manipulative experiments;

3. to construct and validate a coupled empirical-process model of timber growth, yield, quality and carbon sequestration including non-harvestable fractions, operating at the stand scale. This will be achieved using data collected under objectives 1 and 2, and additional validation being provided by flux experiments at monitored sites. This model will be based on widely accepted functions in an innovative modular structure;

4. to simulate the impacts of future scenarios of atmospheric composition (climate change) on timber growth, yield and carbon sequestration at different spatial scales (stand and regional). The most up-to-date Global Climate Model outputs and predictions of atmospheric composition change will be used as drivers for the model developed under objective 3;

5. to simulate and quantify the impact of forest management on timber growth, yield and quality allowing the optimisation of economic return and/or carbon sequestration and energy cost: benefits through sustainable practices of production;

6. to simulate and quantify the impact of forest management on the industrial energy and carbon balances as a significant contribution towards a full life cycle assessment of wood timber production and forestry as an important land use system.

2. PROJECT WORKPLAN

2.1 INTRODUCTION

The work-plan can be separated into 4 major components:

1. the monitoring component;

2. the manipulative component,
3. the laboratory component, and
4. the modelling component.

Each is outlined in overview in the paragraphs below, and the methodology, deliverables and milestones associated with each component are described in detail in the individual work-packages.

2.1 PROJECT COMPONENTS

2.1.1 The Monitoring Component

The **MONITORING COMPONENT** is designed to characterise the relationships between site conditions, growth, yield prediction and timber quality and how this varies as a function of multi-purpose forest management practices. It will combine field measurements of site conditions, forest growth, and of quality for standing timber, together with an assessment of forest product usage.

Primary sites. Existing monitoring protocols will be carried out as prescribed in the relevant technical manual of the UN/ECE ICP Forests Level II Forest Health Monitoring Network. A summary of the measurements carried out under this programme is given in the table below:

Mensurational	Climate	Pedological	Foliage	Site characteristics
Diameter at breast height (DBH) of all trees to the nearest 0. 1 cm	Automated meteorological weather stations for collection of sub-hourly data on: Temperature Precipitation Wind-speed Solar radiation Relative humidity **OR** Standard climatological weather stations providing the same parameters	Soil water content	Foliar chemical analysis	Species composition
Total height of (a) 100 largest trees by diameter per ha (b) 10 trees selected through the diameter distribution		Water release curve	Crown condition	Crop details: (a) Planting year (b) Establishment year (c) Crop history (brashing, thinning) (d) Windblows
Tree shape, e.g. swelling, leaning, forked		Soil profile description	Litter fall quantification	Major soil type (FAO classification)
Crown width and depth	Atmospheric deposition	Soil solution sampling analysis	Phyto-pathological observations	Row spacing
Stem form		Rooting depth	Phenology	Aspect, slope
Branching habit		Soil chemical analysis	Ground vegetation analysis	Altitude

Sampling frequency and analysis of existing data.

		Frequency	
	Start year	***Sampling***	***Analysis***
Foliar analysis	1995	2 years	2 years
Soil analysis	1995	10 years	10 years
Growth increment	1995-96	5 years	5 years
Crown condition	1995	1 years	
Meteorology	1994	Hourly	Automatic
		Daily	Manual
Ground vegetation	1998	3 years	3 years
Litter fall	1998	2 weeks (autumn) 4 weeks (rest of year)	2 weeks (autumn) 4 weeks (rest of year)
Soil solution	1995	2 weeks	4 weeks
Phenology	1998	2 weeks	

Additionally, the following data will be collected:

	UK		**Belgium**		**Germany**		**Italy**	
	1/0	*Timestep*	*1/0*	*Timestep*	*1/0*	*Timestep*	*1/0*	*Timestep*
Tree height	P	Yrs 1, 3	P	Yrs 1, 3	P	Yrs 1, 3	P	Yrs 1, 3
Root depth	P	Yrs 1, 3	P	Yrs 1, 3	P	Yrs 1, 3	P	Yrs 1, 3
Needle/leaf mass ha^{-1}	P	Yrs 1, 3	P	Yrs 1, 3	P	Yrs 1, 3	P	Yrs 1, 3
DBH	P	Yrs 1, 3	P	Yrs 1, 3	P	Yrs 1, 3	P	Yrs 1, 3
Root mass		Yrs 1,3	P	Yrs 1,3				Yrs 1,3

A protocol designed to describe the quality of timber applicable to the processing industry will be added to these existing measurements, to provide comprehensive data sets of stand characteristics that will be used to calibrate and validate the coupled empirical-process model of stand growth and quality. An indication of the approach that will be adopted is given in the following section.

Quality assessment of standing timber at primary and secondary sites. Assessment of stem straightness will be carried out at primary and secondary sites, which specifies that:

a. Bow should not exceed 1 cm for every 1m length, and that this is in one plane and one direction only.
b. Bow is measured as the maximum deviation at any point of a straight line joining centres at each end of the log from the actual centre line of the log.

The full assessment protocol for timber quality is based on four log length categories that are associated with different value wood products, to ensure the straightness measure would indicate product potential.

SCORE	MAXIMUM LOG LENGTH OBSERVED	QUALITY ASSESSMENT
1	No straight logs < 2 m	Lengths are generally too short for high volume saw-milling and are more suitable for industrial processing, e.g. pulp and panel board manufacture. New technology enables shorter lengths to be joined together to make longer logs.
2	2 m+ and less than 3 m (1 or 2 logs per stem)	The main market for straight logs of these lengths is fencing, pallets and packaging. They are usually too short for processing into carcassing timber but have some potential for studding. New technology enables shorter lengths to be joined together to make longer logs.
3	• 3 m < 4 m (1 log per stem)	Straight logs of these lengths can be marketed to the construction market although they are less sought after, but they also have market potential in the fencing and packaging industry.
4	• 4 m (1 only per stem)	Straight logs of these lengths are important for the structural timber and carcassing markets and further expansion into these markets will depend on the ability to produce a significant volume of these lengths.

Field restrictions. The stem straightness assessment is restricted to the first 6 m butt section of standing trees, because the butt section is the most important for higher value products. In practice, it is difficult to see clearly above 6 m, particularly in unthinned stands. Using this method there are six possible combinations of log lengths, as shown stylistically in Figure 1.

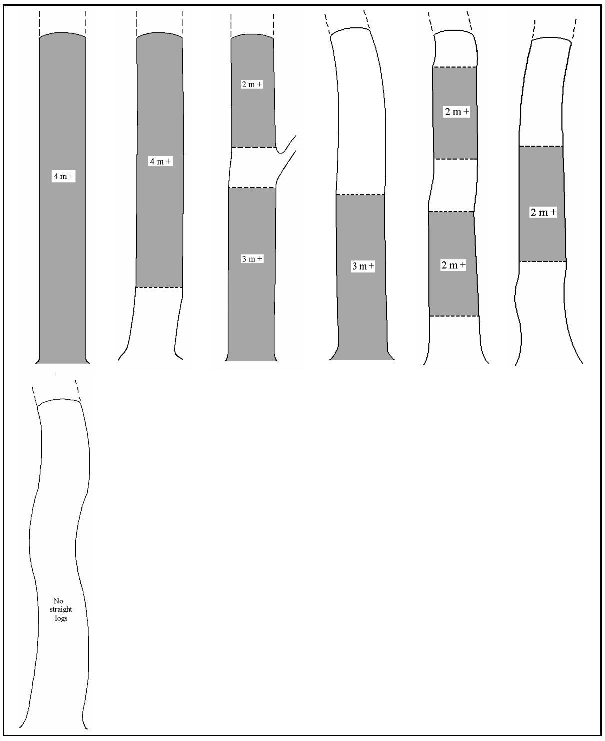


Figure 1. Different combinations of log lengths in the basal 6 m showing a gradual reduction in quality from left to right. A 4 m+ can only occur on its own; a 3 m+ can only occur on its own or in combination with a 2 m+; a 2m+ can occur on its own or in combination with a 2 m+ or a 3 m+.

Preliminary field trials and the statistical evaluation of field assessments against observed outputs of log lengths at a commercial sawmill indicate that the scoring system is able to detect potential quality differences in stands of trees of the same species and in different locations.

Secondary sites. Eddy- covariance measurements are performed at all secondary sites, with data on fluxes of water, carbon and energy exchanges continuously measured above the forest canopy in real time, and stored together with meteorological data at sub-hourly intervals. A comprehensive suite of physiological parameters is also available for all sites, whilst individual studies of hydrological and carbon balance are available at most. These data-sets will be collated to validate and inform the process level sub-models (photosynthesis, respiration and transpiration) of the integrated modelling system.

2.1.2 The Manipulative Component

The **MANIPULATIVE COMPONENT** at the tertiary sites will use existing facilities, consisting of open top chambers and closed growth chambers together with appropriate methods of experimental control. The experimental protocols used at these facilities are well documented and their success in providing the necessary parameters for modelling activities is widely accepted. Three specific activities will be carried out in these facilities:
(a) induce the individual and combined treatment effects of CO_2**,** temperature and precipitation using established experimental infrastructure;
(b) produce new juvenile plant material grown under ambient (≅350-370 μmol mol^{-1}) and enhanced CO_2 atmospheres (≅700 μmol mol^{-1}) with individual and combined effects of temperature and precipitation for use in assessing timber growth and quality;
(c) produce new information to inform model parameterisation, calibration and validation on growth through non-destructive monthly measurements of physiological growth parameters, annual measurements of mensurational parameters and destructive sampling of biomass from tree compartments to develop allometric mass distribution ratios.

2.1.3 The Laboratory Component

The **LABORATORY COMPONENT** will use established laboratory infrastructure and procedures to assess whether the anatomy, biochemical composition and mechanical properties of wood vary as a result of growth conditions (climate and CO_2 concentration). Laboratory procedures will be used to assess these characteristics for:
(a) new plant material from the monitoring and manipulative experiments;
(b) existing plant material produced in previous manipulative experiments;
(c) over-mature standing timber, to contrast properties for timber grown at ambient (≅350-370 μmol mol^{-1}) and elevated CO_2 concentrations (≅700 μmol mol^{-1}).

Anatomical	Biochemical	Mechanical
Lumen diameter	Non-structural and structural carbohydrate content	Wood density
Vessel/fibre length	Total lignin, cellulose and hemicelluose content	Mechanical stress
Tissue wall thickness of early and latewood	Total N content (also for other compartments e.g. leaf, branch, stem, fine and coarse roots)	Drying distortion
Ratio between tissue types		Knot area
Annual ring widths		Slope of grain / spiral grain
Compression/reaction wood		Juvenile and compression wood area
Wood decomposition by saprophytic fungi and micro-organisms		Micro-fibre angle

This component will provide invaluable information on the likely effects of enhanced atmospheric CO_2 concentrations on a suite of biochemical, anatomical and mechanical properties that are directly relevant to the modelling of timber quality, and its coupling to the modelling of growth and yield.

2.1.4 The Modelling Component

The **MODELLING COMPONENT** of the research will build upon existing state-of-the-art empirical and process-based models available in the consortium, simulating timber yield at the forest stand scale under current and future scenarios of atmospheric composition, integrated with:

Ø a coupled empirical-process sub-model of timber quality as affected by ambient and modified atmospheric composition, environmental change and management;

Ø sub-models for estimating the productivity of a range of wood products;

Ø energy budget sub-model for the energy costs of production and exploitation of wood products.

In turn, the forest growth-quality stand scale model will inform an existing and upgraded large-scale scenario model which up-scales stand features to the forest management scale.

2.1.4.1 The Stand Scale Growth-Quality Model

In the model, microclimate state variables (T_{min}, T_{max}, total radiation and PPFD, precipitation, relative humidity, windspeed) and biophysical variables (photosynthesis, soil water balance, stomatal conductance, transpiration, carbon balance, crown growth, cambial activity, height and diameter growth for above and belowground parts) will be simulated at a daily time step.

2.1.4.1.1 Weather generator. A stochastic-deterministic weather generator will be used to downscale monthly- time step inputs. The model requires a minimum of five inputs to produce estimates at different timescales (daily, hourly or smaller) of up to 18 weather variables. Time series of the model outputs are estimated from climatic statistics derived from instrumental data, and have the same 'intrinsic' properties as the instrumental meteorological data from which they are derived. Monthly instrumental weather data for mean temperature, precipitation and wind speed are input into a first-order Markov chain, coupled to an auto-correlation intensity factor, to generate daily scale estimates of mean, maximum and minimum temperature and wind speed. The same approach is used in a two-state domain to estimate the mean amount of precipitation on a rain day. Algorithms are used to estimate precipitation intensity and duration, and relative humidity. Total, direct and diffuse solar radiation is approximated using a spherical geometry approach, corrected for altitude and latitude. The model will be validated for a representative number of sites within Europe, illustrating a range of climates. The model will be used to simulate transient climates as developed by General Circulation Models (GCMs), for which monthly-time step data are available at the European scale at a 0.5 degree resolution.

2.1.4.1.2 Soil water balance. Soil water balance will be calculated by a daily-time step, multi-horizon capacity model where the spatial and temporal variability of soil water content is determined by changes in soil hydraulic conductivity, soil water storage capacity and the pathways of water movement through the soil and across soil types. Soil water content will be simulated at horizon level; limits on the amount of drainage from one horizon to the next allows the formation of temporary perched water tables, lateral drainage, matric potential and surface runoff. Simulations have shown that the capacitance-type model provides good approximations of point-scale experimental data under a range of soil, climate and drainage management conditions in temperate latitudes. Simulations are close to those developed by a mechanistic model, suggesting that the capacity model can be applied to describe the water balance of multi-horizon soil profiles. The modelling approach used is considered to be applicable to the wide range of soil lower boundary conditions, ranging from free-draining to impermeable, which occur in Europe.

2.1.4.1.3 Growth model. In this model, a tree will be represented by five principal compartments: foliage, branches, stem, structural roots and fine roots, arranged according to a simple model of tree shape. A process-based physiological model of carbohydrate productivity simulates carbon production, where assimilation will be assumed to be proportional to individual tree crown size. Partitioning of dry matter will be based on the model of tree shape, which is used to estimate the relative sizes of different tree compartments and therefore their respiration and demand for assimilates for growth. Changes in tree shape and the relative sizes and growth rates of tree compartments will be determined internally by reference to the pipe theory and externally by competition. Diameter growth will be driven by the pipe theory, while height growth is based on a simplistic model of the relationship between foliage accumulation and branch increment. Growth of structural roots will depend on the quantity of fine roots that needs to be sustained, which in turn depends directly on the quantity of active foliage. Tree stem volume will be integrated from sectional diameters estimated at different heights of the stem. These variables act as an efficient description of the gross shape of individual trees, and their development through time are a record of the effects of environmental and competitive influences upon each tree. For example, a detailed representation of the crown may be generated from $h_{u,t}$, $h_{l,t}$ and $d_{c,t}$, , and their progression through time summarise changes in crown development and interaction with neighbours through time. Although mensurational variables are less well defined below ground, in principle the system of variables described above could be extended to the root systems of trees. In the current version of the model, gross root dimensions are represented by two variables (d_r and h_r).

Figure 2. Simple model of tree morphology based on mensuration variables.

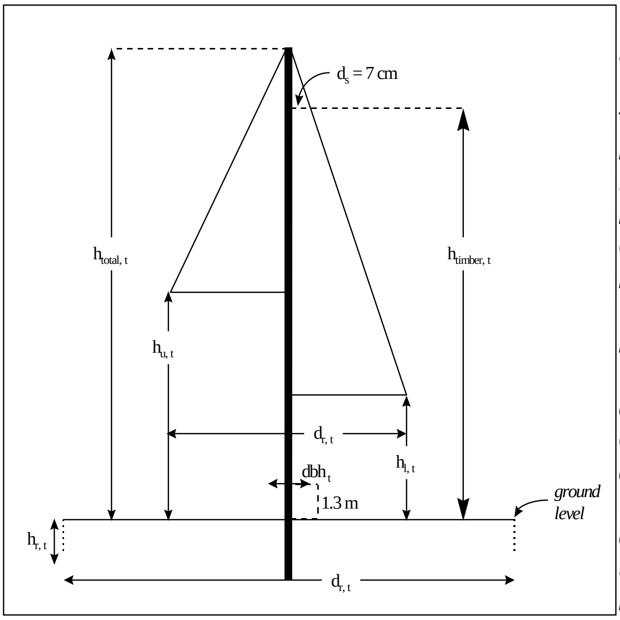


Figure 2 shows a simplistic representation of a coniferous tree in terms of fundamental mensuration variables as implemented, with the following interpretation:
$h_{total,t}$ = total height of tree from ground at time t (m);
$h_{timber,t}$ = height to point on main stem that is 7 cm diameter over bark (m);
$h_{u,t}$ = 'upper crown', height of lowest complete live whorl of branches (m);
$h_{l,t}$ = 'lower crown', height of lowest live branch (m);
dbh_t = 'diameter at breast height', stem diameter 1.3 m from ground (cm);
$d_{c,t}$ = average projected diameter of crown (m);
$d_{r,t}$ = average diameter of structural root plate at time t (m);
$h_{r,t}$ = average depth of structural root plate (m).

2.1.4.1.4 Carbon production. The model for CO_2 uptake and conversion into carbohydrate 'building blocks' allocated to tree compartments will be a coupled solution to assimilation, stomatal conductance, net radiation, transpiration and leaf temperature. In the model CO_2 demand by photosynthetic tissues will be balanced by CO_2 supply describing inter-cellular CO_2 diffusion from the atmosphere via the stomata and cuticle to the sites of photosynthesis; nitrogen effects on photosynthesis are also described. An additional sub-model will describe the response of stomata to physiological and environmental variables.

2.1.4.1.5 Cambial growth. The cambial processes of division, enlargement, wall thickening and functional specialisation of a row of xylem cells within an annual growth ring, at different development stages (cambial initial, maturing and fully mature), are regulated by crown growth rate, photosynthetic activity and stem water potential, as determined by stomatal resistance. Processes controlling cell growth result in variations in cell size and wall thickness as the cell matures until its death at full maturation. Functional specialisation of cell types (support, conductive and reserve tissues) will be introduced into the model based on empirical probability ratios derived from the laboratory phase, which will link the field data developed through manipulative experimentation and modelling. Timing of growth will be regulated by bud burst that is driven by a phenology sub-model.

2.1.4.1.6 Linking growth with quality. The proposed research will integrate the stand growth model with growth-related quality sub-models predicting:

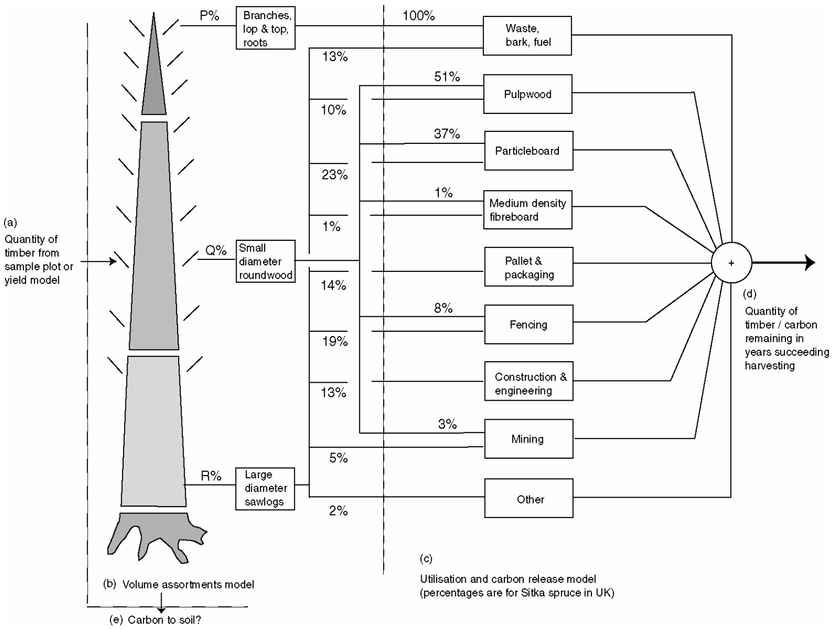
Ø profiles of annual ring development along the stem of the tree, with the potential to allow for inter-annual variation;

- Ø inception year, position and distribution of primary branches along the stem of the tree, as well as branching angle and branch diameter;
- Ø gross stem curvature, presence of 'stops' or forks and more complex departures from straightness.

2.1.4.1.7 Wood products sub-model. A wood product out-turn sub-model will be developed, building on existing models of tree architecture adapted to predict aspects of stem quality, such as ring width, knot distribution and branching characteristics, as an integral component of the growth and yield model. One component of this sub-model will be used to predict stress grade yields from measured growth characteristics. Complementary methods of practical field assessment will be developed for use as input to model forecasts.

2.1.4.1.8 Energy budget sub-model. A policy-level energy and carbon accounting 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, will be developed. The modelling approach is summarised in diagrammatic form in Figure 4. 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. Simulation of European cross-sector energy budgets in relation to policy and economic scenarios is beyond the scope of the proposed research and is specifically excluded.

Figure 3. Diagrammatic representation of a typical energy budget sub-model.



2.1.4.1.9 Model parameterisation. The essential data required to inform the parameters required by the forest stand model will, in part, be obtained from previous and ongoing experiments that represent the state-of-the-art and developed by individual partners in the consortium. However the successful coupling of the sub-models will rely heavily upon new data, to be obtained both from the monitoring and the manipulative components of the project. Data from the primary sites will be used in the model development and calibration, whilst data from the secondary sites, where growth measurements in enhanced CO_2 will be made, will be used for model validation for scenarios of future atmospheric composition.

2.1.4.1.10 Prototype. The forest stand scale model for predicting timber yield and quality will be developed into a prototype system with improved information as to the sensitivity of the response of production forests and of timber quality to current and future scenarios of atmospheric change and management.

