producing actively growing callus cultures were determined. These cultures have been maintained for over a year. In addition, the cells have been placed in suspension culture for several months, and then brought back to callus culture on a semisolid medium. Roots have been regenerated from newly produced callus, and both roots and shoots have been produced from cultured hypocotyl segments through normal manipulation. Current efforts are directed at regenerating entire plants from callus cultures so that any yield improvements made in vitro can be tested in regenerated plants.

Triterpene biosynthesis in callus cultures: Since tissue cultures quite frequently do not synthesize the secondary metabolites characteristic of the parent plant at all, or do so in minute amounts, it was necessary to establish first whether *E. lathyris* callus tissue produces any terpenoids. By using our previously established techniques for triterpenoid isolation and characterization, we determined that *E. lathyris* callus cultures grown in the dark do produce 0.1–0.2% triterpenoids on a dry weight basis. This yield is comparable to that reported for secondary metabolism in other callus species.

Since *Euphorbia lathyris* tissue cultures do have the capability of triterpenoid biosynthesis, we now have a system which can be effectively exploited for the selection of desirable callus lines as well as for the exploration of secondary metabolic pathways.

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1 M. Calvin, Bioscience *29,* 533 (1979); Naturwissenschaften *67,* 525 (1980).
2 R. Sachs, Agronomic Studies with *E. lathyris* – A Potential Source of Petroleum-like Products, in: Energy from Biomass and Wastes, V. Institute of Gas Technology, in press 1981.
3 E.K. Nemethy, J.W. Otvos and M. Calvin, J. Am. Oil chem. Soc. *56,* 957 (1979).
4 E.K. Nemethy, J.W. Otvos and M. Calvin, Pure appl. Chem, in press (1981).
5 P.B. Weisz, W.O. Haag and P.G. Rodewald, Science *206,* 57 (1979).
6 W.O. Haag, P.G. Rodewald and P.B. Weisz, Catalytic Production of Aromatics and Olefins from Plants Materials. Presented at ACS National Meeting, Las Vegas, Nevada, August 1980.
7 J.D. Johnson and C.W. Hinman, Science *208,* 460 (1980).
8 E.K. Nemethy, J.W. Otvos and M. Calvin, High Energy Liquid Fuels from Plants, in: Fuels from Biomass. Ed. D.L. Klass and G.H. Emert. Plenum Press, New York, in press (1981).

Wood as biomass for energy: results of a problem analysis

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1. *Wood as biomass for energy*

Under the pressure of a world-wide crisis in nutrition, raw materials and energy, a new field of research has evolved which attempts, through interdisciplinary cooperation, to promote the production of economically convertible 'biomass' rapidly and effectively using modern biotechnological methods. Biomass is defined as all organic material produced by living things. Biomass has potential uses as food, as raw material for economically important products and as an energy source.

One of the main aims of this new research is to find suitable organisms producing the greatest quantity of economically convertible biomass under well-adjusted conditions. Trials on the cultivation of fast-growing woody plants in intensively managed plantation-type monocultures and the production – with the shortest possible time lapse between planting and cropping (short-rotation forestry) – of a maximum of woody biomass for energy or chemistry, are to be evaluated from this viewpoint. This cultivation method for fuel wood differs in several ways from the common practice in forestry to date. Therefore it is expedient to examine more closely the widespread suggestion that fuel wood be produced on special farms; we will do this within the framework of a general survey of the topic 'Wood as raw material and energy source'.

2. *Systems analysis approach*

Forest management is a very complex dynamic system, which can be divided into 4 closely interrelated subsystems:

a) the *ecological* sub-system deals with the relationship between woody plants and their animate and inanimate environment;

b) the *forestal* sub-system is founded on all those observations made during the course of man's efforts to guide the development of wood-producing plants towards specific aims;

c) the *timber-economic* sub-system concerns itself with the production, processing, distribution and utilization of wood in the commercial sector, and its restoration to the natural ecosystem;

d) these 3 systems are superimposed by the management system. It seeks to bring the economically-, politically- and socially-based demands on forest management into harmony with one another and with forestal realities and the ecological limits of wood production.

Such a systems analysis approach has proved especially useful for investigating the ways in which new demands of forest management affect ecology, forestry and timber economics, and for indicating possible changes in the balance of the entire system.