2.1.4.1.11 The Upscaling Model. The upscaling model incorporates an existing forest inventory database, held by Partner 3, that includes forest area, standing volume and increment from 30 European countries; these data are queried by country, region, owner class, site class, tree species and age class. Forest area covered in the database is 146.4 millions ha, distributed across 2527 forest types; the level of detail varies between countries. Outputs of the up-scaling model will inform policy advisors as to the sensitivity of the response of production forests and of timber quality to current and future scenarios of atmospheric change and management.

2.1.4.1.12 Description of EFICEN. EFISCEN is a forest resource assessment model, especially suitable for strategic, large scale (> 10,000 ha), long-term (20–70 years) analysis. EFISCEN 2.0 is suitable for assessments of the future state of forest under assumptions of future felling levels. EFISCEN 2.0 consists of a module for even aged forests and one for uneven aged forests.

The core of the growth simulator of the even aged part of EFISCEN 2.0 (European Forest Information Scenario) model is based on a model developed by Ola Sallnäs at the Swedish University of Agricultural Sciences for even-aged forests. The original aim was to develop a forest growth model that could be incorporated into a forest sector model. During the early 1990's this model was modified and used by IIASA (International Institute for Applied Systems Analysis) to study the effect of air pollution on European forests.

EFISCEN is currently in use and under further development at the European Forest Institute (EFI) for developing new forest resource projections at the European level and in the Russia. At the EFI the model has been validated with historical data (Nabuurs et al. 2000). The main advantage of this model is that it is not very data intensive, requiring rather basic forest inventory data which most of the European countries have available in a harmonised way. This makes the model suitable for use in a large number of countries.

The basic input data of the EFISCEN 2.0 even aged model are forest area, growing stock and increment by age classes, i.e. data that are gathered in most national forest inventories. The basic output of the model consists of forest states at five years interval, in terms of e.g. growing stock, increment, felling and age class distribution. If additional input data about growth change in future is provided, the model can adjust the growth of the forest inventory. Furthermore, if data of distribution of biomass and litter production is provided, the model can calculate the forest carbon budget.

In the even aged part of EFISCEN 2.0 the following adaptations have been introduced into the model:

- Thinnings have been incorporated in a different way in the model, resulting in more realistic growth after thinning;
- The growth rates at high growing stocks have been modified;
- All calculations are now carried out for five-year age classes;
- Transient growth rate changes due to e.g. environmental changes can now be incorporated;
- Full forest biomass balance can be calculated including soil carbon.

Some countries in Europe gather their forest inventory data by diameter classes. This so-called uneven-aged approach is in use for parts of Belgium, France and Italy and the whole of Spain.

The EFISCEN model is under constant development and version 3.0 will incorporate natural mortality rates and a stochastic approach for natural disturbances. EFISCEN version 4.0 will incorporate a multi country module that links the countries through consumption rates and wood products trade flows.

For the LTEEF-II project, the model has been adjusted to calculate the carbon budgets of the trees, the forest soil and wood products. With this adapted model, it is also possible to adjust forest growth under changing climatic conditions according to predictions of process based models. For the carbon budget calculations, biomass distribution parameters, weather data and litter production data are also needed.

Forest management in EFISCEN is provided for in terms of thinning and final felling regimes, and total volumes to be thinned and clear-cut by tree species group. Final felling is expressed as a probability, dependent on the stand age or actual standing volume. These probabilities are converted into a proportion of the area in each cell that can be felled. The actual area felled in a cell depends of the requested volume to be harvested and volume available in the species group. A felled area is moved to a bare-forest-land class. Regeneration is regarded as transition of area from the bare-forest-land class to the first volume and age class. The amount of area that is regenerated is regulated by a parameter that expresses the intensity of the regeneration (young forest coefficient). This parameter is a percentage of the area in the bare-forest-land class that will move to the first volume and age class during the following five years.

Harvested timber is processed into products in a wood products sub-model. This model keeps track of the products until they are removed from use and the carbon in the products then is released back into the atmosphere. The conversion of timber into wood products is based on product/timber units typical for the wood processing industry. The final products are divided into eight usage categories to describe the use of raw material in production and the use of products. At the end of its primary use, products can be recycled, burned to generate energy or disposed of into landfills. In landfills, disposed products decompose slowly, releasing carbon into the atmosphere. Running the model with harvesting data dated from 1960 initialises the wood product model.

Carbon stocks and stock changes in tree biomass, soil and products are calculated per region but are usually presented by country. In order to allow comparison with flux measurements and flux modelling, gross primary production (GPP, net primary production plus respiration of tree biomass), net primary production (NPP, net tree biomass carbon balance plus litter production and timber harvesting), net ecosystem exchange (NEE, = NPP plus net soil carbon balance), net biome production (NBP, = NEE minus timber harvesting), net product exchange (NPE, net product carbon balance), and net sector exchange (NSE, = NBP plus NPE) are calculated. Carbon budgets are presented as average values per hectare (average for the area) or for the whole area in consideration.

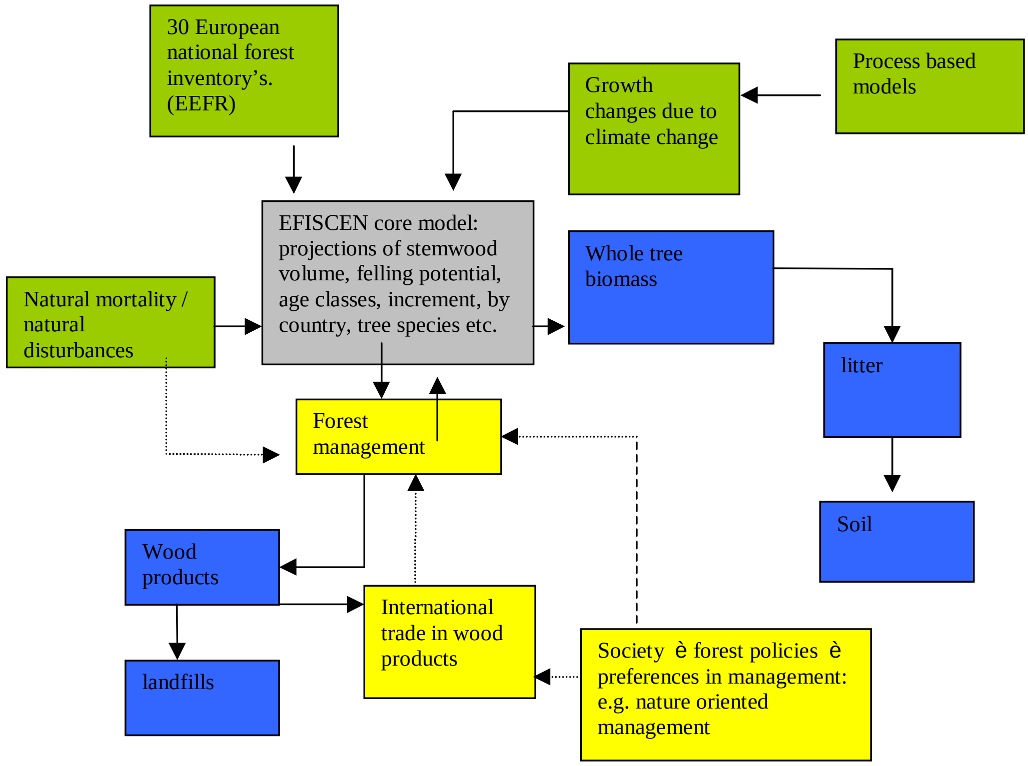
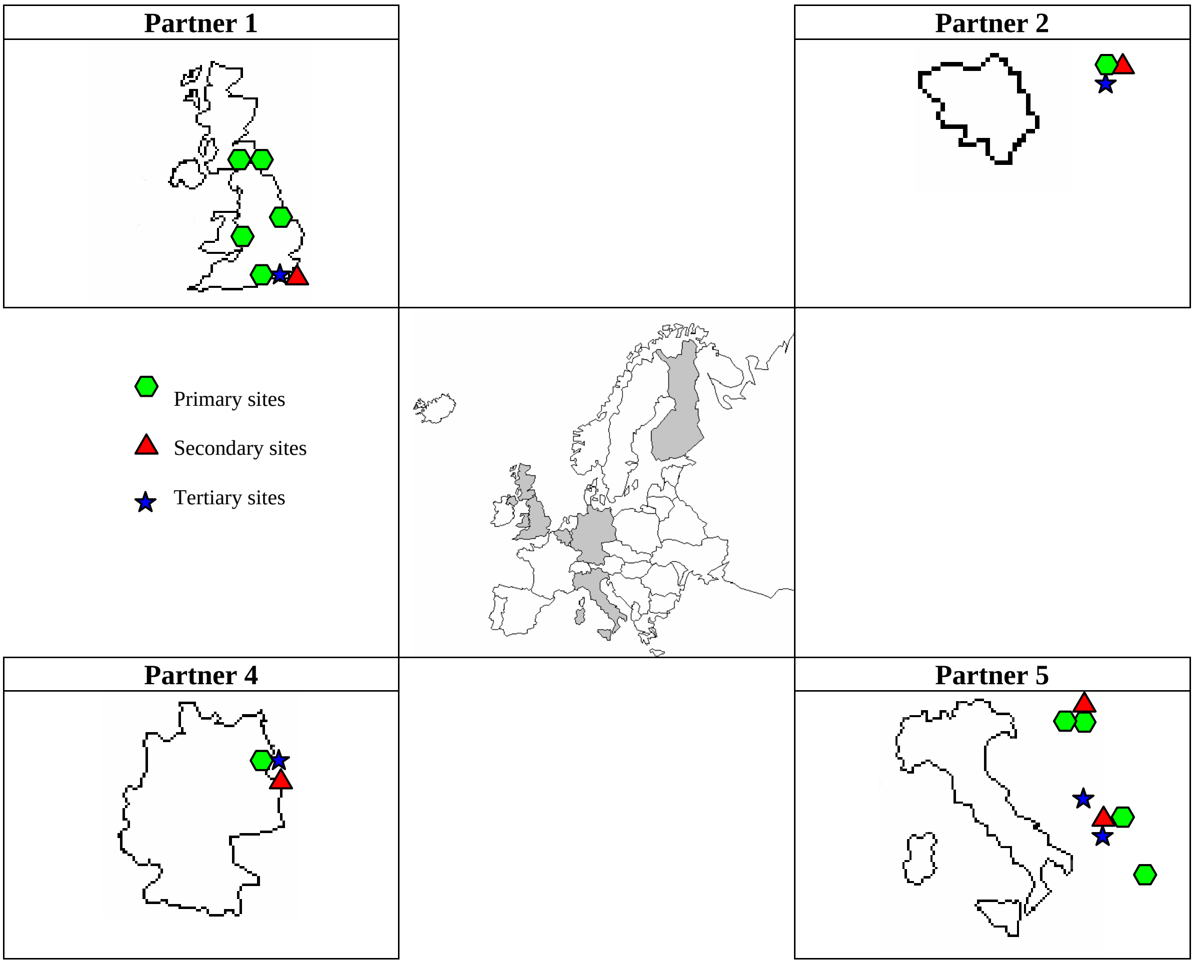


Figure 4. Outline of the EFISCEN model. The EFISCEN model can simulate development of forest resources and forest sector carbon budget on a regional and country levels with given input data and scenarios (forest inventory data as input, possible changes in the increment, biomass allocation and litter production, management regimes).

2.1.4.1.13 Model integration. The stand scale process-based model will inform the projections of the up-scaling model of forecasted changes in growth, timber yield and quality at stand scale resulting from the combined effects of environmental change and management practices by explicitly simulating those physical, biophysical and biological processes associated with plant growth. When integrated with existing and new data on growth response to management practices, standing volume, increment/yield projection and quality functions will be developed for a number of production species in Europe, namely oak (OK), beech (BE), poplar (PO), Scots pine (SP), Sitka spruce (SS) and Norway spruce (NS). The formal coupling with the large-scale scenario model will be achieved through the increment/yield projection and quality functions for each species. By coupling the new yield/quality functions to the existing database on standing volume and increment held within the up-scaling model, this 'nested' approach permits the prediction of changes of both wood productivity and quality resulting from future environmental change and management practice at the regional levels. This approach will be applied to the regions/countries studied as part of this project and tested under current climates using available forest statistics, life cycle analysis data and wood products inventories.

2.2 THE SITES

Figure 4. Distribution map of primary, secondary and tertiary sites.



Site responsibilities

	Number of Sites		
Responsible Partner	***Primary***	***Secondary***	***Tertiary***
1. Forestry Commission – UK	5	1	1
2. Antwerpen – Belgium	1	1	1
4. Berlin – Germany	1	1	2
5. Tuscia – Italy	4	2	2
TOTAL	**11**	**5**	**6**

2.2.1 Primary Sites

At each site sample plots will be established within existing spacing, thinning and fertiliser experiments in managed forests. In these plots standing trees will be assessed, using a standard protocol across all partners, to generate data for growth and quality model calibration and validation. To maximise the use of existing data, selected sites from the UN/ECE ICP Forests Level II Forest Health Monitoring Network in the Partners' member states will also be used, where data collection is ongoing[1]. A quality protocol will be introduced to assess timber quality potential of standing trees. Primary sites also provide the sources for additional field observations and locations for monitoring. Samples of plant material will be taken for anatomical, chemical and structural analyses to identify climatic/latitudinal, management and treatment effects on wood quality. Sites have been selected to represent a limited number of productive species in Europe, namely oak (OK), beech (BE), poplar (PO), Scots pine (SP), Sitka spruce (SS) and Norway spruce (NS).

Partner 1. Two series of primary sites are listed below. Paired UN/ECEICP Level II plots (for oak, Scots pine and Sitka spruce) are available for single species model calibration and validation. In addition, three experimental stands have been selected to enable the effect of management intervention on stand growth and quality to be investigated. Whilst these experimental sites do not have the same intensive environmental monitoring activities as at the Level II plots, they were all established as permanent mensuration sample plots over 50 years ago. Thus, a long run of increment data are available and will demonstrate the effect of management on a mature crop. Sites have been selected to allow both model calibration and validation.

(1) *Site 1* **(Straits – UK)** is a relatively homogenous and mono-specific forest block planted with oak in the 1930s covering an area of approximately 70 ha. There are UN/ECEICP Forests Level I and II forest health plots within the block. Other species (mostly ash, *Fraxinus excelsior*) make up 10% of the tree cover and the understorey is dominated by hazel *(Corylus avellana),* hawthorn *(Crataegus monogyna), Rubus* spp. and various grass and herbaceous species. The soil is a pelo-stagnogley with a depth of 80 cm to the C horizon of the Cretaceous clay. The pH is 4.6 and 4.8 in the organic and mineral horizons respectively. Top height and DBH were 19.3 m and 25.9 cm respectively in 1995 at a density of 606 trees per hectare resulting in a basal area of 22 m^2 ha^{-1}; general yield class is 6 and the site was last thinned in 1995 (and 1991). Daily meteorological data are available from 1955 (within 5 km of the stand), and an automatic weather station was installed in 1994. Total nitrogen deposition was 9.1 and 7.4 kg ha^{-1} in 1996 and 1997, respectively, and a continuous pollution record (hourly concentrations of SO_2, NO_x, O_3) is available from 1987, and NH_3 (monthly values) from 1996. Mean annual rainfall is 780 mm, and mean annual temperature 10.6 °C.

(2) *Site 2* **(Coalburn – UK)** is a Sitka spruce plantation established in 1974 and designated an UN/ECEICP Level II forest health monitoring plot in 1994. It is part of a large upland (300 m a.s.l.) production coniferous forest Mean top height is 10.9 m, DBH 27.1 cm, stocking density 2118 trees per hectare resulting in a basal area of 47.1 m^2 ha^{-1}. General yield class is 18 and the site is unthinned. The soil type is a cambic stagnohumic gley, with an

[1] Approval has already been granted by the Intensive Monitoring Programme of Forest Ecosystems in Europe Programme (DG VI) for this project to use the experimental sites and historical data collected in long-term monitoring plots.

effective rooting depth of 35 cm. Ground vegetation is limited to mosses and lichens. The area has been the subject of a catchment study of water quality and quantity since 1971, and automatic weather station data are available from 1980, with a long-term weather (1959) and pollution (1974) data-set available for a site within 20 km and 50 m altitude. Annual rainfall is approximately 1200 mm and total nitrogen depositon (after REF. 70) was 11.9 and 10.2 kg ha^{-1} in 1996 and 1997, respectively.

(3) *Site 3* **(Tummel – UK)** is a Sitka spruce plantation (400 m a.s.l.) established in 1969. Mean top height is 14.7 m, DBH 15.8 cm, stocking density 2747 trees per hectare, resulting in a basal are of 59.2 m^2 ha^{-1}. General yield class is 16 and the site was thinned in 1997. The site was designated an UN/ECE ICP Level II tree health monitoring plot in 1995. The soil type is a ferric podzol with an effective rooting depth of 50 cm. Ground vegetation is absent. Annual rainfall is approximately 1500 mm. Long term weather records are available for a site 30 km distant and the data from the automatic weather station at Site 4 (see below) is applicable to this site, given their proximity. Total nitrogen deposition is approximately 6 kg ha^{-1} a^{-1}.

(4) *Site 4* **(Rannoch – UK)** is an unthinned upland Scots pine plantation (470 m a.s.l.) established in 1965. Mean top height is 11.1 m, DBH 12.7 cm, stocking density 2776 trees per hectare, resulting in a basal area of 32.8 m^2 ha^{-1}. General yield class is 8. Annual rainfall is approximately 1500 mm, and an automatic weather station was installed in 1997. The site was designated an UN/ECE ICP Level II tree health monitoring plot in 1995. The soil is a humo-ferric gley podzol with an effective rooting depth of 85 cm, and grasses and mosses dominate 100% ground cover. Nitrogen deposition and climate are similar to that at site 3.

(5) Site 5 **(Grizedale – UK)** is an oak plantation (120 m a.s.l.) established in 1920. The plot is within a mixed species forest with rolling/mountainous topography. Mean top height is 18.4 m, DBH 30.2 cm, and stocking density 310 trees per hectare (under-stocked at present) resulting in a basal area of 20 m^2 ha^{-1}. The soil is a brown podzol with an effective rooting depth of 50 cm. Mean annual precipitation is 1800 mm. Understorey vegetation cover is approximately 50%, and is dominated by grasses, bilberry, bracken and mosses. A long-term weather station is located within 2 km, and an above canopy weather station was installed in 1998. The site was designated as an UN/ECEICP Level II tree health monitoring plot in 1995 and a pilot study to upgrade the Level II protocol to enable process modelling of tree growth has been in operation for two years. General yield class is 4, and total nitrogen deposition approximately 19 kg ha^{-1} a^{-1}.

(6) *Site 6* **(Thetford – UK)** is a Scots pine plantation (30 m a.s.l.) established in 1967 in a flat lowland area. Mean top height is 12.7 m, DBH 15 cm and stocking density 1720 trees per hectare resulting in a basal area of 37 m^2 ha^{-1}. The site was thinned in 1994 when it was established as a Level II plot. Ground vegetation cover is complete and is dominated by grasses, bracken, mosses and nettles. In addition to Scots pine, the canopy includes a scattering of other species *(Pinus strobus,* sycamore and oak). The soil is a brown calcareous sand with an effective rooting depth of 80 cm. Annual rainfall is 600 mm and nitrogen deposition is 15 kg ha^{-1} a^{-1}. Long-term weather data are available within 1 km of the stand.

(7) *Site 7* **(Rheola – UK)** is a Sitka spruce plantation (240 m a.s.l.) planted in 1935 with four spacing intervals (0.9, 1.2, 1.8, 2.4 m) and four thinning treatments. The site is a permanent mensurational plot that has been assessed in 1962, 1967, 1973, 1978, 1984, 1991 and 1996. The soil is an upland brown earth. No ground vegetation is recorded.

(8) *Site 8* **(Sawley – UK)** is a Sitka spruce plantation (230 m a.s.l.) planted in 1943 with a 2.7 m spacing interval and three thinning regimes. The site is a permanent mensurational plot that has been assessed in 1974, 1979, 1984, 1989 and 1997. Ground vegetation is sporadic, with occasional *Deschampsia,* mosses and ferns. The site is a moorland plateau, and the soil type is a brown earth with an effective rooting depth of 40 cm.

(9) *Site 9* **(Dalby – UK)** is a Sitka spruce plantation (120 m a.s.l.) planted in 1924 with 1.5, 1.8, 2.1, 2.4 m spacing intervals and no thinning. Soil type is a podzolised brown earth with an effective rooting depth of 85 cm. No ground vegetation is recorded. Annual rainfall is 690 mm.

Partner 2.

(1) *Site 10* **(Brasschaat – Belgium)** is at 15 m a.s.l. The site is on moderately wet sandy soils with a tendency to podsol, planted with 70 a old mixed pine-deciduous vegetation comprising *Pinus sylvestris L., Quercus robur* L. and *Fagus sylvatica* L. Understorey species mainly include *Rhododendron ponticum, Prunus serotina* Ehrh. and *Molinia caerulea. The* average stand height is 23 m and the annual volume increment of the Scots pine is 7 m^3 per year. The total area of the forest is over 150 ha. Mean annual temperature is 10°C and annual precipitation is 750 mm. The site is an UN/ECE ICP Level II observation plot of the European programme for Intensive Monitoring of Forest Ecosystems.

Partner 4.

(1) Site 11 **(Grunewald – Germany)** is at ca. 50 m a.s.l. The soil is a Ferric Cambisol developed on alluvial sand with a tendency to Podsol; pH is in the range of 3.0 - 4.8. The site is indicated as a 140 a old *Pino-Quercetum,* but dendrochronological analyses have identified only a few *Pinus sylvestris* L. and *Quercus robur* L. individuals older than 100 as. Dominant species are *Pinus sylvestris* L. and *Quercus robur* L., with subdominant individuals of *Fagus sylvatica* L. and *Quercus petreae* (Matt.) Lieb.; the shrub layer is composed of *Prunus serotina* Ehrh. and *Sorbus aucuparia* L. Herbaceous layer is dominated by seedlings of *Acer pseudoplatanus L., Avellana (Deschampsia) flexuosa* (L.) Parl., *Agrostis tennuis* Sibth., *Luzula campestris* (L.) DC., *Rumex acetosella* L. and *Hypericum perforatum* L. Mean tree height is 21.9 m for pine and 10.5 m for oak, with a max rooting depth of 4.5 m and 196 pine and 973 oak trees in the research plot. Mean annual increment of stem and branch wood is 1,573 kg ha^{-1} a^{-1} for pine and 849 kg ha^{-1} a^{-1} for oak, respectively; needle dry mass is 5.9 t ha^{-1} and leaf dry mass is 3.3 t ha^{-1}. The site has been part of UNESCO's MAB programme since 1987 and the EU Forest Ecosystem Research Network since 1988.