In the present article, the study of fuel wood production in plantations following the short rotation forestry principle serves as a basis for such an all-encompassing evaluation. The correlations within the aforementioned sub-systems are examined by addressing the following questions:

- What measures can be implemented to increase the production of woody biomass in plantations? (forestal sub-system);
- which fast-growing, highly-productive shrubs and trees are suitable for cultivation in plantations? (forestal sub-system);
- what demands do these species make on their growth sites? (ecological sub-system);
- are there ecological objections to the growing of these species in intensively cultivated monocultures? (ecological sub-system);
- how well can the plantation method compete with other methods of producing fuel wood and with other energy resources? (timber-economic sub-system);
- what are the repercussions of introducing new production methods on the collective system 'wood as raw material and energy source?' (Management system).

In answering these questions, potentials and effects of fuel wood plantations are outlined.

3. *Forestal aspects*

Short rotation forestry practice. In short-rotation forestry, the time between the establishment of a stand and wood harvesting is kept short, i.e. usually 2-10 years. In these few years the dense plantations (5000-100,000 plants per ha) produce thin stems which are mechanically cut and harvested. Work is being done in several countries on the development of suitable cropping machines, partly within the framework of a project of the International Energy Agency (IEA).

Numerous trials on the cultivation of fast-growing woody plants in short harvest cycles have been running for some years (USA, Canada, Sweden, Denmark, Federal Republic of Germany etc.)[1].

In their work on the afforestation of polders, Dutch

Figure 2. Willows grown in short rotation in Flevoland, Netherlands. 75% of the planted area (1973: 172 ha) consists of selected clones of the species *Salix viminalis* and 25% of *Salix tiandra.* A normal yield is: with a rotation of 2 years: 1700 bundles of shoots per ha; with a rotation of 3 years: 2300 bundles of shoots per ha. A bundle is after 2 years 3.5 m long, with 70 cm circumference at 30 cm from the bottom. A bundle weighs fresh 20 kg, dry 10 kg. (Photo: Ir. H.A. van der Meiden, Wageningen).

Figure 1. A cropping machine in the Netherlands is harvesting willow-rods grown in short rotation (Photo: Rijksdienst voor de Ijsselmeerpolders, Lelystad).

Figure 3. A planting machine with 6 rows is used for planting the willows. The rows are 70 cm apart, distances in the row are 50 cm. The planting stock consists of unrooted cuttings with a length of 23 cm. (Photo: Rijksdienst voor de Ijsselmeerpolders, Lelystad).

specialists have adapted the extensive experience of many years to a special form of short-rotation forestry, although not for the production of fuel wood. Cultures of a particularly fast-growing clone of *Salix* produce strong shoots within 3 years. These rods are used in large bundles to stabilize the sand as a first stage in dike construction. Propagation by short-rotation is very suitable for this special use of shoots. (Information from the Research Institute for Forestry and Landscape Planning, Wageningen, The Netherlands.)

Similar experience has been obtained with the propagation of plant material for engineering-biological constructions. The specifications for such plant material are very exact in comparison to the purely quantitative considerations in the production of wood for energy conversion.

Planting is done with cuttings, especially with bred types (e.g. poplar). The selected species should, as far as possible, display strong growth in youth as well as high sprouting capacity after several croppings.

Wood production in short rotation entails cultivation of the soil, planting in a very close arrangement, fertilization, pest control (with pesticides and insecticides), some degree of irrigation and the most efficient mechanized cropping possible[2]. In this, the technique resembles that of agriculture but differs considerably from conventional forestry methods. The term 'wood-farming' is as apt as 'short-rotation forestry'.

Potential increase in yield. The production of maximum yields requires favorable sites, care and protection. Cannell and Smith[3] compared and examined 11 reports on cultivation trials carried out under favorable growth conditions; the average yield (dry stem- and branch-wood, with bark, without leaves) did not exceed 10–15 t/ha. year for rotation times of 1–5 years.

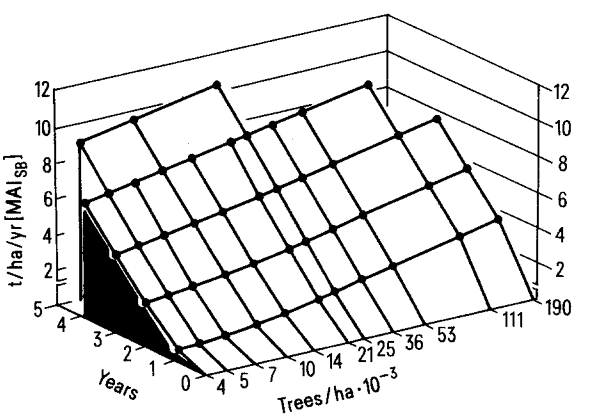

Figure 4. Dry weights of stems and branches with bark yielded by closely-planted hardwoods 1–5 years after planting.
Mean annual increments of dry stems and branches with bark (gross yield/age) (MAI_{SB}), in the 1st rotation after planting (not coppicing) with the given number of plants per ha (Figure from Cannell and Smith[3], p. 424; with permission).

The yields during the first few years after coppicing can be 10–30% greater than those after planting. The level of yields can be approximated by conventional forestry methods; agrarian cultures produce higher yields. Hence it appears doubtful whether higher yields really can be attained with extremely short rotation times than by conventional forestry methods.

In order to determine the net yield in terms of energy, an energy budget must be prepared. The energy consumed in soil cultivation, fertilization, pest control, harvesting, drying and transport must be subtracted from the gross yield. Short-rotation forestry entails an increased energy input, which correspondingly reduces the net yield.

Availability of fast-growing woody plants with high sprouting capacity. A tree species is described as fast-growing if, on good sites in central Europe, it attains a mean total increment of more than 9 solid meters by its 30th year and more than 12 solid meters by its 50th[4,5]. The requirements for sprouting capacity, fuel value, or depending on the intended use timber quality (fiber length etc.), limit the number of suitable tree species. Current projects are working mainly with the following:

- bred and selected clones of various poplar species *(Populus)*
- willow species *(Salix)*
- plane (*Platanus occidentalis* L.)
- black locust (*Robinia pseudoacacia* L.)
- alder species *(Alnus)*
- elm species *(Ulmus)*
- eucalyptus species (*Eucalyptus*)
- red oak (*Quercus rubra* D. R.)
- hornbeam (*Carpinus betulus* L.).

A more extensive survey of species suitable for fuel wood production is given by Burley[6]. The range of suitable types for any given site is, however, generally small, although Cannell and Smith[3] have shown that the choice of species influences the yield less than the density of planting and the rotation time.

4. *Ecological observations*

The growth of shrubs and trees is strongly influenced by environmental factors. Among the bioclimatic requirements in temperate zones, the temperature sum during the annual vegetation period is particularly important. Hence the growth performance of alpine trees deteriorates with increasing altitude[7,8]. A similar reduction in annual growth can be observed in local species at their northern limits of distribution in northern Europe and North America[9]. Trees in general perform less well on suboptimal sites. The implications for the cultivation of fast-growing, highly-productive species in plantations are obvious:

- the selected species must be planted on sites where it experiences optimal growth conditions.

- conditions in areas of the temperate zones with low temperatures during the growth period are unfavorable for fast-growing woody species.

The withdrawal of nutrients from the soil is higher in silvicultural energy plantations than in conventionally managed forests. It is often suggested that fertilizers be used to compensate for this loss, but this increases the load of nutrients in the ground water, as is also the case in agricultural areas.

From the ecological point of view, it must also be emphasized that silvicultural monocultures (especially where the trees are of the same age) may be swept by epidemics of plant and animal pests causing extensive and permanent damage[10]. Prolonged application of pesticides may therefore be necessary, which is disquieting from the forest ecology viewpoint. Forests represent one of the last more or less natural environments and have not only productive but also ecological functions to fulfil. These premises argue that such multiple objectives can best be achieved with natural silvicultural techniques[11], whereas a monoculture of woody coppice sprouts, cropped every few years is biased towards the productive function alone. Ecologically, short-rotation forestry can be regarded as a special form of agriculture.