Partner 5.

(1) *Site 12* **(Collelongo – Italy)** is at ca. 1500 m a.s.l. The site is on calcareous brown earth and is a natural regeneration stand of approximately 100-yr old *Fagus sylvatica.* The stand is within a 3000 ha community forest that is part of a wider forest area, included in a national park. The stand has been studied for tree biomass distribution above- and below-ground, stem growth (stem analysis) and biomass productivity. Biomass study involved the felling and analysis of 25-30 trees distributed over the diameter range of the forest trees. Below-ground biomass was investigated on 6 of those trees; results indicated that 25% of a total woody biomass of 280.8 t ha^{-1} is made up from roots, while root/shoot ratio is 0.33. Mean annual increment of total biomass is 2.81 t ha^{-1} a^{-1} and that of root is not negligible, reaching about 0.7 t ha^{-1} a^{-1}. Dominant beech trees are still growing in height and this is true also for dominated trees, although to a lesser extent. Aboveground net primary production (stem, leaves, branches) is around 578 g m^2 a^{-1}. Belowground NPP is *ca.* 1016 g m^2 a^{-1}, divided into 106 g m^2 a^{-1} for main root apparatus increment and 910 g m^2 a^{-1} for total fine root turnover. In total, the NPP reached 1594 g m^2 a^{-1} with more than 60% allocated to below-ground components. The mean annual temperature of the site is 6.2°C, while the mean annual precipitation is 1100 mm. Absolute maximum temperature can be higher than 30 °C, while absolute minimum can reach –25°C. Snow cover can last 3.5 months, from the end of December to mid April. The growing season is between early May and early October (140-160 days). The climate can be considered as montane-mediterranean, and the occurrence of summer water stress is not unusual. The environmental and structural conditions of the stand are representative of the region's beech forests and the structural features of these stands reflect the history of their silvicultural management, as well as the peculiar characteristics of the environmental conditions of the mediterranean-mountain vegetation. Since the early 1990s structural studies have been conducted out in 7 sampling sites in two different and contrasting areas. *Area 1* (1600 m a.s.l.), with trees covering the upper zone of the mountain with flat areas alternating with more or less steep slopes, and *Area 2* (1300-1500 m a.s.l.), a fairly steep, fresh and north facing valley. At both sites several stands will be identified with different structure and developmental stage, as well as stands growing on different mountain

aspects and slopes. *Area 1* is an UN/ECE ICP Level II observation plot of the European programme for Intensive Monitoring of Forest Ecosystems.

(2) Site 13 **(Catena Costiera – Italy)** at ca. 1500 m a.s.l. This site offers an optimum environment for *Fagus sylvatica.* Some of the stands have been recently thinned. *Area 1* (915 m a.s.l.) is an UN/ECE ICP Level II observation plot of the European programme for Intensive Monitoring of Forest Ecosystems, managed by the Ministry of Agricultural Policies. Within these forests a representative forest stand will be identified and described for its structure, species composition, stem form and quality.

(3) Site 14 **(Tesino –Italy)** *is* from 800 to 1600 m a.s.l. The community forests covers a total area of about 10,000 ha and are composed mainly of mixed coniferous stands of *Picea abies* L. and *Abies alba* Mill., with a small proportion of *Fagus sylvatica* L. These are all managed forests with an uneven age structure and a MAI of about 5 t ha^{-1} a^{-1}. Within these forests a representative forest stand will be identified and described for its structure, species composition, stem form and quality.

(4) Site 15 **(Renon – Italy)** is at ca. 1700 m a.s.l. The existing research area has a surface area of 9000 m^2 and it is inside a forest of *Picea abies* L. with the sporadic presence of *Pinus cembra and Larix decidua.* The understorey is rich in small shrubs, mainly blueberries *(Vaccinium myrtillus* L. and *V. vitis-idaea* L.), and herbs *(Melampaum sylvaticum L., Homogyne alpina L., Hieracium sylvaticum).* Sampling all the trees with a DBH greater than 12.5 cm, showed that the forest stand has a density of 270 trees ha^{-1}, with a basal area of 25.7 m^2 ha^{-1} and a standing volume of 241.3 m^3 ha^{-1}. The mean height of the 10 larger trees is 24.8 m. Mean age of the stand is 80 years. The stand is of natural origin and is managed through selective fellings, although less intensively in recent years. In terms of stem volume, larch and pine are present in the same proportion (8.3%), while the dominance of spruce is confirmed (83.5%). The distribution in diameter classes is homogenous for spruce, indicating an uneven aged structure; pine is characterised by the presence of very few large specimens, while larch is present with large trees and an absence of a regeneration layer. In the vicinity of this site is an UN/ECE ICP Level II observation plot of the European programme for Intensive Monitoring of Forest Ecosystems. Within this site a representative forest stand will be identified and described for its structure, species composition, stem form and quality.

2.2.2 Secondary Sites

Secondary sites will be located at existing monitoring sites where flux data from standing forests are currently being collected under ongoing EU projects which involve partners from the current project, to generate data for short term validation of the growth model.

Partner 1

(1) Site 1. A system for measuring CO_2 and H_2O and energy fluxes was installed in March 1998, and a continuous record is available from May 1998. Net ecosystem flux from June 1998-May 1999 was 3.3 t C ha^{-1} with leaf area index of the over canopy rising to 4.7 in mid-summer.

Partner 2

(1) *Site 10* described above. A 40 m tall self-supported square tower is installed at the site, with an eddy covariance flux measuring system (three-dimensional sonic anemometer and fast-response gas analyser) and an extensive set of meteorological sensors above and within the canopy installed on the tower. Fluxes of water, carbon and energy exchanges are continuously being measured above the canopy in real time, and stored together with meteorological data at half hour intervals.

Partner 4

(1) Site 11 described above. The field station is equipped with gas exchange measuring instrumentation, a tower and a mast for microclimatic measurements. Gas exchange measurements at different heights in the canopy have been conducted since 1997.

Partner 5

(1) *Site 12* is a site where eddy covariance measurements are performed as part of ongoing EU projects. Data were collected for a whole year between spring 1993 and spring 1994

and some daily campaigns were collected in 1995. Since 1996 data have been collected continuously.

(2) *Site 16* **(Selva Piana – Italy)**. The site is fully equipped with micrometeorological sensors and all the instrumentation required, measuring canopy fluxes of carbon and water vapour.

2.2.3 Tertiary Sites

Tertiary sites are located at, or close to, the established centres of field research participating in this project, where existing facilities for experimental manipulation of CO_2, temperature, water supply and fertilisation are available. These sites will be used to generate new data for the growth and quality model calibration and validation under conditions of enhanced CO_2. Tertiary sites will be used for experimental observation, where samples of plant material will be taken for anatomical, chemical and structural analyses to identify single and combined effects of enhanced CO_2, temperature and droughtiness effects on wood quality. To maximise the use of existing data, plant material generated from past and ongoing manipulative experiments will also be used to develop new model calibration and validation data.

Partner 1.

(1) Site 17 **(Headley Nursery – UK)**. 16 open top chambers were installed in 1985 and modified to allow manipulation of soil moisture, CO_2 and ozone concentrations in 1994. The chambers are 4 m tall, 3 m in diameter, and airflow is adjusted to two air changes per minute. The soil within the chambers is a heavily cultivated humo-ferric podzol with a pH of approximately 4.0. Chambers are covered to allow more precise manipulation of available water. Ventilation is maintained by removing one layer of glass from the side walls. Available plant material from completed elevated CO_2 experiments includes the following species: *Pinus sylvestris, Fraxinus excelsior, Quercus petraea, Q. robur and Q. rubra.* Seeds of *Q. robur, Fagus sylvatica, Nothofagus obliqua, Acer pseudoplatanus, Pinus nigra* (var. *maritima*) and *Pseudotsuga menzeii* have been sown in a greenhouse at 600 ppm CO_2 and will be planted in the open top chambers in March 2000. All chambers will receive ambient or ambient precipitation reduced by 25% and ambient or 600 ppm CO_2. This will therefore allow the effect of rising atmospheric CO_2 and drought on wood quality parameters for six lowland forest tree species to be investigated. Plant material (currently held elsewhere) is also available from an identical facility where *Alnus glutinosa, Pinus sylvestris, Picea abies, Picea sitchensis and Betula pendulans* were exposed to combinations of elevated CO_2 concentrations and nutritional regimes.

Partner 2.

(1) *Site 18* **(Antwerpen – Belgium)**. Several open top chambers are being used for impact studies of increased levels of atmospheric CO_2 on different tree species. Each decagonal open top chamber has a usable ground area of 7.1 m^2 and air volume is changed nearly twice per minute. Two different atmospheric CO_2 concentrations are supplied to the chambers, i.e. one at ambient CO_2 concentration (ca. 350 •mol mol^{-1}) and one at elevated CO_2 concentration (ambient + 400 •mol mol^{-1}). In the past impact studies have been carried out for three years on different poplar clones, while since 1996 Scots pine seedlings have been monitored under both CO_2 concentrations. Three-year-old seedlings of local provenance were planted in the open top chambers in March 1996 and have been treated continuously in the open top chambers since April 1996. To reduce boundary effects, each open top chamber is surrounded by seedlings of the same provenance and seed lot. Measurements of growth, physiology, development and productivity have been made over the last three years and will continue in the future. Long-term treatments with different CO_2 concentrations are being envisaged for the future continuation of the experiment.

Partner 4

(1) *Site 19* **(Berlin – Germany)**. Six acrylic glass mini-greenhouses covering an area of 0.8x0.8 m^2 over a 0.4 m^3 nutrient rich garden soil block have been used since 1996 to investigate responses of juvenile stands to elevated CO_2 concentrations (698±10 •mol mol^{-1}) for beech and pedunculate oak. All greenhouses are acclimatised to the ambient microclimate (temperature variation ± 0.5°C, relative humidity ± 15%, wind speed within the

0.2 - 0.5 m s^{-1} range). Three greenhouses serve as ambient air controls (360±34 •mol mol^{-1} CO_2). Four greenhouses were planted with beech and 2 with 1.5-yr old oak saplings. Soil water content is maintained constant manually at a volume of 20% and soil water content is monitored at 3 different depth using the TDR technique. The aerial parts of the greenhouses are replaced each year in order to follow stand growth, and are currently ca. 3 m^3. Four adjacent open plots have the same number of saplings (starting number = 48 per plot, n = 36 in the 2nd and n = 25 in the 3rd year, respectively). Continuous monitoring Of CO_2 gas exchange rates in the stand, including the rooted soil compartment has been monitored continuously since planting.

(2) *Site 20, located near site 18* **(Berlin – Germany)**. Ten phytotron cabinets have been established to investigate the combined temperature and CO_2 effects on growth, morphology and anatomy of potted beech, pedunculate oak and Scots pine. The facility houses automated equipment for measuring and regulating CO_2, temperature and relative air humidity. Using the local 1909-1969 baseline, for minimum monthly nightly and maximum daily air temperature, temperature levels are adjusted each month. A new experiment has started using CO_2 concentrations of 390 and 700 •mol mol^{-1}, with 5 replicates per experiment, each with 10 beech and 6 Scots pine saplings in 10-litre pots with homogenised medium fertile garden soil; these plants will be used as part of the research proposed under this proposal.

Partner 5.

(1) *Site 21* **(Montalto di Castro – Italy)**. The site is a CO_2 enriched experimental site in a Mediterranean evergreen forest ecosystem. Dominant trees of *Quercus ilex L.* are 4 to 6 m high, with accompanying woody shrubs *Phillaea angustifolia L., Matus communis* L. and *Pistacia lentiscus* L. making up a dense, multi-layer canopy. Woody plants are clumped in a typical structure, where the crowns of the dominant trees *(Q. ilex)* intermix with *P. angustifolia,* emerging from a lower layer of *P. lentiscus. The* low palatability of *P. lentiscus* leaves for mammals present in the study ecosystem, suggests a strong interaction between forest structure development and herbivory. The climate of the area is typically temperate-Mediterranean, with rainfall distribution peaking in February and in November. Maximum temperature in summer can be greater than 35°C and is associated with a long dry season. Minimum temperature, generally in January, can be less than -5°C. In this forest, six large open top chambers (OTC) were installed in early spring 1992 to test the effect of atmospheric CO_2 enrichment at community level. Three chambers were randomly assigned to the enriched treatment that consists of a constant addition of 350 •l l^{-1} of incoming air. The resulting doubled atmospheric CO_2, is around 710 •mol mol^{-1}. The remaining three chambers were treated with air at ambient CO_2 concentration. In each OTC, the woody vegetation clump (about 30-years old) is made up on average, of 2xQ. *ilex* trees, 4xP. *angustifolia* and 7x*P. lentiscus shrubs.*

(2) *Site 22* **(Viterbo – Italy)** is at an altitude of 25 m a.s.l., where a FACE system has been developed not far from a CO_2 production plant. The main objective of this experimental site is to determine the functional responses of a cultivated, agro-forestry system, a poplar plantation, to current and future atmospheric CO_2 concentrations, and to assess the interactive effects of this anthropogenic perturbation with the other natural environmental constraints on key biological processes and structures. In the context of this research programme, poplar plantations represent a particular type of intensively managed ecosystem where the emphasis is placed on maximising biomass production over a relatively short time-scale. At the experimental site, six FACE rings each 20 m in diameter, have been installed. CO_2 experimental treatments are enriched and ambient: in the enriched treatment, in three replicate rings CO_2 is being added to reach a concentration of 550 •mol mol^{-1}, which corresponds to the anticipated value for ca. 2050; in the ambient treatment no additional CO_2 is being supplied. Poplar trees are grown under short rotation intensive culture at high density (2x1 m^2 and 1x1 m^2); the first harvest will occur at the 3rd year when trees will be approximately 10 m tall. Within the rings, spacing among trees is close enough to achieve (1) a sufficient number of trees available to conduct the various experimental measurements, and (2)

the development of a full canopy after one year from planting. Each ring will be partitioned in two halves corresponding to two different nitrogen-fertilisation treatments. Each fertilisation plot will be divided in three slices (subplots), each planted with a different poplar clone.

Description of the experimental infrastructure held by each Partner.

Country	Species	Age	STRUCTURE OTC	Phytotron	FACE rings	Natural/Planted	Size	Air flow rate
BELGIUM	*Pinus sylvestis*	7 yrs	4			Planted	3 m diameter x 6 m height	5000 $m^3 h^{-1}$
GERMANY	*Fagus sylvatica, Quercus robur*	1.5 yrs	6			Planted	0,8 x 0,8 m^2	
	Fagus sylvatica, Quercus robur, Pinus sylvestis			10				
ITALY	*Quercus ilex, Phillyrea angustifolia, Pistacia lentiscus*	30 yrs	16			Natural	4 m diameter x 6 m height	12000 $m^3 h^{-1}$
	Populus nigra, P. alba, P.x euramericana	2 yrs			6	Planted	350 m^2 each	
UK	*Pinus sylvestris, Fraxinus excelsior, Quercus petraea, Q. robur and Q. rubra*	4 yrs	6			Planted	3 m diameter x 4 m height	

Description of the treatments available at the experimental infrastructure held by each Partner.

Country	***Treatment No.***	***Name***	***CO_2 ppm***	***Temperature change***	***Nutrient status***	***Water status***	***Ozone status***	***Enclosed***
BELGIUM	OTC 1.	Ambient CO_2	Ambient	0	Moderate	Moderate	-	Yes
	OTC 1.	Elevated CO_2	Ambient+400	0	Moderate	Moderate	-	Yes
GERMANY	OTC 1.	Ambient CO_2	360 ± 34	0		Low		Yes
	OTC 2.	Elevated CO_2	698 ± 10	0		Low		Yes
	OTC 3.	External control		0		Low		No
	Phytotron 4.	Ambient CO_2	390	-4, -2, 0 = basis, +2, +4				Yes
	Phytotron 5.	Elevated CO_2	700	-4, -2, 0 = basis, +2, +4				Yes
ITALY	OTC 1.	External control	360	0	Low	Low	Low	No
	OTC 2.	Ambient CO_2	360	0	Low	Low	Low	Yes
	OTC 3	Elevated CO_2	710	0	Low	Low	Low	Yes
	FACE 1.	Ambient CO_2	350	0	Low	Low	Low	No
	FACE 2.	Elevated CO_2	550	0	Low	Low	Low	No
UK	OTC 1.	Ambient CO_2	350	0	Low	Low	Low	Yes
	OTC 2.	Ambient CO_2+ O_3	350	0	Low	Low	High	Yes
	OTC 3.	Elevated CO_2+ O_3	700	0	Low	Low	High	Yes
	OTC 4.	Elevated CO_2	700	0	Low	Low	Low	Yes
	OTC 5.	External control	350	0	Low	Low	Low	No

2.3 Project Structure, Planning and Timetable

2.3.1 Table 1. List of Participants

Participant	Role	Principal Scientist	Address	Telephone	Telefax	E-mail
P1	Full Partner	S.P. Evans	Forestry Commission Research Agency Alice Holt Lodge Wrecclesham, Farnham Surrey GU10 4LH, UK	+44-(0)1420-22255 ext. 2276	+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	T. Karjalainen	European Forest Institute Torikatu 34, FIN-80100 Joensuu FINLAND	+358-(0)13-252.0240	+358-(0)13-124.393	Timo.Karjalainen@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	gascaras@unitus.it
AP6	Associated Partner	R. Van de Velde	Universiteit Gent` Faculteit van de Landbouwkundige en Toegepaste Biologische Wetenschappen Vakgroep Bos- en Waterbeheer Coupure links 653 9000 Gent, BELGIUM	+32 9 264 61 24	+32 9 264 62 33	Riet.Vandevelde@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

2.3.2 Table 2. Workpackage List

Work-Package No	Work Package Title	Responsible Partner No.	Person-Months	Start Month	End Month	Deliverables No.
1.	Stand growth and yield data in field conditions for a range of management practices at primary and secondary sites	1	28	1	36	1-3
2.	Analyses of qualitative properties in standing timber	5	19	1	23	4-6
3.	Analyses of qualitative properties in manipulative experiments	2	34	2	23	7-9
4.	Analyses of wood anatomical properties in laboratory conditions	4	24	2	34	10-12
5.	Analyses of wood biochemical properties in laboratory conditions	4	16	2	27	13-15
6.	Analyses of wood physico-mechanical properties in laboratory conditions	6	16	3	27	16-18
7.	Modelling of wood quality and tree growth at stand scale for representative sites across Europe	2	52	1	33	19-23
8.	Development of the energy budget sub-model	3	15	4	8	24-26
9.	Protocol for model integration and upscaling	3	36	7	34	27-32
10.	Validation and application of model integration and upscaling	3	28	17	34	33-35
	TOTAL		**268**			

2.3.3 Table 3. Timetable of Project Workpackages

Work Packages will be monitored both by the partner having overall responsibility of the Work Package and through the Steering Group by the Co-ordinator, using the agreed dates for delivery of deliverables from each Work Package.

Work Package	Title of Working Step	Partners	1st year												2nd year												3rd year											
			1	2	3	4	5	6	7	8	9	10	11	12	1	2	3	4	5	6	7	8	9	10	11	12	1	2	3	4	5	6	7	8	9	10	11	12
1	a. Establishment of permanent sampling plots at primary sites	P1 (P2, P4, P5)						■	■																													
	b. Primary site plot sampling protocol	P1 (P5)					■																															
	c. Secondary site plot sampling protocol	P2 (P1, P5)					■																															
	d. Monitoring and data collection from secondary sites	P2 (P1, P5)	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■						
	e. Growth & yield data collection from primary and secondary sites	P1 (P2, P4, P5)		■	■							■	■	■	■									■	■	■	■											
2	a. Development & training in Timber Quality Assessment protocol	P1 (P5, AP6, P7)						■			■																											
	B. Standing timber quality assessment	P1 (P2, P5, AP6, P7)										■	■											■	■													
3	a. Tertiary site sampling protocol	P5 (P1, P2, P4)		■																																		
	B. Monitoring and data collection from tertiary sites	P5 (P1, P2, P4)										■	■											■	■					■	■							
4	a. Wood anatomy protocol	P4 (AP6, P7)						■	■																													
	b. Wood anatomical laboratory studies (existing and new material)	P4 (AP6, P7)			■	■	■	■	■	■	■	■					■	■	■	■	■	■	■	■						■	■	■	■	■	■			
5	a. Wood chemistry protocol	P4 (P7)		■	■																																	
	b. Wood chemical laboratory analyses (existing and new material)	P4 (P7)			■	■							■	■	■	■	■								■	■	■	■	■									
6	a. Wood physico-mechanical protocol	P7 (AP6)				■	■																															
	b. Wood physico-mechanical analyses (existing & new material)	AP6 (P7)					■	■	■						■	■	■										■	■	■									
7	a. Plot scale model modelling protocols	P2 (P1, P5)						■	■																													
	b. Plot scale model development and calibration	P2 (P1, P5)	■	■	■	■	■											■	■																			
	c. Plot scale model validation and application	P1 (P2, P5)																		■	■	■									■	■	■	■	■				
	d. Modelling carbon sequestration at the plot	P2 (P1, P4, P5)																															■	■	■			

Work Package	Title of Working Step	Partners	1st year (months 1–12)	2nd year (months 1–12)	3rd year (months 1–12)
	scale				
	e. Modelling productivity of wood products at the plot scale	P1 (P1, P2, P3, P5)			
8	a. Energy budget sub-model modelling protocols	P3 (P1, P7)			
	b. Energy budget sub-model development and calibration	P3 (P1, P7)			
9	a. Prototype integrated system modelling protocols	P3 (P1, P2, P5)			
	b. Development of the prototype integrated model at regional scale	P3 (P1, P2, P5)			
	c. Application of climate change scenarios	P3 (P1, P2, P5)			
	d. Application of socio-economic scenarios	P3 (P1, P2, P5)			
10	a. Prototype regional integrated model validation and application	P3 (P1, P2, P5, P7)			
11	a. Development of consortium database and data exchange protocols	P1 (P2, P3, P4, P5, AP6, P7)			
	b. Data exchange	P1 (P2, P3, P4, P5, AP6, P7)			
	c. International workshop	P1 (P2, P3, P4, P5, AP6, P7)			
	d. Web site updates	P3 (P1, P2, P4, P5, AP6, P7)			
	e. Annual and Final Reports	P1 (P2, P3, P4, P5, AP6, P7)			
	f. Consortium meetings	P1 (P2, P3, P4, P5, AP6, P7)	1, 2	3, 4	5, 6
	g. MILESTONES		I, II-III, IV, V	VI, VII, VIII-X	XI, XII, XIII-XIV, XV-XIX

2.3.4 Table 4. Participant Contribution and Timetable.

This table identifies contribution to working steps lead by each Partner only.