5. *Timber economy considerations*

From the viewpoint of timber economy the production of fuel wood in plantations with short rotation must be compared with other possible energy supply methods. So far, under fuel wood the following has been understood:
- dry fallen wood;
- trimmings from felled trees;
- small-sized timber from thinning operations (also used as raw material for the pulp and particle board industries);
- specially-prepared classes of firewood;
- residual wood from sawmills (also used as raw material for the pulp and particle board industries);
- residual wood from wood-processing;
- unwanted wooden artifacts;
- wood resulting from the cutting and clearing of orchards, hedges, windbreaks, and shrubs and trees in parks and gardens.

The combustible end-products of industrial wood conversion (e.g. fiberboard, particle board, cardboard, paper) can also be used for energy production when they are not needed any more.

Fundamentally it can be seen that an ecologically and economically rational exploitation of wood should direct as much freshly-harvested wood as possible into commercial circulation as a raw material, and use it for energy production only as a last stage in conversion. From an overall point of view, the use of wood primarily as a raw material whether in a single form or in successive stages, and lastly, as an energy source, appears to be the most sensible and effective utilization of this natural resource.

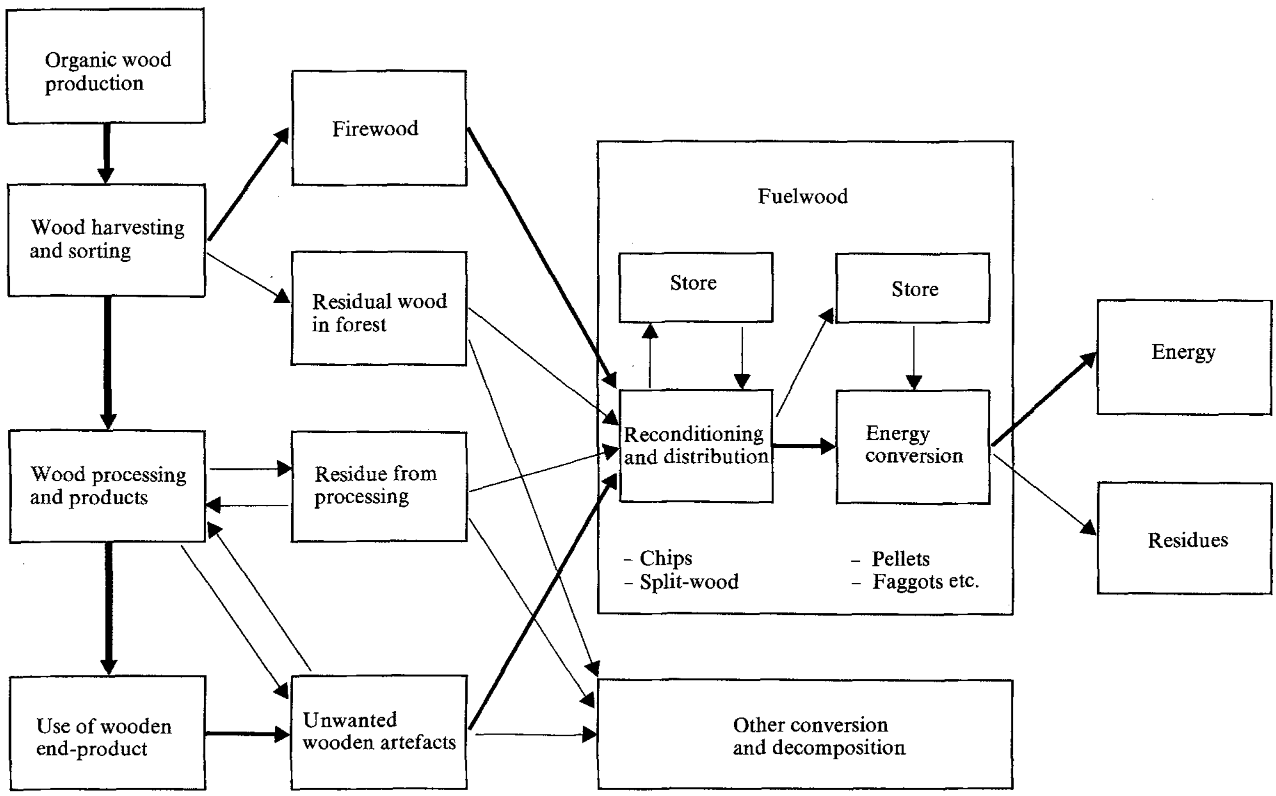

Figure 5. Schematic diagram of the sources of fuel wood in the flow of wood materials.