		1st year												2nd year												3rd year											
	Title of Working Step	1	2	3	4	5	6	7	8	9	10	11	12	1	2	3	4	5	6	7	8	9	10	11	12	1	2	3	4	5	6	7	8	9	10	11	12
Participant 1	1a Establishment of permanent sampling plots at primary sites						X	X																													
	1b Primary site plot sampling protocol					X																															
	1e Growth & yield data collection from primary and secondary sites		X	X							X	X	X	X									X	X	X	X											
	2a Development & training in Timber Quality Assessment protocol						X			X																											
	2b Standing timber quality assessment										X	X											X	X													
	7c Plot scale model validation and application																		X	X	X								X	X	X	X	X				
	7e Modelling productivity of wood products at the plot scale																													X	X	X					
	11a Development of consortium database and data exchange protocols								X	X	X																										
	11b Data exchange											X												X											X	X	
	11c International workshop																																			X	
	11e Annual and Final Reports												X	X											X	X								X	X	X	X
Participant 2	1c Secondary site plot sampling protocol					X																															
	1d Monitoring and data collection from secondary sites	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X						
	7a Plot scale model modelling protocols						X	X																													
	7b Plot scale model development and calibration	X	X	X	X	X											X	X																			
	7d Modelling carbon sequestration at the plot scale																															X	X	X			
Participant 3	8a Energy budget sub-model modelling protocols				X	X	X																														
	8b Energy budget sub-model development and calibration						X	X	X																												
	9a Prototype integrated system modelling protocols							X	X	X																											
	9b Development of the prototype integrated model									X	X	X	X	X	X																						

		1st year												2nd year												3rd year											
	Title of Working Step	1	2	3	4	5	6	7	8	9	10	11	12	1	2	3	4	5	6	7	8	9	10	11	12	1	2	3	4	5	6	7	8	9	10	11	12
	at regional scale									X	X	X	X	X	X																						
	9c Application of climate change scenarios																															X	X	X			
	9d Application of socio-economic scenarios																																X	X	X		
	10a Prototype regional integrated model validation and application																	X	X	X	X	X											X	X	X		
	11d Web site updates			X											X												X										X
Participant 4	4a Wood anatomy protocol						X	X																													
	4b Wood anatomical laboratory studies (existing and new material)			X	X	X	X	X	X	X	X					X	X	X	X	X	X	X	X						X	X	X	X	X	X			
	5a Wood chemistry protocol		X	X																																	
	5b Wood chemical laboratory analyses (existing and new material)			X	X							X	X	X	X	X								X	X	X	X	X									
Participant 5	3a Tertiary site sampling protocol		X																																		
	3b Monitoring and data collection from tertiary sites										X	X											X	X					X	X							
A Participant 6	6b Wood physico-mechanical analyses (existing & new material)					X	X	X						X	X	X										X	X	X									
Participant 7	6a Wood physico-mechanical protocol				X	X																															
All	11f Consortium meetings	1										2				3							4					5						6			
All	11g Milestones		I				II-III			IV		V			VI		VII							VIII-X						XI		XII		XIII-XIV		XV-XIX	

2.3.5 Table 5. List of Milestones

Milestone No	Associated WPs	Title	Delivery Date	Participants		Description
				Lead	Assoc.	
I.		Project WWW site	Month 3	P3		Interactive WWW site for use both by partners in the consortium and external browsers
II.	1,2,3,4	Sampling and analytical protocols	Month 6	P5	P1, P2	Completion of sampling protocols for primary, secondary and tertiary sites
III.	5,6	Laboratory and analytical protocols	Month 6	P4	AP6, P7	Completion of laboratory and analytical protocol for wood anatomy, wood chemistry and wood physico-mechanical properties
IV.	8	Energy budget model	Month 8	P3	P1, P7	Carbon and energy book-keeping model to quantify the fossil fuel energy inputs and associated CO_2 emissions of individual forest operations and timber conversion procedures.
V.		First Annual Report	Month 12	P1	P2, P3, P4, P5, AP6, P7	Completion of annual report to European Commission
VI.	1,2,3,4,5,6	Completion of Phase 1 sampling programme	Month 13	All		Completion of all sampling programme for year 1 at the primary, secondary and tertiary sites.
VII.	7	Prototype mechanistic dynamic model at plot scale	Month 16	P2	P1, P3, P4, P5, AP6, P7	A prototype coupled mensuration mechanistic dynamic model of tree growth, timber production and wood quality operational at the stand scale

Milestone No	Associated WPs	Title	Delivery Date	Participants		Description
				Lead	Assoc.	
VIII.		Scientific Papers	Month 24	All		Completion of 6 scientific papers for publication in peer-reviewed journals
IX.		Technical Papers	Month 24	All		Completion of 6 technical papers for publication in national timber industry journals
X.		Second Annual Report	Month 24	P1	P2, P3, P4, P5, AP6, P7	Completion of annual report to European Commission
XI.	1,2,3,4,5,6	Completion of Phase 2 sampling programme	Month 30	All		Completion of all sampling programme for year 2 at the primary, secondary and tertiary sites.
XII.	5,6	Completion of laboratory studies	Month 32	P4	AP6, P7	Completion of all laboratory studies on wood anatomy, wood chemistry and wood physico-mechanical properties.
XIII.	9	Regional scale model	Month 34	P3	P1, P2, P4, P7	An integrated model which accounts for tree growth and production, wood quality, carbon sequestration, fossil energy and GHG balances and timber pricing operational at the regional scale.
XIV.		International Workshop	Month 35	P1	P2, P3, P4, P5, AP6, P7	International workshop on “Forecasting the dynamic response of timber quality to management and environmental change from the site to the regional scale: experimental and modelling approaches”.

Milestone No	Associated WPs	Title	Delivery Date	Participants		Description
				Lead	Assoc.	
XV.		Scientific Papers	Month 36	All		Completion of 6 scientific papers for publication in peer-reviewed journals
XVI.		Technical Papers	Month 36	All		Completion of 6 technical papers for publication in national timber industry journals
XVII.	1,2,3,4,5,6	Unified database of data from the monitoring, experimental, laboratory and manipulative components	Month 36	P1	P2, P3, P4, P5, AP6, P7	Unified relational database with all monitoring, experimental, laboratory and manipulative data collected during the programme.
XVIII.	9,10	Database of modelling scenarios	Month 36	P3	P1, P2, P5	Portfolio of model predictions at the regional scale
XIX.		Final Report	Month 36	P1	P2, P3, P4, P5, AP6, P7	Completion of final report to European Commission

2.3.6 Table 6. List of Deliverables

Work-Package No.	Deliverable No.	**Deliverable title**	Delivery Date	Nature [2]	Dissemination Level [3]	Dissemination Target [4]
1.	1.	Standardised methodology for site characteristics, physiological, eco-physiological and mensurational data for observed forest stands	Month 6	O	CO	C
	2.	Data-base of site characteristics, physiological, eco-physiological and mensurational data for a range of species, environmental conditions and management options	Month 36	O	CO	C S P
	3.	Calibration and validation data for coupled mensuration-mechanistic dynamic model of tree growth, yield and quality; growth and yield	Month 36	O	CO	C
2.	4.	Standardised methodology for timber quality assessment for forest stands, applicable across the European Union.	Month 6	O	CO	C S I
	5.	Data-base on timber quality assessment for forest stands for a range of species, environmental conditions and management options	Month 22	O	CO	C S I
	6.	Calibration and validation data for coupled mensuration-mechanistic dynamic model of tree growth, yield and quality; qualitative properties in standing timber	Month 24	O	CO	C
3.	7.	Standardised methodology for assessing growth patterns and allocation of juvenile plants grown in manipulative experimental conditions.	Month 30	O	CO	C
	8.	Data-base on growth patterns and allocation from individuals for a range of species, environmental conditions, management options and atmospheric change	Month 32	O	CO	C S I
	9.	Calibration and validation data for	Month 34	O	CO	C

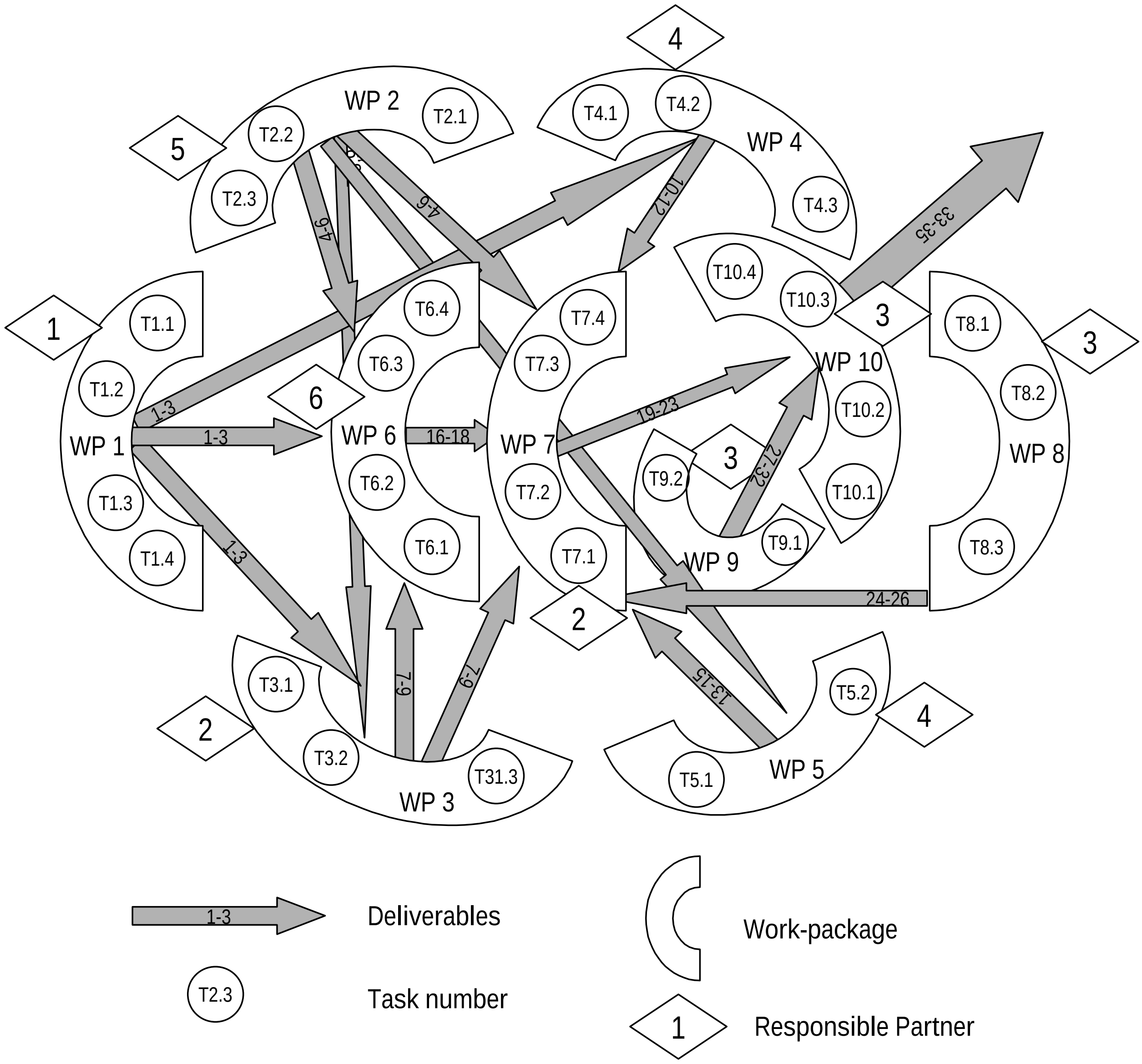
[2] **Nature of Deliverables:**
R = Report
P = Prototype
D = Demonstrator
O = Other
[3] **Dissemination Level:**
PU = Public
RE = Restricted to group specified by Consortium (including Commission Services)
CO = Confidential, only for members of the Consortium (including Commission Services)
[4] Target audience of potential users/beneficiaries of the deliverable:
C = Restricted to group specified by Consortium (including Commission Services)
CO = CommissionServices
S = Scientific users
I = Industry users

Work-Package No.	Deliverable No.	Deliverable title	Delivery Date	Nature [2]	Dissemination Level [3]	Dissemination Target [4]
		coupled mensuration-mechanistic dynamic model of tree growth, yield and quality; manipulative experiments				
4.	10.	Standardised methodology for determining selected anatomical wood properties.	Month 6	O	CO	C S
	11.	Data incorporated into a database on the anatomical properties of wood from trees for a range of species, environmental conditions, management options, atmospheric and climate change	Month 34	O	CO	C S I
	12.	Calibration and validation data for coupled mensuration-mechanistic dynamic model of tree growth, yield and quality; anatomical properties	Month 34	O	CO	C S
5.	13.	Standardised methodology for determining selected biochemical wood properties.	Month 6	O	CO	C S
	14.	Data incorporated into a database on the biochemical properties of wood from trees for a range of species, environmental conditions, management options, atmospheric and climate change	Month 27	O	CO	C S I
	15.	Calibration and validation data for coupled mensuration-mechanistic dynamic model of tree growth, yield and quality; biochemical properties	Month 31	O	CO	C
6.	16.	Standardised methodology for determining selected wood physico-mechanical properties.	Month 6	O	CO	C
	17.	Data-base on the physico-mechanical properties of wood from trees for a range of species, environmental conditions, management options, climate and atmospheric change	Month 27	O	CO	C S I
	18.	Calibration and validation data for coupled mensuration-mechanistic dynamic model of tree growth, yield and quality.	Month 29	O	CO	C
7.	19.	Protocol for integration of sub-modules.	Month 6	O	CO	C
	20.	A prototype coupled mensuration mechanistic dynamic model of tree growth, timber production and wood quality operational at the stand scale.	Month 16	p	CO	C
	21.	A user-friendly version of the model available as a prototype decision support system.	Month 18	P	PU	C S I
	22.	Predictions of timber production accounting for tree quality across a representative range of sites and	Month 32	R	PU	C S I

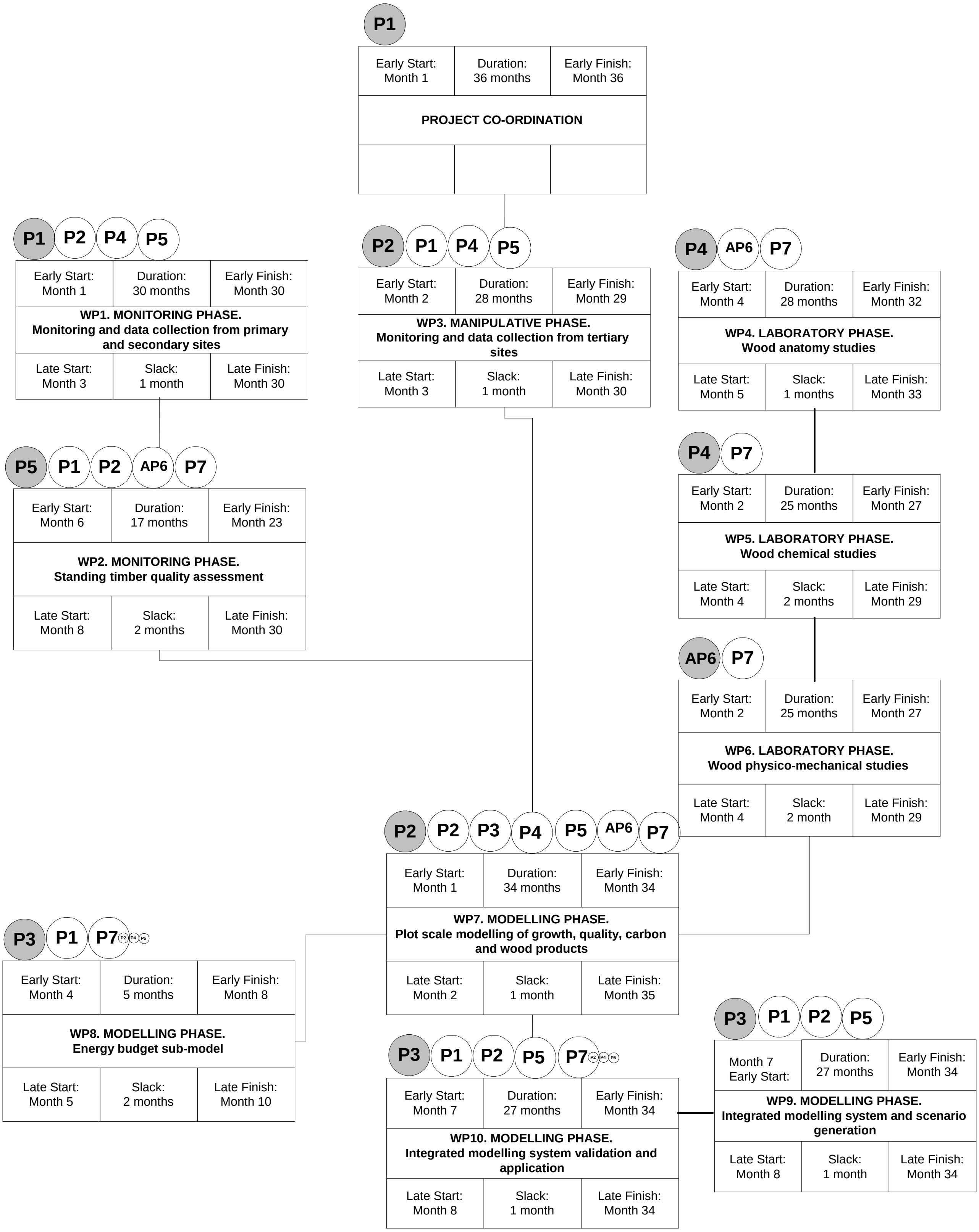
Work-Package No.	Deliverable No.	Deliverable title	Delivery Date	Nature [2]	Dissemination Level [3]	Dissemination Target [4]
		silvicultural regimes in participating countries, also accounting for scenarios of future environmental change.				
	23.	Predictions of environmental impact in terms of current and future forest stand composition and structure, its nutrient status and dynamics, and ecosystem carbon balance across a representative range of sites and silvicultural regimes in participating countries, also accounting for scenarios of future environmental change.	Month 33	R	PU	C S I
8.	24.	A review of forestry working practices, wood processing methods and implicit fossil energy inputs.	Month 6	O	CO	C
	25.	A computer-based model of fossil energy and carbon-based balances Available as source code, or executable user-friendly interface.	Month 8	p	PU	C
	26.	Sub-model within integrated model to evaluate impacts of environmental and silvicultural changes on fossil energy requirements and greenhouse gas balances of wood production processes.	Month 18	p	CO	
9.	27.	Protocol for model integration and upscaling	Month 14	R	CO	C
	28.	An integrated model accounting for tree growth and production, wood quality, carbon sequestration, fossil energy and GHG balances and timber pricing operational at the scale of EU Member States.	Month 29	P	CO	C S I
	29.	Data-base integrated with the model of plausible future Environmental socio-economic and management scenarios applicable to the EU forestry and wood products sector.	Month 30	O	PU	C S I
	30.	Validation of model outputs against empirical databases of processes observed in the monitoring and manipulative components of the project.	Month 34	O	PU	C
	31.	A portfolio of plausible future environmental socio-economic and management scenarios applicable to the EU forestry and wood products sector.	Month 36	O	PU	C
	32.	A portfolio of model predictions for all variables listed above, (listed in deliverable 28) produced by running the above model using empirical data from earlier work-packages and simulation	Month 36	O	PU	C

Work-Package No.	Deliverable No.	Deliverable title	Delivery Date	Nature [2]	Dissemination Level [3]	Dissemination Target [4]
		data from the stand- scale model as input.				
10.	33.	Standardised model assessment tools incorporated into the integrated model software to assess uncertainty in model predictions associated with output sensitivity to input parameters and scaling effects.	Month 34	R	PU	C
	34.	A selection of environmental, socio-economic and management scenarios for the EU forestry and wood products sector.	Month 35	O	PU	C S I
	35.	A portfolio of model predictions for all variables listed above (listed in deliverable 28), produced by running the improved upscaling model using empirical data from earlier work-packages and simulation data from the stand- scale model as input with an associated uncertainty interval.	Month 35	O	PU	C S I
Other	36.	Papers in peer-reviewed scientific journals.	Month 18-3	R	PU	C S
	37.	Reports at international and national scientific meetings.	Month 18-3	R	PU	S
	38.	Reports in forestry and timber-processing industry journals in participating countries and international bulletins.	Month 18-3	R	PU	I
Mana g	39.	First Annual Report	Month 13	R	CO	CO
	40.	Second Annual Report	Month 26	R	CO	CO
	41.	Final Report	Month 36	R	CO	CO
	42.	International Workshop	Month 35	O	PU	S I
	43.	WWW page	Month 3	O	PU	S I

2.3.7 Schematic Diagram of Project Components



2.3.8 Project Management Structure



2.4 WORKPACKAGES

WP1. Stand growth and yield data in field conditions for a range of management practices at primary and secondary sites

Workpackage number:	1						
Start Date:	Month 1						
Completion Date:	Month 30						
Partners Responsible:	**P1**, P2, P4, P5						
Person-months per Partner	P1	P2	P3	P4	P5	AP6	P7
	10	3		3	9		

OBJECTIVES

The main objective will be to generate stand growth and yield data in field conditions for a range of management practices at primary and secondary sites. This will be achieved by:

1.1 Collection of historical stand data on growth and yield from the primary monitoring sites.

1.2 Collection of contemporary data on growth and yield from the primary monitoring sites for a range of representative management conditions as practised in the partners' Member States:

- Ø even-age single species [intensive silviculture]
- Ø uneven age single species
- Ø uneven-age multi-species [continuous cover forest]

1.3 Sampling of wood from tree compartments (branch and stem) from timber felled as a result of national forest management practices. Thinning will take place according to standard national forest management practices.

1.4 Generation of CO_2 and H_2O flux datasets using existing infrastructure for validating short-term process models.

METHODOLOGY AND STUDY MATERIALS

Available historical stand and yield data will be integrated with ongoing annual monitoring of stand growth and yield assessments at well characterised primary and secondary sites, for a representative range of management conditions. These data are required to parameterise, validate and calibrate the mensurational sub-module of the forest stand scale model.

A standardised mensurational protocol will be introduced to achieve harmonisation of the experimental protocol and develop a unified set of growth and yield data for selected sites across Europe. Training will be carried out by Partner 1, who has the primary responsibility to ensure standardised application of the mensurational protocol.

The following monitoring measurements will be carried out at secondary sites, with each Partner responsible for his national sites.

		UK		**Belgium**		**Germany**		**Italy**		
		1/0	*Timestep*	*1/0*	*Timestep*	*1/0*	*Timestep*	*1/0*	*Timestep*	*Remarks*
Meteo	Air temperature	P	30 mins	P	30 mins	P	30 mins	P	30 mins	
	Soil Temperature	P	30 mins	P	30 mins	P	30 mins	P	30 mins	
	Wind speed	P	30 mins	P	30 mins	P	30 mins	P	30 mins	
	Vapour pressure	P	30 mins	P	30 mins	P	30 mins	P	30 mins	
	Wind direction	P	30 mins	P	30 mins	P	30 mins	P	30 mins	
	Light interception	P	30 mins	P	30 mins	P	30 mins	P	30 mins	
	Solar radiation	P	30 mins	P	30 mins	P	30 mins	P	30 mins	
	Net radiation	P	30 mins	P	30 mins	P	30 mins	P	30 mins	
	Throughfall volume	P	30 mins	P	30 mins	P	30 mins	P	30 mins	
Soil Water	30 cm	P	30 mins	P	1 week					
	0-15 cm	P	30 mins	P	1 week	P	1 week	P	1 week	
	15-30 cm	P	1 week	P	1 week	P	1 week	P	1 week	
	30-60 cm	P	1 week	P	1 week	P	1 week	P	1 week	
	60-90 cm	P	1 week	P	1 week	P	1 week	P	1 week	
	90-120 cm	P	1 week	P	1 week					
Physiology	CO_2 flux	P	30 mins	P	30 mins	P	30 mins	P	30 mins	Growing season
	TranspiraH_2O flux	P	30 mins	P	30 mins	P	30 mins	P	30 mins	Growing season
	Transpiration flux	P	15 mins	P	1 g.s.					Growing season
	Girth increment	P	30 mins	P	1 g.s.	P	1 week	P	1 week	

Equipment used for the measurements.

		UK	*Belgium*	*Germany*	*Italy*
Meteo	Air temperature		five heights		24.5,21.18.11.2.0.5 m
	Soil Temperature	30 cm height	5 cm depth	30 cm height	-0.05,-0.2 m
	Wind speed	Sonic and conventional anemometer	Sonic and conventional anemometer	Sonic and conventional anemometer	27,23,21 m
	Vapour pressure	Psychrometer and IRGA	Psyschrometer and IRGA	Psychrometer and IRGA	24.5,2,0.5 m
	Wind direction		Sonic anemometer		27 m
	Light interception	Tube solarimeter above and below canopy	Tube solarimeter	Tube solarimeter	
	Solar radiation	Dome solarimeter	Solarimeter	Solarimeter	26 m
	Net radiation		Net radiation	Net radiation	24.5 m
	Throughfall volume				20 automatic samplers
Soil Water	30 cm	Theta probe	Theta probe	Theta probe	
	0-15 cm	TDR probe	TDR probe	TDR probe	TDR probe
	15-30 cm	TDR probe	TDR probe	TDR probe	TDR probe
	30-60 cm	TDR probe	TDR probe	TDR probe	TDR probe
	60-90 cm	TDR probe	TDR probe	TDR probe	TDR probe
	90-120 cm	TDR probe	TDR probe	TDR probe	
Physiology	CO_2 flux	Edisol flux system	Edisol flux system	Edisol flux system	Eddy fluxes
	TranspiraH_2O flux	Edisol flux system	Edisol flux system	Edisol flux system	Eddy fluxes
	Transpiration flux	Granier sap-flow guages	Energy balance method	Energy balance method	
	Girth increments	Wheatstone bridge strain guages	Dendrometers		Traditional dendrometers

The following parameters will be measured annually from 10 juvenile trees harvested at the end of the growing season over the 3 year period:

Parameter	***UK (n=10)***	***Germany (n=10)***	***Italy (n=10)***	***Belgium (n=10)***
stem length	P	P	P	P
stem diameter (2x)	P	P	P	P
number of branches	P	P	P	P
number of buds		P		
number of leaves		P		
leaf area	P	P	P	P
dry mass of stem	P	P	P	P
dry mass of fine roots	P	P	P	P
dry mass of coarse roots	P	P	P	P

DELIVERABLES

1. Standardised methodology and protocol for site characteristics, physiological, eco-physiological and mensurational data for observed forest stands.
2. Data-base of site characteristics, physiological, eco-physiological and mensurational data for a range of species, environmental conditions and management options
3. Calibration and validation data for coupled mensuration-mechanistic dynamic model of tree growth, yield and quality using flux data, increment and other mensuration datasets.

MILESTONES

Milestone No	Title	Delivery Date	Participants	
			Lead	Assoc.
II. (Partial)	Sampling and analytical protocols	Month 6	P5	P1, P2
VI. (Partial)	Completion of Phase 1 sampling programme	Month 13	All	
XI. (Partial)	Completion of Phase 2 sampling programme	Month 30	All	
XVII. (Partial)	Unified database of data from the monitoring, experimental, laboratory and manipulative components	Month 36	P1	P2, P3, P4, P5, AP6, P7

WP2. Analyses of qualitative properties in standing timber

Workpackage number:	2						
Start Date:	Month 1						
Completion Date:	Month 25						
Partners Responsible:	**P5**, P1, P2, AP6, P7						
Person-months per Partner	P1	P2	P3	P4	P5	AP6	P7
	6	2			4	4	2

OBJECTIVES

To apply a standard classification system for assessing quality in forest stands and consistent with sawmill outputs will be used across all the primary sites. This allows an assessment of straightness and quality scoring of both trees and stands and will be employed to develop a database across a range of species at well-characterised sites and for a representative range of management options. These data are required to parameterise, validate and calibrate the standing timber quality sub-module of the stand scale growth-quality model.

The main objective will be to determine the qualitative properties of standing timber. To be achieved by:

2.1 Developing the standardised methodology for timber quality assessment for forest stands, applicable across studied regions.

2.2 Non-destructive single measurement of standing tree characteristics for straightness and branchiness.

2.3 Creating a data-base on timber quality assessment for forest stands across a range of species, environmental and management perturbations.

METHODOLOGY AND STUDY MATERIALS

An existing system to assess timber quality of forest stands based on an evaluation of stem straightness and branchiness in conifers will be adopted and extended by this project. Log quality is determined principally through stem features, summarised for the following categories:

- Stem form: straightness, sweep, bend, lean
- Branchiness: presence and size of knots, limbs, forks, multi-stems
- Damage: scar defects, browsing, extraction

The definition of straightness specifies:

(1) Bow not to exceed 1 cm for every 1 m length and this in one plane and one direction only;

(1) Bow is measured as the maximum deviation at any point of a straight line joining centres at each end of the log from the actual centre line of the log (Figure 1).

At both primary and secondary sites, the quality protocol will be applied on all standing trees present in a surface area of 0.1 ha. It is anticipates the number of trees will vary between 50÷300, as a function of stand age and local management practices. It is further anticipated repeated site visits will be required to modify the protocol and to produce a standard methodology and data-set valid for all sites.

Tree felling. Felling of trees is not allowed in the permanent Level II sites. Thus a sample of trees, representative of those inside the permanent plot, will be felled from outside the plots. These trees will have to located in a position where this will not no influence or damage individuals growing inside the permanent plots, so as not to affect the ongoing long-term experiment. It is therefore necessary to identify a plot similar to the permanent plot in terms of site and mensurational characteristics; this will therefore require a new series of measurements to be carried out. It is assumed that all other variables remain constant between the two plots.

Felled trees will be used to:

a. Validate the quality assessments made on the standing timber.

b. Provide the plant material required for the laboratory-based WPs 4-6.

The number of trees to be felled will vary as a function of the number of individuals present, their age and species, the stand characteristics as well as the variability observed in the results of the quality assessment protocol.

Tree felling, sampling of wood material and transportation will be responsibility of individual Partners.

Training. Training for field staff on the quality protocol is required in order to ensure inter-Partner standardisation and will be provided by Partner 1.

DELIVERABLES

4. Prototype standardised methodology for timber quality assessment for forest stands, applicable across studied regions.
5. Data-base on timber quality assessment for forest stands for a range of species, environmental conditions and management options.
6. Calibration and validation data for coupled mensuration-mechanistic dynamic model of tree growth, yield and quality.

MILESTONES

1. New data on the quantification of the standing quality of timber from trees across a range of species, environmental and management options in participating Member States.

Milestone No	Title	Delivery Date	Participants	
			Lead	Assoc.
II. (Partial)	Sampling and analytical protocols	Month 6	P5	P1, P2
VI. (Partial)	Completion of Phase 1 sampling programme	Month 13	All	
XI. (Partial)	Completion of Phase 2 sampling programme	Month 30	All	
XVII. (Partial)	Unified database of data from the monitoring, experimental, laboratory and manipulative components	Month 36	P1	P2, P3, P4, P5, AP6, P7

WP3. Analyses of qualitative properties in manipulative experiments

Workpackage number:	3						
Start Date:	Month 2						
Completion Date:	Month 29						
Partners Responsible:	**P2**, P1, P4, P5						
Person-months per Partner	P1	P2	P3	P4	P5	AP6	P7
	9	11		4	9		

OBJECTIVES

This work package will produce material for an assessment of the specific way in which allocation may be influenced by elevated CO_2 treatment and the biochemical, anatomical and bio-mechanical properties to be used in successive WPs. The main objective will be to analyse the qualitative properties of timber from manipulative experiments. This will be achieved by:

3.1 Non-destructive seasonal measurements of physiological growth parameters: bud burst, photosynthesis, stomatal conductance, transpiration, photosynthesis, leaf chlorophyll content, leaf and needle loss to inform model parameterisation, calibration and validation. Use will also be made of existing information;

3.2 Non-destructive annual measurements of mensurational parameters: etc. to inform model parameterisation, calibration and validation;

3.3 At final harvest, destructive sampling biomass of tree compartments (leaves, buds, twigs, branches, stems, fine roots (0 < 2 mm) and coarse roots (0 > 2 mm)) will be made to develop allometric mass distribution ratios to inform model parameterisation, calibration and validation.

METHODOLOGY AND STUDY MATERIALS

FACE, OTC growth chambers and mini-ecosystems will be employed to raise the temperature and CO_2 levels and modify water and N availability of experimental plots at each experimental manipulation site. Saplings and juvenile individuals of selected species will be grown and the performance of each established seedling will be recorded over a period of three years. The impact of manipulated growth conditions upon the growth components will be assessed using non-destructive estimates of aboveground biomass and destructively at final harvest to also provide estimates of below ground biomass. Partner 2 will develop appropriate protocols to achieve consistent and standardised results between Partners in this Work Package.

The following monitoring measurements will be carried out at tertiary sites, with each Partner responsible for his national sites.

		UK		Belgium		Germany		Italy		
		1/0	*Timestep*	*1/0*	*Timestep*	*1/0*	*Timestep*	*1/0*	*Timestep*	*Remarks*
Meteo	Air temperature	P	30 mins		-	P	30 mins	P	30 mins	
	Soil Temperature	P	30 mins		-	P	30 mins	P	30 mins	
	Wind speed	P	once		-	P	once	P	1 min	
	Solar radiation	P	30 mins	P	1 hr	P	30 mins	P	30 mins	
	Vapour pressure	P	32 mins	P	1 hr	P	32 mins	P	30 mins	
	CO_2	P	32 mins	P	30 mins	P	32 mins	P	1 min	
	O_3	P	32 mins		-	P	32 mins			
	CO_2 exchange					P	30 mins			
	H_2O exchange					P	30 mins			
Soil Water	20 cms	P	30 mins		-	P	30 mins			
Physiology	Photosynthesis	P	g.s.	P	g.s.	P	g.s.	P	g.s.	Growing season
	Transpiration	P	g.s.	P	g.s.	P	g.s.	P	g.s.	Growing season
	Stomatal conductance	P	g.s.	P	g.s.	P	g.s.	P	g.s.	Growing season
	Sapflow		g.s.				g.s.	P	g.s.	

The following growth parameters will be measured annually from 10 juvenile trees harvested at the end of the growing season over the 3 year period:

Parameter	***UK (n=10)***	***Germany (n=10)***	***Italy (n=10)***	***Belgium (n=10)***
stem length	P	P	P	P
stem diameter (2x)	P	P	P	P
number of branches	P	P	P	P
number of buds		P		
number of leaves		P		
leaf area	P	P	P	P
dry mass of stem	P	P	P	P
dry mass of fine roots	P	P	P	P
dry mass of coarse roots	P	P	P	P

DELIVERABLES

7. Standardised methodology and protocol for assessing growth patterns and allocation of juvenile plants grown in manipulative experimental conditions.
8. Data-base on growth patterns and allocation from individuals for a range of species, environmental conditions, management options and atmospheric change.
9. Calibration and validation data for coupled mensuration-mechanistic dynamic model of tree growth, yield and quality.

MILESTONES

New data on the quantification of carbon allocation from trees across a range of species grown in plausible future scenarios of atmospheric composition change.

Milestone No	Title	Delivery Date	Participants	
			Lead	Assoc.
II. (Partial)	Sampling and analytical protocols	Month 6	P5	P1, P2
VI. (Partial)	Completion of Phase 1 sampling programme	Month 13	All	
XI. (Partial)	Completion of Phase 2 sampling programme	Month 30	All	
XVII. (Partial)	Unified database of data from the monitoring, experimental, laboratory and manipulative components	Month 36	P1	P2, P3, P4, P5, AP6, P7

WP4. Analyses of wood anatomical properties in laboratory conditions

Workpackage number:	4						
Start Date:	Month 2						
Completion Date:	Month 32						
Partners Responsible:	**P4**, AP6, P7						
Person-months per Partner	P1	P2	P3	P4	P5	AP6	P7
				15		6	3

OBJECTIVES

The aim is to correlate anatomical modifications with changes identified through biochemical and bio-mechanical analyses. In addition to new plant material, existing material from completed manipulative experiments will also be investigated. The main objective will be to analyse the anatomical properties of wood from the monitoring and manipulative experiments in laboratory conditions. This will be achieved by:

4.1 Qualitative determination of the different portions of cell types, cell *lumina* and cell wall thickness of plant material grown: (a) in ambient CO_2 from different sites and for a representative range of forest management conditions; (b) new plant material after one, two and three years Of CO_2 enrichment and/or manipulation of climatic and management factors; (c) existing plant material after up to five years of CO_2 enrichment and/or manipulation of climatic and management factors.

4.2 Qualitative determination of cell wall growth and lignification at elevated CO_2 concentration.

4.3 Assess changes in tension and compression wood proportion as these are considered to be important criteria for quality evaluation. The transition zone between juvenile and mature wood will be evaluated from anatomical analysis and the amount of juvenile wood will be compared for plant material grown under ambient and elevated CO_2 conditions.

METHODOLOGY AND STUDY MATERIALS

Wood biochemical studies will be carried out for all experimental sites on both juvenile and adult material on a representative number of samples (approx. 10 trees per site/experiment, where appropriate), with a total of approx. 4000 samples analysed. Additionally, existing material from the German sites will also be investigated, up to a total of 120 samples.

<u>Morphological and biochemical assessment</u>. Cross-sectional examination of thin sections (30 •m) of wood will be employed to assess changes in the proportion of cell types (conductive [vessel/tracheid] tissue, storage (parenchymatic and structural [fibre] tissues) tension, compression and juvenile wood from plant material from the monitoring and manipulative sites. Instrumentation used will include optical microscopy, microtome and standard staining procedures (phloroglucine + HCl). Partner 4 will develop appropriate protocols to achieve consistent and standardised results.

<u>Sample preparation procedure</u>. In outline, the sample preparation procedure will be as follows:

1. Cut samples from logs or bore using Pressler corer.
2. Preparation of samples -- this is slow and must be completed with care – cutting, polishing and staining each sample can take up to 1 hour.
3. Microscopic measurements and assessments.
4. Data preparation and manipulation.

<u>Step 3</u>. Following staining stem anatomy will be assessed under a microscope in the cross, tangential and radial sections with the following measurements taken per section:

Anatomical
1. Cell wall thickness (longitudinal + tangential sections)
2. Cell lumina (cross section)
3. Tree ring width (whole sections)
4. Grade of lignification – half quantitative (whole sections)

Total sample. In total, it is foreseen approximately 19,000 data points will result from the anatomical studies carried out on the plant material sampled at the primary, secondary and tertiary sites.

DELIVERABLES

10. Standardised methodology for determining selected anatomical wood properties.
11. Data incorporated into a database on the anatomical properties of wood from trees for a range of species, environmental conditions, management options, atmospheric and climate change
12. Calibration and validation data for coupled mensuration-mechanistic dynamic model of tree growth, yield and quality.

MILESTONES

New data on the quantification of wood anatomical characteristics from trees across a range of species, environmental and management perturbations in participating Member States, and across a range of plausible future scenarios of atmospheric composition change.

Milestone No	Title	Delivery Date	Participants	
			Lead	Assoc.
II. (Partial)	Sampling and analytical protocols	Month 6	P5	P1, P2
VI. (Partial)	Completion of Phase 1 sampling programme	Month 13	All	
XI. (Partial)	Completion of Phase 2 sampling programme	Month 30	All	
XVII. (Partial)	Unified database of data from the monitoring, experimental, laboratory and manipulative components	Month 36	P1	P2, P3, P4, P5, AP6, P7

WP5. Analyses of wood biochemical properties in laboratory conditions

Workpackage number:	5						
Start Date:	Month 2						
Completion Date:	Month 27						
Partners Responsible:	**P4**, P7						
Person-months per Partner	P1	P2	P3	P4	P5	AP6	P7
				12			2

OBJECTIVES
The main objective will be to analyse the biochemical properties of wood from the monitoring and manipulative experiments in laboratory conditions. This will be achieved by:
5.1 Enzymatic determination of stem wood and coarse root metabolism (*d*-glucose, *d*-fructose, sucrose and starch);
5.2 Quantitative analytical determination of sucrose, starch and cell wall components.

METHODOLOGY AND STUDY MATERIALS
Wood biochemical studies will be carried out for all experimental sites on both juvenile and adult material on a representative number of samples (approx. approx. 10 trees per site/experiment, where appropriate). Additionally, existing material from the German sites will also be investigated, up to a total of 120 samples.

Samples from stems and coarse roots of juvenile individuals of selected species grown in manipulative experimental facilities and probe samples extracted from adult trees at the monitoring sites, will be taken at the end of three subsequent vegetation periods. Special below-ground containers in the experimental facilities, which enclose soil blocks of 0.4 m^3**,** will enable the extraction of root samples with only minimal impact on the individual tree. In addition to new plant material, existing plant material from completed manipulative experiments are available for selected investigations of biochemical wood properties. Established laboratory techniques will be employed to determine modifications in the metabolism of secondary products through the comparison between analysed plant material from the monitoring and experimental manipulation sites. Destructive samples of above- and below-ground compartments will be taken from the manipulative experiments over a period of 3 years and any changes to biochemical properties assessed. Standard laboratory methods in Good Laboratory Practice (GLP) conditions for total quality control will be used to analyse:
(a) Sucrose , glucose, fructose (spectrophotometrically, microtitre plate reader);
(b) Starch (spectrophotometrically, microtitre plate reader);
(c) Cell wall components (GC-MS).
Partner 4 will develop appropriate protocols to achieve consistent and standardised results between Partners in this Work Package.

Sample preparation procedure. In outline the sample preparation procedure will be:

1. Cut samples from logs.
2. Sample preparation.
3. Analysis.
4. Data preparation and manipulation.

Step 3. The following parameters will be estimated:

Biochemical
Non-structural and structural carbohydrate content
Total lignin, cellulose and hemicelluose content
Total N content (also for other compartments e.g. leaf, branch, stem, fine and coarse roots)

In detail, the following elements will be determined quantitatively:

1) D- Glucose
2) D-Fructose
3) Sucrose
4) Starch
5) Lignin
6) Residuals
7) Cellulose
8) Ash (mineral)

Total sample. In total, it is foreseen approximately 5,500 data points will result from the biochemical studies carried out on the plant material sampled at the primary, secondary and tertiary sites.