In the industrial lands of central Europe, the last 3 decades have seen an increasing displacement of firewood as the energy source by electricity, oil or gas in many households; some of this 'redundant' firewood is industrially converted to cellulose, paper, particle and fiber-board, while the nonconvertible residue from felling is either burned on the spot or left lying in the forest.

This contempt of wood as an energy source in the past years is in marked contrast to the attitude of earlier generations who, before the introduction of electricity and liquid fuels, were far more dependent on wood for heating and cooking.

Today there is a great interest in the utilization of wood as an energy resource for reasons of supply policy. A rapidly growing demand for firewood following the oil crisis of 1973/74 led, in Switzerland and in other countries, to a considerable price increase and the sale of some industrial wood as firewood. Consequently, efforts are being made today to increase the supply of wood for energy correspondingly. The possibilities are as follows:

- opening-up of as yet unused forest for wood production,
- intensified utilization of forest stands which, because of economic considerations, have been insufficiently exploited thus far,
- afforestation of areas abandoned by agriculture.

The production of wood in plantations can supplement these measures by replacing agriculture in mechanically cultivable areas as far as agropolitical considerations allow.

The requirements for the economical running of such wood farms on the short-rotation forestry or wood-farming principle would have to be fulfilled.

6. *Problems and conflicting aims in optimal wood production management*

Technologically, energy conversion of wood presents no particular problems. At present there is some interest in the development of plants for the production of wood gas which is a suitable fuel for engines with heatpower-coupling[12].

Many sections of the transport industry point out the possibility of producing alcohols, which are miscible with petrol, from wood.

Purely energy-economic considerations argue for the definite promotion of fuel wood in all those countries with sufficiently high wood production which depend on imported oil for a considerable portion of their energy supply. When the unusual versatility of wood as a raw material is considered, however, great objections arise over extending the energy conversion of wood at the expense of other utilization forms and thereby risking a crisis in commercial timber supply (Global 2000 report to the President, 1980)[13].

In Switzerland, for example, problems of this type would be particularly likely if the pressure towards the manufacture of fuels from wood increased. The production potential of forests in Switzerland can cover at best a small percent of the present total energy requirement[14], but a switch to energy wood plantations for the production of additional quantities of energy-convertible wood is only rational if large areas, which possess favorable conditions for wood-producing plants and are not otherwise utilized, are available.

The production of wood for energy must be assessed not only on the basis of energy-political aspects, but also from the silvicultural point of view. Forestry sees wood production as only one of the many functions a forest has to fulfil, both ecologically and socio-economically. As the history of forestry shows, over-utilization for economic reasons and biased promotion of particular commercial species sooner or later leads to progressive destabilization of the natural ecosystem. As custodians working on behalf of the public, the forestry bodies advocate the continued maintenance of the forests in their full capacity, the ensuring of ecological stability and the limiting of commercial forest exploitation in accordance with the sustained increase by natural growth.

7. *Political consequences*

In light of available information, ecological and overall economic considerations permit only the partial satisfaction of supply policy demands for a more energy-oriented timber management. At present the following positions are taken regarding the use of wood in energy production:

- wood production by the existing forestry methods is to be maintained within a framework which ensures the continued preservation and ecological stability of the forests;
- an increase in wood crop potential is primarily to be achieved through the opening-up of as yet unused forest, the improvement of forest tending and the afforestation of fallow and otherwise unused areas;
- the primary utilization of available wood as a raw material clearly takes priority over its use as an energy resource; a manifold conversion of wood over various stages and a final conversion for energy is ecologically and economically sound;
- otherwise non-convertible wood is to be used as much as possible for energy production;
- the production of fuel wood in special plantations may be considered if the potential production areas are suitable for the cultivation of fast-growing tree species and are not otherwise used. As a special form of agriculture, these plantations should not be subject to forest laws;

- in relation to energy supply policy, it is clear that no energy-production program can be convincing without a corresponding energy-saving program.

8. *Summary*

1. Wood has been used by man as a fuel since prehistoric times and therefore holds a special place among the energy-convertible forms of biomass.