DELIVERABLES

13. Standardised methodology for determining selected biochemical wood properties.
14. Database of biochemical properties of wood from trees for a range of species, environmental conditions, management options, atmospheric and climate change.
15. Calibration and validation data for coupled mensuration-mechanistic dynamic model of tree growth, yield and quality.

MILESTONES

New data on the quantification of wood biochemical characteristics for trees for a range of species, environmental and management conditions in participating Member States, and across a range of plausible future scenarios of atmospheric composition change.

Milestone No	Title	Delivery Date	Participants	
			Lead	Assoc.
III. (Partial)	Laboratory and analytical protocols	Month 6	P4	AP6, P7
VI. (Partial)	Completion of Phase 1 sampling programme	Month 13	All	
XI. (Partial)	Completion of Phase 2 sampling programme	Month 30	All	
XII. (Partial)	Completion of laboratory studies	Month 33	P4	AP6, P7
XVII. (Partial)	Unified database of data from the monitoring, experimental, laboratory and manipulative components	Month 36	P1	P2, P3, P4, P5, AP6, P7

WP6. Analyses of wood physico-mechanical properties in laboratory conditions

Workpackage number:	6						
Start Date:	Month 3						
Completion Date:	Month 27						
Partners Responsible:	**AP6**, P7						
Person-months per Partner	P1	P2	P3	P4	P5	AP6	P7
						10	8

OBJECTIVES

The main objective will be to analyse the physico-mechanical (biomechanical) properties of wood from the monitoring and manipulative experiments in laboratory conditions.

The main aim of this work package is to quantify changes in a range of wood physico-mechanical properties (static bending, compression parallel to grain, density and moisture content) to correlate with results of chemical and anatomical modifications. This will be achieved by:

6.1 Measurement and comparison of growth ring width of trees grown under ambient and elevated conditions and width of early- and latewood increment, at breast height of the test trees

6.2 Quality assessment of structural timber grown in manipulative experiments.

6.3 Assessment of drying distortions of timber grown in manipulative experiments.

6.4 Quality assessment of samples of timber grown in manipulative experiments to determine key mechanical and physical properties.

METHODOLOGY AND STUDY MATERIALS

Wood density, mechanical stress, juvenile and compression wood will be carried out on approx. 10 trees/site from at least 2 stem heights with as many replicates per height as possible (not more than 10).

Sampling. The following parameters will be assessed:

Mechanical
Wood density
Mechanical stress
Drying distortion
Knot area
Slope of grain
Juvenile and compression wood area

Sample preparation, mechanical and physical properties assessment will based on industry-standard tests carried out on 20x20x10 and 50x50x5 mm cross-section samples cut from l m long logs. Samples will be cut from the North and/or East direction of each log radiating out from the pith. One sample from juvenile wood, one from the interface between juvenile and adult wood and one from adult wood will be tested.

1. Growth rings. A LINTAB III positioned linetable connected with a computer and a microscope with an accuracy of 1/100 mm, will be used for the width measurements. To evaluate specific responses of wood characteristics to elevated CO_2, in order to reconstruct the impact of historical increases in CO_2, dendro-chronological techniques will be used.

2. Quality assessment of structural timber. Quality assessment according to standard industrial practice, as well as a more discriminating assessment *via* the strength and stiffness of the timber. Short logs will be converted in partner countries; cut samples will be delivered wet and wrapped for successive drying and testing and 2.4 m battens produced using standard milling practices to assess axial compression strength tests using an electro-mechanical Zwick testing machine; compression and tension wood will be microscopically measured by colour tests; mechanically stress grade using a machine to record modulus of elasticity at 100 mm intervals; classify according to C16 or C25 or reject structural

classification; establish true modulus of elasticity [MOE] and modulus of rupture [MOR] under 4 point bending according to CEN Standards, at the weakest point.

3. Assessment of Drying Distorsions. Straightness after initial drying and in service is the second important criteria for structural use. Battens for Objective 1 will be kiln dried to 15% moisture content (MC) and assessed to measure: nominal density of wood samples (the question of the applicability of these analyses to commercial timber should be born in mind, as the young trees used here consist largely of juvenile wood, although the results can be extrapolated by resistograph drilling); percentage of shrinkage, together with the influence of juvenile wood, tension and compression wood on dimensional stability; drying distortion (twist spring and bow) on a flat slate; MC at centre of each batten at two depths (5 and 15 mm) to produce the moisture gradient; knot area on the middle 30 cm of the 200 cm distortion measurement span; slope of grain in this position, area of juvenile wood and any compression wood.

4. Quality assessment by small clear samples to determine mechanical and physical properties**.** Where longer logs are not available, from example from the tertiary sites, small samples (60x20x20mm) will be examined to assess basic structural wood properties of knot free wood. Partner 7 will develop appropriate protocols to achieve consistent and standardised results between Partners.

Number of Samples. For machine stress grading / distortion assessment and 4 point bending approx. 30-50 samples will be used for each site.

Methodology

1. Structural sizes. For structural sizes the following procedure will be adopted:
   a. Sample from logs 2-3 battens per log dry without constraint to 15-18% MC gives inherent distortion.
   b. Machine grade - giving details of individual spans (every 100mm up batten - 900mm is the grading span).
   c. Measure drying distortion - twist , spring and bow - link to moisture content.
   d. Carry out 4 point bending to destruction giving MOR - Rupture strength and MOE stiffness- MOE takes considerable time because a cradle holding a transducer is attached to the batten before testing.
   e. Analyse.
2. Small clears. For small clears the bending test will be used:
   a. Cut samples from log.
   b. Dry / condition at 20 degrees Celsius and 65% Rh.
   c. Final machining of samples.
   d. Test MOR and MOE (MOE again takes considerable time - but is an important factor).
   e. Analyse.
3. Juvenile and compression wood. Juvenile and compression wood will be analysed on microtome slides:
   a. Preparation of samples -- this is slow and must be completed with care – cutting and staining each sample can take up to 1 hour.
   b. Microscopic measurements and assessments.
   c. Data preparation and manipulation.

Total sample. In total, it is foreseen approximately 35,000 data points will result from the physico-mechanical studies carried out on the plant material sampled at the primary, secondary and tertiary sites.

DELIVERABLES

16. Standardised methodology for determining selected wood physico-mechanical properties.
17. Data-base on the physico-mechanical properties of wood from trees for a range of species, environmental conditions, management options, atmospheric and climate change.
18. Calibration and validation data for coupled mensuration-mechanistic dynamic model of tree growth, yield and quality.

MILESTONES

New data on the quantification of wood physico-mechanical properties from trees across a range of species, environmental and management perturbations in participating Member States, and across a range of plausible future scenarios of atmospheric composition change.

Milestone No	Title	Delivery Date	Participants	
			Lead	Assoc.
III. (Partial)	Laboratory and analytical protocols	Month 6	P4	AP6, P7
VI. (Partial)	Completion of Phase 1 sampling programme	Month 13	All	
XI. (Partial)	Completion of Phase 2 sampling programme	Month 30	All	
XII. (Partial)	Completion of laboratory studies	Month 32	P4	AP6, P7
XVII. (Partial)	Unified database of data from the monitoring, experimental, laboratory and manipulative components	Month 36	P1	P2, P3, P4, P5, AP6, P7

WP7. Modelling of wood quality and tree growth at stand scale for representative sites across Europe

Workpackage number:	7						
Start Date:	Month 1						
Completion Date:	Month 33						
Partners Responsible:	**P2**, P1, P3, P4, P5, AP6, P7						
Person-months per Partner	P1	P2	P3	P4	P5	AP6	P7
	12	12	3	4	5	10	4

OBJECTIVES

The objective of this work package is to produce a workable coupled mensuration - mechanistic dynamic model operating at the stand scale, encompassing C, N and H_20 responses, to provide predictions of wood quality, tree growth and form as a function of environmental and management conditions, for present and future climates. The main objective will be to model wood quality and tree growth at the stand scale for representative sites across Europe. This will be achieved by:

7.1 Integrating empirical mensuration models with process-based dynamic models of relevant physical, biophysical and biological processes at an appropriate spatial and temporal scale to improve predictions of tree growth at stand level.

7.2 Coupling growth with tree form to predict quality of standing timber.

7.3 Coupling growth with biochemical and mechanical properties of wood to predict quality.

7.4 Developing the coupled mensuration - mechanistic dynamic model operating at the stand scale, encompassing relevant C, N and H_2O responses, to provide predictions of wood quality, tree growth and form as a function of environmental and management conditions, for present and future climates.

METHODOLOGY AND STUDY MATERIALS

Existing soil-plant-atmosphere models operating at the stand scale, which couple growth responses in the xylem and in the canopy to C, N and H_20, will be integrated with existing mensuration models of stand structure and architecture. Data developed under Work Packages 3 – 7 will be used to develop and refine modules of timber quality. The coupled model will be calibrated using existing mensuration models and data-sets, and new data collected from the monitoring sites collected for this purpose. The model will simulate, sequentially, single species stands or combinations of single and multiple-species forests, and the quality of the timber produced. A major by-product of the model will be estimates of carbon sequestration from forest stands across a range of sites, as a function of representative management conditions and in relation to timber and wood quality. State-of-the-art scenarios of future atmospheric compositions developed by the most recent General Circulation Models (GCMs) and placed in the public domain through the EU-ECLAT 2 (ENV4-CT98-0734) project will be used to inform the climate input to the coupled model. The integrated model will thus comprise several process modules that are either written from published literature, modified from previously published models or constructed for this purpose. All models will be developed in Object Orientated code using C- or object oriented Fortran 90, and the Delphi programming language to provide the user interface. This approach allows the characteristics and behaviour of an object to be coupled and allows for a modular programming approach, with all outputs available for use by any other model. Partners 1 and 2 will be responsible for developing appropriate modelling protocols to integrate existing modelling procedures into the unified framework.

DELIVERABLES

19. Protocol for integration of sub-modules.
20. A prototype coupled mensuration mechanistic dynamic model of tree growth, timber production and wood quality operational at the stand scale.
21. A user-friendly version of the model available as a prototype decision support system.

22. Predictions of timber production accounting for tree quality across a representative range of sites and silvicultural regimes in participating, countries, also accounting for scenarios of future environmental change.
23. Predictions of environmental impact in terms of current and future forest stand composition and structure, its nutrient status and dynamics, and ecosystem carbon balance across a representative range of sites and silvicultural regimes in participating countries, also accounting for scenarios of future environmental change.

MILESTONES
New integrated (empirical and process-based) model on tree growth, yield and wood quality at forest stand scale for a range of species, environmental conditions, management options, and also across a range of plausible future scenarios of atmospheric composition change.

Milestone No	Title	Delivery Date	Participants	
			Lead	Assoc.
VII.	Prototype mechanistic dynamic model at plot scale	Month 16	P2	P1, P3, P4, P5, AP6, P7

WP8. Development of the energy budget sub-model

Workpackage number:	1						
Start Date:	Month 4						
Completion Date:	Month 8						
Partners Responsible:	**P3**, P1, P7						
Person-months per Partner	P1	P2	P3	P4	P5	AP6	P7
	3		7				4

OBJECTIVES

A carbon book-keeping model will be developed and will be integrated with the stand scale model (WP7) through the C outputs inherent to this model. Data on timber processing fossil fuel inputs will be collated and incorporated into the model, in the form of a data-base which informs the model. A series of forest management and wood processing scenarios will be developed and expressed in terms of activities and operations, using protocols defined for the energy budget sub-model. The integration of the sub-model into the prototype integrated model (Work Package 9) will permit a cost:benefit analysis of forest management options to be evaluated in terms of fossil fuel energy inputs *versus* product out-turn, and GHG emissions *versus* carbon sequestration potential for the scenarios of interest.

The main objective will be to develop an energy budget sub-model. This will be achieved by:

8.1 Developing an energy and carbon book-keeping sub-model.

8.2 Integrating the sub-model with the prototype integrated model

8.3 Applying the prototype integrated model to scenarios of multi-objective and forest production management and timber pricing.

METHODOLOGY AND STUDY MATERIALS

Available and process-derived data on forestry working practices, timber and wood processing methods and fossil fuel energy inputs will be integrated with new data and plausible (hypothetical) descriptions of a representative range of silvicultural prescriptions including potential future scenarios accounting (for example) for constraints on harvesting and chemical use. These data will be incorporated into data-bases for use as input variables to the carbon and energy book-keeping models. Existing computer based models that account for energy inputs and outputs and GHG balances of bio-energy production systems will be extended to represent general timber and wood production processes. The models will be reprogrammed in object oriented languages (C++ or object oriented Fortran 90), and integrated with the stand and regional scale models described under Work Packages 7 and 9. The Delphi programming language will be used to provide a stand-alone interface to the sub-model.

DELIVERABLES

24. A data-base comprising data on forestry working practices, wood processing methods and implicit fossil energy inputs,

25. A computer-based model of fossil energy and carbon-based balances available as source code, or executable user-friendly interface.

26. Sub-model within the integrated model to evaluate impacts of environmental and silvicultural changes on fossil energy requirements and greenhouse gas balances of wood production processes.

MILESTONES

Upgraded energy budget sub-model for integration with the forest patch scale model for cost:benefit analysis of forest management options to be evaluated in terms of fossil fuel energy inputs *versus* product out-turn, and GHG emissions *versus* carbon sequestration potential for the scenarios of interest for a range of species, environmental conditions, management options, and also across a range of plausible future scenarios of atmospheric composition change.

Milestone No	Title	Delivery Date	Participants	
			Lead	Assoc.
IV.	Energy budget model	Month 8	P3	P1, P7

WP9. Protocol for model integration and upscaling

Workpackage number:	9						
Start Date:	Month 1						
Completion Date:	Month 34						
Partners Responsible:	**P3**, P1, P2, P5						
Person-months per Partner	P1	P2	P3	P4	P5	AP6	P7
	4	3	20		7		

OBJECTIVES

The objective of this work package is (a) to integrate the wood quality and tree growth model, developed under work-package 7 and (b) the energy budget model, developed under work-package 8, to inform, through model integration, an upscaling model operating at regional and national level. In turn, the upscaling model will forecast implications of environmental change and forest management on timber yield and quality, on economic return and productivity of wood products and carbon sequestration. State-of-the-art and future socio-economic scenarios placed in the public domain through EU-ECLAT 2 (ENV4-CT98-0734) project will be used to inform the input to the coupled model. For the sake of clarity, the integrated model is understood in this project as the stand level model combined with energy and wood products models, developed in earlier WPs. The main objective will be to improve the existing upscaling model to apply it to the needs of this project. This will be achieved by:

9.1 To incorporate growth effects on timber quality as a function of environmental and management conditions into an existing up-scaling model based on empirical and simulation data developed by earlier work-packages.

9.2 To develop future scenarios of timber quality at regional level accounting for a range of forest management practices under changing climatic conditions.

METHODOLOGY AND STUDY MATERIALS

a. Overview. This work package will allow further refining of the upscaling model and incorporation of a new quality sub-module for standing timber and basic structural and physico-chemical properties of processed wood products. Timber quality and changes in timber quality as a consequence of environmental and management change identified in WP 7 will be scaled up to country level in this work package. The existence of the upscaling model and of broad, detailed and individually validated sub-modules, making up the forest stand model makes the realisation of the prototype integrated system an achievable task. The regional and national scale model of forest resources in Europe describes scenarios of forest state in terms of area distribution over age and volume classes. Dynamics of volume increment are expressed as transitions between volume and age classes within an area-based forest. Management practices such as thinning and final felling (harvesting), and regeneration can also be simulated in the model. Harvested timber is processed into wood products. Timber pricing is developed through integration between production costs and socio-economic and trade scenarios. This model can be run for a range of regions included in the forest inventory database. More recently, additional modules have been incorporated to account for whole tree biomass, thus allowing stemwood volumes to be converted to whole tree biomass by region, age class and tree species. Biomass can also be converted into equivalent carbon units. Carbon book-keeping allows calculation of forest and wood product carbon budgets. Plausible socio-economic scenarios will inform timber pricing under different management scenarios. The model is predisposed for further integration with the types of model outlined at WP 8 to allow net annual increment, biomass allocation and litter production to be adjusted to changing atmospheric conditions. Different forest management scenarios can be applied to current and changing climatic conditions to: (a) provide predictions of future developments of forest stand structures, forest and wood products; (b) at work package 9 to allow carbon book-keeping to allow calculation of forest and wood products carbon budgets and follow harvested timber processed into products until such products are removed from use and oxidised; (c) translate changes in timber quality to stumpage prices paid at regional and national levels. The integrated model will allow a range of forest management to be applied to current and changing climatic conditions to provide predictions of the future development of forest structures, forest and wood product carbon stocks and fluxes, separately and concurrently for different regions of Europe.

b. Model integration. Model integration between the stand model and EFISCEN will occur using a response surface of selected outputs developed by the integrated stand-scale model, provided from WP7. The energy budget sub-model developed in WP8 will be integrated into the large-scale scenario model as part of WP9. Details of the integration will be sorted out in collaboration with the leading partner of the relevant WPs. Modifications and new features to the existing large scale scenario model EFISCEN will be needed and these will be carried out as part of WP9.

c. Scenarios.

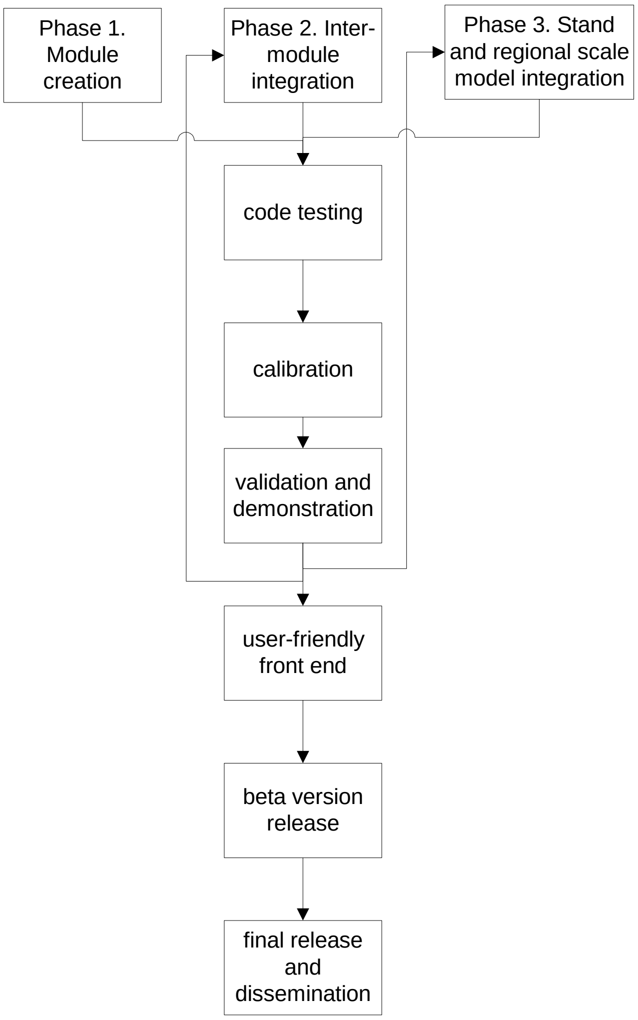
c1. Climate change scenarios. Results from a selection of climate change simulations performed by a number of climate modelling centres will be used, as made available through the public IPCC Data Distribution Centres network. These data extract results from transient, warm-start simulations which include both greenhouse gas only and greenhouse gas and sulphate aerosol forcings. Fields will be mean monthly changes on the 1961-1990 mean baseline climatology and also full monthly time series; daily data will be available in some cases from the respective modelling centres. The appropriate grid squares will be selected and temporally downscaled using the weather generator to be developed as part of WP 5.

c2. Socio-economic and management scenarios. Socio-economic and management scenarios will take into account the extent of possible implications of changes in: stumpage prices (based on tree species, wood quality); forest management (felling levels, if for example certain tree species will be favoured etc.); products manufacturing (based on the wood quality and species, production of certain products may change). Implications are investigated in terms of future forest resources, carbon pools in trees, soil and wood products, emissions of fossil carbon from harvesting and manufacturing wood products and the use of other primary energy. Socio-economic aspects are considered in terms of mean net revenues of a land-owner (difference between annual stumpage returns and regeneration costs) and value of products sequestration in the forest sector, emissions from use of fossil energy, income for forest owner and value of products based on average (export) prices.

d. Modelling Effort. Overall, The modelling effort is therefore significant, with work under this heading summarised as follows:

1. Stand scale growth model. The following steps are foreseen:
   a. Development of a single model from existing procedures available to the relevant consortium partners.
   b. Calibration and validation of the new stand scale for project sites using data from WP1 – WP3.
2. Empirical-process based model of timber quality. The following steps are foreseen:
   a. Adaptation of existing and appropriate models of cambial growth
   b. Incorporation into the stand scale model.
   c. Testing and validation of the model based on results of WP4 and WP5
3. Wood products model. The following steps are foreseen:
   a. Development of wood products model.
   b. Incorporation into the stand scale model.
   c. Testing against available literature data.
4. Energy sub-model.
   a. Development of energy sub-model.
   b. Incorporation into the stand scale model.
   c. Testing against available literature data.
5. Model integration between the stand scale and regional scale models.
   a. See section 2.1.4.1.12 Description of EFICEN.

The proposed modelling procedure can be summarised as follows:



DELIVERABLES

27. Protocol for model integration and upscaling.

28. An integrated model and model output accounting for tree growth and production, wood quality, carbon sequestration, fossil energy and GHG balances and timber pricing operational at the scale of EU Member States.

29. Data-base integrated with the model of plausible future environmental socio-economic and management scenarios applicable to the EU forestry and wood products sector.

30. Validation of model outputs against empirical databases of processes observed in the monitoring and manipulative components.

31. A portfolio of plausible future environmental, socio-economic and management scenarios for the EU forestry and wood products sector.

32. A portfolio of model predictions for all variables listed in deliverable 28, produced by running the improved upscaling model using empirical data from earlier work-packages and simulation data from the stand-scale model as input.

MILESTONES

1. Improved upscaling model modified to account for wood quality.
2. Agreed scenarios of environmental, socio-economic and management practice.
3. Integration and upscaling analyses at regional scale.

Milestone No	Title	Delivery Date	Participants	
			Lead	Assoc.
XIII.	Regional scale model	Month 34	P3	P1, P2, P4, P7
XVIII.	Database of modelling scenarios	Month 36	P3	P1, P2, P5

WP10. Validation and application of model integration and upscaling

Workpackage number:	10						
Start Date:	Month 7						
Completion Date:	Month 29						
Partners Responsible:	**P3**, P1, P2, P5, P7						
Person-months per Partner	P1	P2	P3	P4	P5	AP6	P7
	4	5	10		6		2

OBJECTIVES

The main objective will be to validate and apply the integrated and upscaling model. This will be achieved by:

10.1 Carrying out validation, sensitivity, uncertainty and robustness analyses to assess the predictive capability of models at a range of spatial and temporal scales.

In this project, the link between experimentation and the validation and application scales occurs at a range of scales, and is developed through nesting combinations of models and data-bases collected at a range of spatial and temporal resolution. This will be explored using demonstration areas at the regional scale within studied countries.

10.2 At the site scale, modelling components developed under WP 8, will be assessed for current and future scenarios of atmospheric composition by simulating climate and management combinations at sites for which existing experimental data are available.

10.3 At the regional scale, assessing the predictive accuracy of the integrated model against available data for selected regions.

10.4 Application Scale. Quantifying the effects of changes in the scale of temporal and spatial inputs in order to assess the reliability of outputs for the region under study.

METHODOLOGY AND STUDY MATERIALS

1. Standardised graphical and quantitative indices and statistics will be used to describe and quantify model predictive ability.
2. A model tool will be incorporated into the integrated system to allow user-defined assessments where suitable empirical data are available.

Site scale. Data from the primary sites will be used in the model development and calibration, whilst flux data from the secondary sites will be used for short-term validation of the growth component of the model. New wood quality data collected through the monitoring and laboratory components will be adopted for model validation.

Regional scale. Available data such as forestry statistics, life cycle analysis, wood product inventories, will be used to validate the regional scale model. Whilst it is not possible to assess the predictive accuracy of projections under future scenarios, the adopted nested approach allows process-level changes observed at the manipulative sites to be encompassed at the coarser level of spatial resolution. In order to develop a range of future scenarios, outputs from a number of General Circulation Models will be used for model runs.

Application Scale. Assessing the quality of the integration process at a range of scales will be achieved through the validation process outlined above. Upscaling requires a quantification of the effects of changes in the scale of temporal and spatial inputs in order to assess the reliability of outputs for the region under study. There have been few rigorous studies of this scaling problem, in which simulated output data - obtained at different scales of resolution of the inputs - have been compared with measured data. There has been even less formalised research into the sensitivity of models and how this may change at scale changes. This will be achieved through a sensitivity analysis where the outputs of the upscaling model will be assessed across a range of outputs provided by the stand scale model. The working hypothesis is that appropriate outputs of site scale can reliably inform simulations at regional scale under current climate, as compared with geo-referenced inventory data.

DELIVERABLES

33. Standardised model assessment tools incorporated into the integrated model software to assess uncertainty in model predictions associated with output sensitivity to input parameters and scaling effects.

34. Portfolio of plausible future environmental socio-economic and management scenarios applicable to the forestry and wood products sectors in a selection of EU countries, with an associated uncertainty interval.

35. Portfolio of model predictions produced by running the above model using empirical data from earlier WPs and simulation data from the stand-scale model as input, with an associated uncertainty interval.

MILESTONES

1. Predictive uncertainty associated with the improved upscaling model.
2. Uncertainty associated with scenarios of environmental and management practice.
3. Uncertainty associated with upscaling to the regional scale.

Milestone No	Title	Delivery Date	Participants	
			Lead	Assoc.
XVIII.	Database of modelling scenarios	Month 36	P3	P1, P2, P5

3. ROLE OF PARTICIPANTS

Partner 1 -- Forest Research (Co-ordinator)

Name:	The Forestry Commission through its agency Forest Research
Address	Forest Research Mensuration Branch Alice Holt Lodge Wrecclesham, Farnham Surrey GU10 4LH, UNITED KINGDOM
Team Leader	Samuel P. Evans
Scientists involved	Janet Methley, Robert Matthews, Barry Gardiner, Mark Broadmeadow, Tracy Houston, Tim Randle, Paul Henshall
Associated Staff	John Proudfoot, Ian Craig, Tim Cooper
Objectives	1. Responsible for scientific and financial co-ordination of the project. 2. Lead partner for WP1. 3. Collect stand growth and yield data from primary and secondary sites in UK. 4. Carry out manipulative experiments into the eco-physiology and functioning of trees at tertiary sites. 5. Develop, calibrate and validate plot-scale process-based model of growth, yield and timber quality. 6. Develop the carbon book-keeping model. 7. Draft scientific and technical papers. 8. Organise international workshop.

Workplan	**WP No**	**Man-Months**	**Remarks**
	1	13	Lead Partner
	2	7	
	3	9	
	4		
	5		
	6		
	7	14	
	8	4	Lead Partner
	9	6	
	10	5	

Deliverables	**WP No**	**Leader for Deliverable No.**	**Associated with Deliverable No.**
	1	1, 2, 3	
	2	4	6
	3		7, 9
	4		
	5		
	6		
	7		19, 20, 22, 23
	8		24, 25, 26
	9		28
	10	33	
	Other	39, 40, 41, 42	36, 37, 38

Work-Package No.	Deliverable No.	Deliverable title	Delivery Date	Nature	Dissemination Level	Dissemination Target
1.	1.	Standardised methodology for site characteristics, physiological, eco-physiological and mensurational data for observed forest stands	Month 6	O	CO	C
	2.	Data-base of site characteristics, physiological, eco-physiological and mensurational data for a range of species, environmental conditions and management options	Month 36	O	CO	C S P
	3.	Calibration and validation data for coupled mensuration-mechanistic dynamic model of tree growth, yield and quality; growth and yield	Month 36	O	CO	C
2.	4.	Standardised methodology for timber quality assessment for forest stands, applicable across the European Union.	Month 6	O	CO	C S I
	6.	Calibration and validation data for coupled mensuration-mechanistic dynamic model of tree growth, yield and quality; qualitative properties in standing timber	Month 24	O	CO	C
3.	7.	Standardised methodology for assessing growth patterns and allocation of juvenile plants grown in manipulative experimental conditions.	Month 30	O	CO	C
	9.	Calibration and validation data for coupled mensuration-mechanistic dynamic model of tree growth, yield and quality; manipulative experiments	Month 34	O	CO	C
7.	19.	Protocol for integration of sub-modules.	Month 6	O	CO	C
	20.	A prototype coupled mensuration mechanistic dynamic model of tree growth, timber production and wood quality operational at the stand scale.	Month 16	p	CO	C
	22.	Predictions of timber production accounting for tree quality across a representative range of sites and silvicultural regimes in participating countries, also accounting for scenarios of future environmental change.	Month 32	R	PU	C S I
	23.	Predictions of environmental impact in terms of current and future forest stand composition and structure, its nutrient status and dynamics, and ecosystem carbon balance across a representative range of sites and silvicultural regimes in participating countries, also accounting for scenarios of future environmental change.	Month 33	R	PU	C S I
8.	24.	A review of forestry working practices, wood processing methods and implicit fossil energy inputs.	Month 6	O	CO	C
	25.	A computer-based model of fossil energy and carbon-based balances available as source code, or executable user-friendly interface.	Month 8	p	PU	C
	26.	Sub-model within integrated model to evaluate impacts of environmental and silvicultural changes on fossil energy requirements and greenhouse gas balances of wood production processes.	Month 18	p	CO	
9.	28.	An integrated model which accounts for tree growth and production, wood quality, carbon sequestration, fossil energy and GHG balances and timber pricing operational at the scale of EU Member States.	Month 29	P	CO	C S I
10.	33.	Standardised model assessment tools incorporated into the integrated model software to assess uncertainty in model predictions associated with output sensitivity to input parameters and scaling effects.	Month 34	R	PU	C
Other	36.	Papers in peer-reviewed scientific journals.	Month 18-36	R	PU	C S
	37.	Reports at international and national scientific meetings.	Month 18-36	R	PU	S
	38.	Reports in forestry and timber-processing industry journals in participating countries and international bulletins.	Month 18-36	R	PU	I

Work-Package No.	Deliverable No.	Deliverable title	Delivery Date	Nature	Dissemination Level	Dissemination Target
Manag	39.	First Annual Report	Month 13	R	CO	CO
	40.	Second Annual Report	Month 26	R	CO	CO
	41.	Final Report	Month 36	R	CO	CO
	42.	International Workshop	Month 35	O	PU	S I

Partner 2 -- University of Antwerpen

Name	Department of Biology		
Address	University of Antwerpen (UIA) Universiteitsplein 1, B-2610 Wilrijk, Belgium		
Team Leader	Reinhart Ceulemans		
Scientists involved	Eric Casella, Ivan A . Janssens, Arnaud Carrara, Gaby Deckmyn, Brigid Gielen, David A. Sampson		
Associated Staff	Ann Fabeck, Nadine Calluy, Fred Kockelbergh		
Objectives			
Workplan	**WP No**	**Man-Months**	**Remarks**
	1	3	
	2	2	
	3	12	Lead Partner
	4		
	5		
	6		
	7	12	Lead Partner
	8		
	9	3	
	10	5	
Deliverables	**WP No**	**Leader for Deliverable No.**	**Associated with Deliverable No.**
	1		1, 3
	2		6
	3	7, 8, 9	
	4		
	5		
	6		
	7	19, 20, 21, 22, 23	
	8	26	
	9	28	
	10		33
	Other		36, 37, 38, 39, 40, 41, 42

Work-Package No.	Deliverable No.	Deliverable title	Delivery Date	Nature	Dissemination Level	Dissemination Target
1.	1.	Standardised methodology for site characteristics, physiological, eco-physiological and mensurational data for observed forest stands	Month 6	O	CO	C
	3.	Calibration and validation data for coupled mensuration-mechanistic dynamic model of tree growth, yield and quality; growth and yield	Month 36	O	CO	C
2.	6.	Calibration and validation data for coupled mensuration-mechanistic dynamic model of tree growth, yield and quality; qualitative properties in standing timber	Month 24	O	CO	C
3.	7.	Standardised methodology for assessing growth patterns and allocation of juvenile plants grown in manipulative experimental conditions.	Month 30	O	CO	C
	8.	Data-base on growth patterns and allocation from individuals for a range of species, environmental conditions, management options and atmospheric change	Month 32	O	CO	C S I
	9.	Calibration and validation data for coupled mensuration-mechanistic dynamic model of tree growth, yield and quality; manipulative experiments	Month 34	O	CO	C
7.	19.	Protocol for integration of sub-modules.	Month 6	O	CO	C
	20.	A prototype coupled mensuration mechanistic dynamic model of tree growth, timber production and wood quality operational at the stand scale.	Month 16	p	CO	C
	21.	A user-friendly version of the model available as a prototype decision support system.	Month 18	P	PU	C S I
	22.	Predictions of timber production accounting for tree quality across a representative range of sites and silvicultural regimes in participating countries, also accounting for scenarios of future environmental change.	Month 32	R	PU	C S I
	23.	Predictions of environmental impact in terms of current and future forest stand composition and structure, its nutrient status and dynamics, and ecosystem carbon balance across a representative range of sites and silvicultural regimes in participating countries, also accounting for scenarios of future environmental change.	Month 33	R	PU	C S I
8	26.	Sub-model within integrated model to evaluate impacts of environmental and silvicultural changes on fossil energy requirements and greenhouse gas balances of wood production processes.	Month 18	p	CO	
9.	28.	An integrated model which accounts for tree growth and production, wood quality, carbon sequestration, fossil energy and GHG balances and timber pricing operational at the scale of EU Member States.	Month 29	P	CO	C S I
10.	33.	Standardised model assessment tools incorporated into the integrated model software to assess uncertainty in model predictions associated with output sensitivity to input parameters and scaling effects.	Month 34	R	PU	C
Other	36.	Papers in peer-reviewed scientific journals.	Month 18-3	R	PU	C S
	37.	Reports at international and national scientific meetings.	Month 18-3	R	PU	S
	38.	Reports in forestry and timber-processing industry journals in participating countries and international bulletins.	Month 18-3	R	PU	I
Manag	39.	First Annual Report	Month 13	R	CO	CO
	40.	Second Annual Report	Month 26	R	CO	CO
	41.	Final Report	Month 36	R	CO	CO
	42.	International Workshop	Month 35	O	PU	S I

Partner 3 -- European Forest Institute

Name	European Forest Institute		
Address	Torikatu 34, FIN-80100 Joensuu FINLAND		
Team Leader	Timo Karjalainen		
Scientists involved	Jari Liski, Ari Pussinen, Gert-Jan Nabuurs		
Associated Staff	Simo Varis, Tujia Lapveteläinen		
Objectives			
Workplan	**WP No**	**Man-Months**	**Remarks**
	1		
	2		
	3		
	4		
	5		
	6		
	7	3	
	8	7	Lead Partner
	9	20	Lead Partner
	10	10	Lead Partner
Deliverables	**WP No**	**Leader for Deliverable No.**	**Associated with Deliverable No.**
	1		
	2		
	3		
	4		
	5		
	6		
	7		20, 22, 23
	8	24, 25, 26	
	9	27, 29, 30, 31, 32	28
	10	34, 35	33
	Other	43	36, 37, 38, 39, 40, 41, 42

Work-Package No.	Deliverable No.	Deliverable title	Delivery Date	Nature	Dissemination Level	Dissemination Target
7.	20.	A prototype coupled mensuration mechanistic dynamic model of tree growth, timber production and wood quality operational at the stand scale.	Month 16	p	CO	C
	22.	Predictions of timber production accounting for tree quality across a representative range of sites and silvicultural regimes in participating countries, also accounting for scenarios of future environmental change.	Month 32	R	PU	C S I
	23.	Predictions of environmental impact in terms of current and future forest stand composition and structure, its nutrient status and dynamics, and ecosystem carbon balance across a representative range of sites and silvicultural regimes in participating countries, also accounting for scenarios of future environmental change.	Month 33	R	PU	C S I
8.	24.	A review of forestry working practices, wood processing methods and implicit fossil energy inputs.	Month 6	O	CO	C
	25.	A computer-based model of fossil energy and carbon-based balances Available as source code, or executable user-friendly interface.	Month 8	p	PU	C
	26.	Sub-model within integrated model to evaluate impacts of Environmental and silvicultural changes on fossil energy requirements and greenhouse gas balances of wood production processes.	Month 18	p	CO	
9.	27.	Protocol for model integration and upscaling	Month 14	R	CO	C
	28.	An integrated model which accounts for tree growth and production, wood quality, carbon sequestration, fossil energy and GHG balances and timber pricing operational at the scale of EU Member States.	Month 29	P	CO	C S I
	29.	Data-base integrated with the model of plausible future Environmental socio-economic and management scenarios applicable to the EU forestry and wood products sector.	Month 30	O	PU	C S I
	30.	Validation of model outputs against empirical databases of processes observed in the monitoring and manipulative components of the project.	Month 34	O	PU	C
	31.	A portfolio of plausible future environmental socio-economic and management scenarios applicable to the EU forestry and wood products sector.	Month 36	O	PU	C
	32.	A portfolio of model predictions produced by running the integrated upscaling using empirical data from earlier work-packages and simulation data from the stand- scale model as input.	Month 36	O	PU	C
10.	33.	Standardised model assessment tools incorporated into the integrated model software to assess uncertainty in model predictions associated with output sensitivity to input parameters and scaling effects.	Month 34	R	PU	C
	34.	A selection of environmental, socio-economic and management scenarios for the EU forestry and wood products sector.	Month 35	O	PU	C S I
	35.	A portfolio of model predictions for all variables listed above, produced by running the above model using empirical data from earlier work-packages and simulation data from the stand- scale model as input with an associated uncertainty interval.	Month 35	O	PU	C S I
Other	36.	Papers in peer-reviewed scientific journals.	Month 18-3	R	PU	C

Work-Package No.	Deliverable No.	Deliverable title	Delivery Date	Nature	Dissemination Level	Dissemination Target
						S
	37.	Reports at international and national scientific meetings.	Month 18-3	R	PU	S
	38.	Reports in forestry and timber-processing industry journals in participating countries and international bulletins.	Month 18-3	R	PU	I
Manag	39.	First Annual Report	Month 13	R	CO	CO
	40.	Second Annual Report	Month 26	R	CO	CO
	41.	Final Report	Month 36	R	CO	CO
	42.	International Workshop	Month 35	O	PU	S I
	43.	WWW page	Month 3	O	PU	S I

Partner 4 -- Technical University of Berlin

Name	Technical University of Berlin
Address	Landschaftsoekologie/Oekologie der Gehoelze, FB 7, Technical University of Berlin, Koenigin-Luise-Strasse 22, D-14195 Berlin, Germany
Team Leader	Dieter Overdieck
Scientists involved	Manfred Forstreuter, Silke Koslowsky Jörn Strassemeyer
Associated Staff	Karin Fenselau, Elfriede West, Annita Kirchner, Eva Templer
Objectives	1. Lead partner for WP 4 and WP 5; 2. Selection of stand growth data from a secondary site in Germany; 3. Contribution of data from measurements of photosynthesis, transpiration and stomatal conductance from manipulative experiments to the data-base for modelling; 4. Standardisation of methods for determining selected anatomical wood properties; 5. Quantification of effects of atmospheric CO_2 concentration and temperature increase on wood anatomy of juvenile and adult trees; 6. Standardisation of the methods for determining selected chemical components of wood; 7. Quantification of effects of atmospheric CO_2 concentration and temperature increase on selected biochemical wood components; 8. Selection of matter allocation data from manipulative experiments; 9. Draft scientific papers; 10. Organisation of project workshop.

Workplan	**WP No**	**Man-Months**	**Remarks**
	1	8	
	2		
	3	11	
	4	39	Lead Partner
	5	32	Lead Partner
	6		
	7	11	
	8		
	9		
	10		

Deliverables	**WP No**	**Leader for Deliverable No.**	**Associated with Deliverable No.**
	1		3
	2		
	3		7, 9
	4	10, 11, 12	
	5	13, 14, 15	
	6		
	7		20, 22, 23
	8		
	9		
	10		
	Other		36, 37, 38, 39, 40, 41, 42

Work-Package No.	Deliverable No.	Deliverable title	Delivery Date	Nature	Dissemination Level	Dissemination Target
1.	3.	Calibration and validation data for coupled mensuration-mechanistic dynamic model of tree growth, yield and quality; growth and yield	Month 36	O	CO	C
3.	7.	Standardised methodology for assessing growth patterns and allocation of juvenile plants grown in manipulative experimental conditions.	Month 30	O	CO	C
	9.	Calibration and validation data for coupled mensuration-mechanistic dynamic model of tree growth, yield and quality; manipulative experiments	Month 34	O	CO	C
4.	10.	Standardised methodology for determining selected anatomical wood properties.	Month 6	O	CO	C S
	11.	Data incorporated into a database on the anatomical properties of wood from trees for a range of species, environmental conditions, management options, atmospheric and climate change	Month 34	O	CO	C S I
	12.	Calibration and validation data for coupled mensuration-mechanistic dynamic model of tree growth, yield and quality; anatomical properties	Month 34	O	CO	C S
5.	13.	Standardised methodology for determining selected biochemical wood properties.	Month 6	O	CO	C S
	14.	Data incorporated into a database on the biochemical properties of wood from trees for a range of species, environmental conditions, management options, atmospheric and climate change	Month 27	O	CO	C S I
	15.	Calibration and validation data for coupled mensuration-mechanistic dynamic model of tree growth, yield and quality; biochemical properties	Month 29	O	CO	C
7.	20.	A prototype coupled mensuration mechanistic dynamic model of tree growth, timber production and wood quality operational at the stand scale.	Month 16	p	CO	C
	22.	Predictions of timber production accounting for tree quality across a representative range of sites and silvicultural regimes in participating countries, also accounting for scenarios of future environmental change.	Month 32	R	PU	C S I
	23.	Predictions of environmental impact in terms of current and future forest stand composition and structure, its nutrient status and dynamics, and ecosystem carbon balance across a representative range of sites and silvicultural regimes in participating countries, also accounting for scenarios of future environmental change.	Month 33	R	PU	C S I
Other	36.	Papers in peer-reviewed scientific journals.	Month 18-36	R	PU	C S
	37.	Reports at international and national scientific meetings.	Month 18-36	R	PU	S
	38.	Reports in forestry and timber-processing industry journals in participating countries and international bulletins.	Month 18-36	R	PU	I
Manag	39.	First Annual Report	Month 13	R	CO	CO
	40.	Second Annual Report	Month 26	R	CO	CO
	41.	Final Report	Month 36	R	CO	CO
	42.	International Workshop	Month 35	O	PU	S i

Partner 5 -- Università degli Studi della Tuscia

Name	Università degli Studi della Tuscia
Address	Dipartimento di Scienze dell'Ambiente Forestale e delle sue Risorse Università degli Studi della Tuscia Via San Camillo de Lellis I-01100 Viterbo, Italy
Team Leader	Giuseppe E. Scarascia-Mugnozza
Scientists involved	Paolo De Angelis, Giorgio Matteucci, Riccardo Valentini, Elena Kuzminsky, Maurizio Sabatti, Alberto Masci, Hocine Larbi, Carmine Angelaccio
Associated Staff	Tullio Oro, Matilde Tamantini, Roberto Bindi, Renato Zompanti, Luigi Sandoletti, Armando Parlante
Objectives	