2. The biotechnological possibilities for biomass production today raise the question of whether a significant increase in wood production per area and time can be achieved through fast-growing, highly-productive shrubs and trees, as compared to production by the usual forestry methods. This method has been suggested principally for the production of fuel wood for combustion, gasification and the manufacture of alcohol as a fuel additive. This wood could also be used as raw material for pulp production and wood chemistry.

3. By means of a systems analysis approach, the demand for the increased production and utilization of fuel wood is examined in terms of its ecological, forest- and overall economic effects, as is the suggestion that fuel wood be produced in plantations on the short-rotation forestry principle.

4. The increase of wood production through short-rotation forestry methods is clearly limited by the ecological requirements of suitable tree species and the slow growth of many others.

5. There are objections to the cultivation of selected, usually vegetatively-propagated, tree species in intensively-managed plantations: - susceptibility of monocultures to epidemics of plant and animal pests, - stressing of the soil through heavy fertilization or residues from pesticides and insecticides, - ecological impoverishment, concomitant with any monoculture.

6. The cultivation of woody plants in plantations requires large areas of land which are not otherwise managed, are mechanically cultivable, and which meet the ecological requirements of the species concerned.

7. Figures on operating costs and possible yields of short-rotation forestry plantations can be expected from current pilot projects within the foreseeable future.

8. The demands in various countries for an increased utilization of wood for energy create serious competition situations for consumers who need wood for a multitude of other purposes.

9. Overall economic considerations demand that all suitable wood be used as a raw material, as far as possible in successive stages, ending with a final conversion for energy.

10. Wood unsuitable for other purposes should, as much as possible, be collected and used in high-efficiency energy conversion processes.

11. Forestry management should yield to a rising demand for fuel wood only in as far as the wood cropping involved does not jeopardize the long-term silvicultural objectives:
- maintenance of the forest in such a way that it can fulfil all its functions, - safe-guarding of the permanent ecological stability of the forest, - limitation of wood harvesting in order to sustain productivity.

1 R. Bachofen, Bioenergie heute ... morgen. Vjschr. naturf. Ges. Zürich *125*, Nr. 5 (1980); Neujahrsblatt 1981.
2 J.B. Jensen, Mulighed for minirotation ved dyrkning af skovtraeer. Dansk Skovforen. Tidsskr. *63*, 1-39 (1978).
3 M.G.R. Cannell and R.I. Smith, Yields of minirotation closely spaced hardwoods in temperate regions: review and appraisal. Forest Sci. *26*, 415-428 (1980).
4 L. Dimitri, Anbau schnellwachsender Baumarten im Kurzumtrieb: Möglichkeiten und bisherige Erfahrungen. SchrReihe forstl. Fak. Uni. Göttingen *69*, 79-92 (1981).
5 E. Roehrig, Waldbauliche Aspekte beim Anbau schnellwachsender Baumarten. Forst-Holzwirt *34*, 106-112 (1979).
6 J. Burley, Selection of species for fuelwood plantations, 8 h World Forestry Congress 1978, paper FPC/3-6.
7 H. Turner, Mikroklimatographie und ihre Anwendung in der Ökologie der subalpinen Stufe. Eidg. Anst. forstl. Versuchswes., report 68, 1971.
8 H. Turner, Bergwald im Kampf gegen Natur und Mensch. Aufforstungsversuche in der oberen Gebirgswaldstufe. Eidg. Anst. forstl. Versuchswes., Report 168, 1976.
9 H.W. Windhorst, Geographie der Wald- und Forstwirtschaft. Teubner, Stuttgart 1978.
10 F. Schwerdtfeger, Die Waldkrankheiten, 3rd edn. Parey, Berlin 1970.
11 H. Leibundgut, Wirkungen des Waldes auf die Umwelt des Menschen. Rentsch, Zürich 1975.
12 J. Buchli and J. Studach, Wärmeversorgung Sent. Pilotprojekt einer möglichst autarken, wirtschaftlichen und umweltgerechten Wärmeversorgung eines Bergdorfes. IGEK, Chur 1980.
13 The Global 2000 Report to the President. Report by the Council of Environmental Quality and the Department of State. OCLC 6572993. US Government Printing Office, Washington DC 1980.
14 E. Wullschleger, Das Nutzungspotential unserer Wälder: Aufgabe und Chance für die Wald- und Holzwirtschaft. Schweiz. Z. Forstw. *130*, 1037-1046 (1979).