Workplan

WP No	Man-Months	Remarks
1	9	
2	4	Lead Partner
3	9	
4		
5		
6		
7	5	
8		
9	7	
10	6	

Deliverables

WP No	Leader for Deliverable No.	Associated with Deliverable No.
1		1, 3
2	5, 6	
3		7, 9
4		
5		
6		
7		20, 22, 23
8		
9		29, 30
10		34, 35
Other		36, 37, 38, 39, 40, 41, 42

Work-Package No.	Deliverable No.	Deliverable title	Delivery Date	Nature	Dissemination Level	Dissemination Target
1.	1.	Standardised methodology for site characteristics, physiological, eco-physiological and mensurational data for observed forest stands	Month 6	O	CO	C
	3.	Calibration and validation data for coupled mensuration-mechanistic dynamic model of tree growth, yield and quality; growth and yield	Month 36	O	CO	C
2.	5.	Data-base on timber quality assessment for forest stands for a range of species, environmental conditions and management options	Month 22	O	CO	C S I
	6.	Calibration and validation data for coupled mensuration-mechanistic dynamic model of tree growth, yield and quality; qualitative properties in standing timber	Month 24	O	CO	C
3.	7.	Standardised methodology for assessing growth patterns and allocation of juvenile plants grown in manipulative experimental conditions.	Month 30	O	CO	C
	9.	Calibration and validation data for coupled mensuration-mechanistic dynamic model of tree growth, yield and quality; manipulative experiments	Month 34	O	CO	C
7.	20.	A prototype coupled mensuration mechanistic dynamic model of tree growth, timber production and wood quality operational at the stand scale.	Month 16	p	CO	C
	22.	Predictions of timber production accounting for tree quality across a representative range of sites and silvicultural regimes in participating countries, also accounting for scenarios of future environmental change.	Month 32	R	PU	C S I
	23.	Predictions of environmental impact in terms of current and future forest stand composition and structure, its nutrient status and dynamics, and ecosystem carbon balance across a representative range of sites and silvicultural regimes in participating countries, also accounting for scenarios of future environmental change.	Month 33	R	PU	C S I
9.	29.	Data-base integrated with the model of plausible future Environmental socio-economic and management scenarios applicable to the EU forestry and wood products sector.	Month 30	O	PU	C S I
	30.	Validation of model outputs against empirical databases of processes observed in the monitoring and manipulative components of the project.	Month 34	O	PU	C
10.	34.	A selection of environmental, socio-economic and management scenarios for the EU forestry and wood products sector.	Month 35	O	PU	C S I
	35.	A portfolio of model predictions for all variables listed above, produced by running the above model using empirical data from earlier work-packages and simulation data from the stand- scale model as input with an associated uncertainty interval.	Month 35	O	PU	C S I
Other	36.	Papers in peer-reviewed scientific journals.	Month 18-36	R	PU	C S
	37.	Reports at international and national scientific meetings.	Month 18-36	R	PU	S

Work-Package No.	Deliverable No.	Deliverable title	Delivery Date	Nature	Dissemination Level	Dissemination Target
	38.	Reports in forestry and timber-processing industry journals in participating countries and international bulletins.	Month 18-36	R	PU	I
Manag	39.	First Annual Report	Month 13	R	CO	CO
	40.	Second Annual Report	Month 26	R	CO	CO
	41.	Final Report	Month 36	R	CO	CO
	42.	International Workshop	Month 35	O	PU	S I

<u>Associate Partner 6</u> -- University of Ghent

Name	University of Ghent		
Address	Faculteit van de Landbouwkundige en Toegepaste Biologische Wetenschappen Vakgroep Bos- en Waterbeheer Laboratory of Wood Technology Coupure links 653 9000 Gent - Belgium		
Team Leader	Riet Van de Velde		
Scientists involved	Joris Van Acker, Marc Stevens		
Associated Staff			
Objectives			
Workplan	**WP No**	**Man-Months**	**Remarks**
	1		
	2	4	
	3		
	4	6	
	5		
	6	10	Lead Partner
	7	10	
	8		
	9		
	10		
Deliverables	**WP No**	**Leader for Deliverable No.**	**Associated with Deliverable No.**
	1		
	2		4, 6
	3		
	4		10, 12
	5		
	6	16, 17	18
	7		20, 22, 23
	8		
	9		
	10		
	Other		36, 37, 38, 39, 40, 41, 42

Work-Package No.	Deliverable No.	Deliverable title	Delivery Date	Nature	Dissemination Level	Dissemination Target
2.	4.	Standardised methodology for timber quality assessment for forest stands, applicable across the European Union.	Month 6	O	CO	C S I
	6.	Calibration and validation data for coupled mensuration-mechanistic dynamic model of tree growth, yield and quality; qualitative properties in standing timber	Month 24	O	CO	C
4.	10.	Standardised methodology for determining selected anatomical wood properties.	Month 6	O	CO	C S
	12.	Calibration and validation data for coupled mensuration-mechanistic dynamic model of tree growth, yield and quality; anatomical properties	Month 34	O	CO	C S
6.	16.	Standardised methodology for determining selected wood physico-mechanical properties.	Month 6	O	CO	C
	17.	Data-base on the physico-mechanical properties of wood from trees for a range of species, environmental conditions, management options, climate and atmospheric change	Month 27	O	CO	C S I
	18.	Calibration and validation data for coupled mensuration-mechanistic dynamic model of tree growth, yield and quality; physico-mechanical properties	Month 29	O	CO	C
7.	20.	A prototype coupled mensuration mechanistic dynamic model of tree growth, timber production and wood quality operational at the stand scale.	Month 16	p	CO	C
	22.	Predictions of timber production accounting for tree quality across a representative range of sites and silvicultural regimes in participating countries, also accounting for scenarios of future environmental change.	Month 32	R	PU	C S I
	23.	Predictions of environmental impact in terms of current and future forest stand composition and structure, its nutrient status and dynamics, and ecosystem carbon balance across a representative range of sites and silvicultural regimes in participating countries, also accounting for scenarios of future environmental change.	Month 33	R	PU	C S I
Other	36.	Papers in peer-reviewed scientific journals.	Month 18-36	R	PU	C S
	37.	Reports at international and national scientific meetings.	Month 18-36	R	PU	S
	38.	Reports in forestry and timber-processing industry journals in participating countries and international bulletins.	Month 18-36	R	PU	I
Manag	39.	First Annual Report	Month 13	R	CO	CO
	40.	Second Annual Report	Month 26	R	CO	CO
	41.	Final Report	Month 36	R	CO	CO
	42.	International Workshop	Month 35	O	PU	S I

Partner 7 -- Building Research Establishment

Name	Building Research Establishment
Address	Centre for Timber Technology and Construction Garston, Watford, WD2 7JR United Kingdom
Team Leader	Keith Maun
Scientists involved	Peter Bonfield, Geoff Cooper, Gerald Moore, Richard Thompson
Associated Staff	
Objectives	1. Lead partner for WP6 2. Assist in the analysis of standing timber and relate to potential products, making due consideration of new technologies. 3. Measure anatomical properties and relate to site parameters 4. Collect data concerning biochemical properties and relate to species and site data 5. Collect data concerning growth characteristics of sawn material cut from trees from different sites. 6. Collect data on mechanical properties and kiln drying distortions of material grown in different site conditions. 7. Analyse growth data and relate to strength and distortion for different sites. Modify a predictive model for properties and predict the effect of climate change on wood quality. 8 With our expertise in LCA for commodity production and forestry, assist in the development of a carbon book keeping model. 9. Draft papers 10. Participate in an international workshop.

Workplan	**WP No**	**Man-Months**	**Remarks**
	1		
	2	2	
	3		
	4	3	
	5	2	
	6	8	
	7	4	
	8	4	
	9		
	10	2	

Deliverables	**WP No**	**Leader for Deliverable No.**	**Associated with Deliverable No.**
	1		
	2		2, 6
	3		
	4		10, 12
	5		13, 14, 15
	6	18	16
	7		19, 20, 22, 23
	8		24
	9		
	10		34, 35
	Other		36, 37, 38, 39, 40, 41, 42

Work-Package No.	Deliverable No.	Deliverable title	Delivery Date	Nature	Dissemination Level	Dissemination Target
2.	6.	Calibration and validation data for coupled mensuration-mechanistic dynamic model of tree growth, yield and quality; qualitative properties in standing timber	Month 24	O	CO	C
4.	10.	Standardised methodology for determining selected anatomical wood properties.	Month 6	O	CO	C S
	12.	Calibration and validation data for coupled mensuration-mechanistic dynamic model of tree growth, yield and quality; anatomical properties	Month 34	O	CO	C S
5.	13.	Standardised methodology for determining selected biochemical wood properties.	Month 6	O	CO	C S
	14.	Data incorporated into a database on the biochemical properties of wood from trees for a range of species, environmental conditions, management options, atmospheric and climate change	Month 27	O	CO	C S I
	15.	Calibration and validation data for coupled mensuration-mechanistic dynamic model of tree growth, yield and quality; biochemical properties	Month 29	O	CO	C
6.	16.	Standardised methodology for determining selected wood physico-mechanical properties.	Month 6	O	CO	C
	18.	Calibration and validation data for coupled mensuration-mechanistic dynamic model of tree growth, yield and quality; physico-mechanical	Month 29	O	CO	C
7.	19.	Protocol for integration of sub-modules.	Month 6	O	CO	C
	20.	A prototype coupled mensuration mechanistic dynamic model of tree growth, timber production and wood quality operational at the stand scale.	Month 16	p	CO	C
	22.	Predictions of timber production accounting for tree quality across a representative range of sites and silvicultural regimes in participating countries, also accounting for scenarios of future environmental change.	Month 32	R	PU	C S I
	23.	Predictions of environmental impact in terms of current and future forest stand composition and structure, its nutrient status and dynamics, and ecosystem carbon balance across a representative range of sites and silvicultural regimes in participating countries, also accounting for scenarios of future environmental change.	Month 33	R	PU	C S I
8.	24.	A review of forestry working practices, wood processing methods and implicit fossil energy inputs.	Month 6	O	CO	C
10.	34.	A selection of environmental, socio-economic and management scenarios for the EU forestry and wood products sector.	Month 35	O	PU	C S I
	35.	A portfolio of model predictions for all variables listed above, produced by running the above model using empirical data from earlier work-packages and simulation data from the stand- scale model as input with an associated uncertainty interval.	Month 35	O	PU	C S I
Other	36.	Papers in peer-reviewed scientific journals.	Month 18-36	R	PU	C S
	37.	Reports at international and national scientific meetings.	Month 18-36	R	PU	S

Work-Package No.	Deliverable No.	Deliverable title	Delivery Date	Nature	Dissemination Level	Dissemination Target
	38.	Reports in forestry and timber-processing industry journals in participating countries and international bulletins.	Month 18-36	R	PU	I
Manag	39.	First Annual Report	Month 13	R	CO	CO
	40.	Second Annual Report	Month 26	R	CO	CO
	41.	Final Report	Month 36	R	CO	CO
	42.	International Workshop	Month 35	O	PU	S I

4. PROJECT MANAGEMENT

4.1 OVERALL CO-ORDINATION

The co-ordinator will spend 2 man-months per year in the overall management supervision of the project. He will ensure timely and accurate delivery of all agreed outputs and milestones. The co-ordinator will be responsible for the assembly and harmonisation of all material (both scientific and financial) forming annual and final reports. Administrative and financial personnel of the co-ordinating institute will support the co-ordinator in his management functions.

4.2 SCIENTIFIC CO-ORDINATION

The co-ordinator will also ensure compliance to agreed quality standards, and where necessary will seek advice from recognised scientists able to provide independent evaluation of deliverables and contributions. He will also actively liaise with the Commission's nominated Scientific Officer throughout the life of the project. Where partners do not comply with the agreed timetable of deliverables, and their quality, the co-ordinator will be responsible for informing the Commission and will initiate appropriate financial action to curtail any negative effects on the overall success of the project.

4.3 FINANCIAL CO-ORDINATION

The co-ordinator will be supported by a nominated finance officer from the co-ordinating organisation. The role will also ensure compliance with Commission guidelines and regulations concerning the financial administration of the contract. Each Partner in the consortium will nominate a financial officer responsible for the timely completion and submission of financial statements to the co-ordinator.

4.4 CO-OPERATIVE SUPERVISION AND DECISION-MAKING

Chaired by the co-ordinator, the Principal Investigators (PI) of each Partner Member State in the Consortium will form a steering group, to whom co-operative supervision of the project is entrusted. The role of the steering group is to provide a strict and effective inspection and supervision framework for the Consortium. The steering group will also develop revision procedures in the eventuality of modification of technical and financial provisions, and withdrawal of partners. In turn, each partner group undertakes to follow the schedule of deliverables and budget specified in the technical provision of this project; the Consortium reserves the right to modify both schedule and deliverables if the financial contribution requested in this project are not met. In view of the uncertain character of some tasks, deliverable timetables are given for information only and will at this stage not incur the liability of the parties. The steering group will communicate on a regular basis in writing and through dedicated sessions at each Project meeting. The co-ordinator reserves the right to call *ad hoc* meetings as and when emerging issues cannot be resolved through normal means.

4.5 WORK-PACKAGE LEADER

Each Partner has been assigned the overall responsibility of a work-package and is responsible for the timely completion of deliverables and milestones to the agreed standard. The Partner will also take overall responsibility for the timely delivery of all reports completed under the work-package for use in the annual and final reports.

4.6 MONITORING OF PROGRESS: SPECIFIED INDICATORS OF IMPACT AND PERFORMANCE

Each partner's progress will be monitored by the timely achievement of each deliverable by the agreed deadline. As indicated at Table 5, a total of 43 deliverables have been identified. Performance and quality will be assessed by the acceptance of the agreed number of papers in peer-reviewed and industry journals.

4.6.1 Development Notes

Scientists responsible for each WP will at the outset of work, propose development notes outlining in some detail the main lines of research to be taken forward by associated partners.

In turn, individual associated scientists will produce development notes that describe key tasks and proposed methodologies.

4.6.2 Collaborative Research Papers

Scientists involved in the research project will be seeking publication of collaborative research papers in peer-reviewed international journals, with a total 17 papers identified as deliverables in the WPs.

4.7 COMMUNICATION BETWEEN CONSORTIUM

Communication between the consortium will be maintained in a number of ways:

4.7.1 Periodic meetings

As indicated at Table 2 the Consortium will hold 5 plenary meetings of all project participants. The initial (kick-off) meeting will be held at the outset of the research programme to develop common protocols for experimental and analytical procedures, data exchange and modelling procedures. Additionally, scientists involved in single work-packages, and under the supervision of the PI for the work-package, will hold periodic progress meetings throughout the activation of research associated with the work-package.

4.7.2 Electronic means

Electronic means of communications (e-mail and internet data exchange facilities) will provide the most common form of communication between partners and individual scientists. As indicated at Section 5.2, Partner 3 will be responsible for the development of the web pages of this project and for the provision of common data-holding and data-exchange facilities.

4.7.3 Video-conferencing facilities

Where facilities exist, Partners will hold video-conferences, to optimise both the frequency of face-to-face contact and to stimulate debate between partners, as well as minimising expenditure against the travel and subsistence budget.

4.7.4 Movement of research personnel, standard operating procedures and training programmes

Movement of personnel will be strongly encouraged, in particular for those work packages requiring commonality in sampling, experimental, analytical and modelling protocols. Therefore, as part of a number of work-packages, individual Partners are identified who will be responsible for the production of Standard Operating Procedures [SOPs] for all associated partners. Training in the use of SOPs for individual scientists will be held at the institution responsible for the work-package; where possible, and to minimise expenditure against the travel and subsistence budget, training sessions will coincide with periodic meetings.

4.8 IPR ISSUES

IPR issues have been considered by consortium members at the submission phase, as this project involves the presence of co-funding bodies who have rights of access to unpublished results resulting from the co-operative effort. The body of this technical annex forms the subject of the co-operative agreement to be entered into by all parties who collectively form the consortium. Sections outlined below will form the body of an agreement to be underwritten by all parties on successful completion of contract negotiation.

4.8.1 Ownership of results

Results from this project will be deemed by all main partners to be systematically jointly owned. Sub-contractors will have no ownership of the results produced within the framework of this project, but where scientific recognition is due, joint publications will be encouraged.
The following IPR guidelines apply to the consortium:

	Knowledge		Pre-existing know-how necessary for the execution of the project or to use its knowledge	
	Access rights for the execution of project	**Use (1)**	**Access rights for the execution of project**	**Use**
Principal contractor	Royalty free	Royalty free to all knowledge (2)	Favourable conditions	Favourable conditions
Assistant contractor (2)	Royalty free / favourable conditions	Favourable conditions / market conditions (2)	Favourable conditions / market conditions	/

(1) Access rights to knowledge for the purpose of use are limited knowledge generated under the project concerned.
(2) Contractors and assistant contractors unable to exploit their own knowledge might grant access rights at reasonable financial or similar conditions, instead of royalty free.

4.8.2 Technical provision
This annex identifies as precise a set of definitions, as are deemed possible at this stage, of the tasks each party intends to undertake. The annex also identifies the relationships between the production programmes of the different participants. All participants undertake to make available the human resources, equipment and facilities and information not subjected to other restrictions required to undertake the tasks identified in this annex. No undertaking is made by the consortium that the schedule of deliverables in irrevocable, as this may be subject to successive negotiations with funding bodies. The technical provisions identified in this technical annex give an overview of the level of co-operation at any one time. The information here provided may therefore undergo changes as the work progresses, in view also of scientific advancements subsequently made available in the public domain.

4.8.3 Confidentiality
Results produced by the Consortium are jointly held by the main partners and will be made available to the wider public through publication in peer-reviewed and publications in industry literature. From time to time, data will be made available in electronic format on internet pages. The quality of information divulged through this means remains the sole responsibility of the individual contributor, who will also ensure distribution will not hinder research conducted by the main partners.

4.8.4 Commercial provision
Utilisation rights of all deliverables within the consortium will be freely available to all main partners for *bona fide* research, which does not foresee the commercial utilisation of deliverables completed under this programme. Should subsequent commercial exploitation of deliverables be recognised as resulting from aspects of this project, all parties will enter into a separate agreement that encourages maximum commercial exploitation of results and identifies the capabilities and roles played by each party.

4.8.5 Movement of research personnel
Temporary secondment of research personnel in the consortium to participating organisations is actively encouraged and will be periodically reviewed by the steering group. Financial provision for all costs (travel expenses, accommodation, remuneration, overtime, medical care and reimbursement of costs, social security items, working conditions, employers liability, insurance, applicable law, arbitration etc.) of seconded personnel will be the responsibility of the home institution, after consultation with the host institution.

5. EXPLOITATION AND DISSEMINATION ACTIVITIES

5.1 LEAD DISSEMINATION PARTNER

Whilst the co-ordinator will have overall responsibility for dissemination, and will inform each partner of their responsibilities with respect to the dissemination of information derived from the project, Partner 3 will act as the lead dissemination Partner. As a leading pan-European research organisation with a commitment to act as a first stop shop for the provision of forestry related information in Europe, Partner 3 has a formalised and well established mechanism for the dissemination of forestry-related issues to the wider forestry and policy communities. Thus, Partner 3 is strategically placed to successfully achieve implementation of key aspects of the dissemination plan.

5.2 INTERNET SITE

A project web site will be established by Partner 3 for the dissemination of publicly available data and reports. This site will also provide a restricted means of making common data-sets available to all partners in the consortium. The co-ordinator will have overall responsibility for the internet site, and will inform each of their responsibilities with respect to the dissemination of information through this medium.

5.3 PUBLICATIONS IN PEER-REVIEWED LITERATURE

All partners will be expected to report their findings and developments by means of papers in the scientific, peer-reviewed literature. At least one paper will be produced involving all members of the consortium and providing a general overview of the project results. On completion of the project a number of papers will be collected together and a relevant scientific journal will be sought in which all papers may be published together in the form of a special issue.

5.4 PUBLICATIONS IN INDUSTRY LITERATURE

In order to disseminate the results of the research to the wider industry communities, and thus inform of the availability of the prototype integrated modelling system, articles will be produced in information notes to the forestry community produced by Partners 1 and 3. Additionally, appropriate national trade magazines will be targeted by partners in each Member State for the publication of key research findings resulting from the project.

5.5 INTERNATIONAL WORKSHOP

The project workshop, to be held in the closing months of the research programme, will be open to scientists from clustered projects and to both the timber industry and to those scientists who have not been partners in the project. Additionally, a limited number of leading scientists with key interests in the research will be invited to participate in the proceedings. As well as presenting the findings of the project for critical appraisal by the wider scientific community, the workshop will review the final project report to be submitted to the EU. A special session will be dedicated to the dissemination of key project findings and the integrated prototype modelling system of the project to the target audience (see Section 5.6).

5.6 NON-SCIENTIST TARGET AUDIENCE AND THEIR INVOLVEMENT

The non-scientist target audience of this project can be separated into three broad classes: forest managers and practitioners; forestry policy informers; the timber industry. The project will target this audience through the provision of data, dissemination of scientific data through non-scientific publications at national levels, specific project deliverables, such as the integrated prototype modelling system, and their participation at the international workshop. Partners 1 and 3, by virtue of their mandate to provide applied scientific products and inform the forestry sector, have well-established and formal links with forest managers and practitioners, forestry policy advisors and the timber industry in their respective Member States. Partner 3 also has well-established international linkages with a number of key production and policy players. These existing links will be further extended to encompass the broader and applied evaluation of the deliverables produced by this programme of research.

5.7 RESOURCES ALLOCATED TO THE DISSEMINATION TASK

In order to achieve key dissemination targets identified above, a small proportion of funds has been allocated to the dissemination targets. These resources will support the development of the internet web pages and contributions to a newsletter produced by Partner 3, which is widely distributed in the forestry community, decision and policy makers. This resource allocation is considered essential by the partners/associated partners of the consortium for achieving a meaningful level of technology transfer between the science community and the non-scientist target audience identified above.