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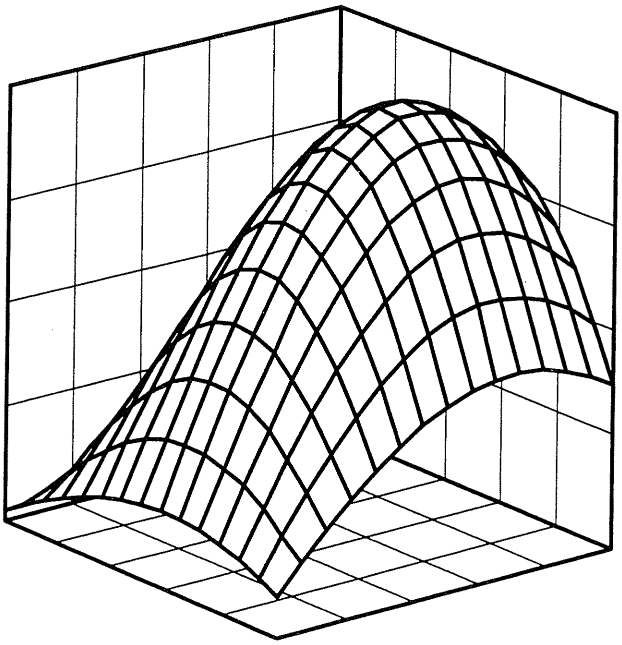

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Harvesting the sun's energy using agro-ecosystems

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Samenvatting

De Europese energievoorziening is momenteel voor het grootste deel gebaseerd op de verbranding van fossiele brandstoffen (23% gas, 38% olie en 24% kolen). Bij het gebruik van deze brandstoffen komen grote hoeveelheden kooldioxide (CO_2) vrij; CO_2 is een broeikasgas en er bestaan sterke aanwijzingen dat een toename van de CO_2-concentratie in de atmosfeer kan leiden tot klimaatveranderingen.

De voorraad aan fossiele brandstoffen is beperkt; als het gebruik van deze bronnen zich voortzet met de huidige snelheid zullen de voorraden in de volgende eeuw uitgeput raken. Het terugdringen van de CO_2-uitstoot en de eindigheid van de voorraad fossiele brandstoffen zijn belangrijke redenen om aandacht te besteden aan de mogelijkheden voor het gebruik van hernieuwbare energiebronnen. Een van de mogelijkheden is het gebruik van (landbouw)gewassen als energiebron. Tijdens hun groei leggen planten CO_2 vast, deze CO_2 komt vrij als het gewas gebruikt wordt, de CO_2 wordt dus 'gerecycled' en er wordt geen extra CO_2 aan de omgeving afgestaan. De efficiëntie waarmee zonne-energie door de plant wordt vastgelegd is laag (ongeveer 2%, terwijl zonnecellen een efficiëntie van 15% hebben). Dit betekent dat voor de energievoorziening met behulp van gewassen grote hoeveelheden land nodig zullen zijn. In de afgelopen decennia is de productiviteit van de landbouw sterk gestegen. Dit heeft tot gevolg gehad dat het areaal dat nodig is voor de voedselvoorziening is afgenomen. De landbouwgronden die niet meer nodig zijn voor de voedselproductie zouden kunnen worden gebruikt voor het verbouwen van energiegewassen.

De afgelopen jaren zijn er diverse studies gedaan naar de mogelijkheden van het gebruik van landbouwgewassen als energiebron. Uit deze studies kwam naar voren dat vooral het gebruik van biomassa als grondstof voor de opwekking van elektriciteit een potentiële mogelijkheid zou zijn. Het gebruik van tarwe of maïs voor de ethanolproductie of koolzaad voor de vervaardiging van biodiesel maakt veel minder kans, omdat er relatief veel energie nodig is voor de omzetting van de landbouwgrondstof in een energiedrager.

Voorbeelden van biomassa-gewassen zijn: snelgroeiend hout in korte rotatie (wilg, populier en Eucalyptus) of rietachtigen zoals Miscanthus. Deze biomassa-gewassen worden op het moment nog nauwelijks verbouwd. Hierdoor bestaat er grote onduidelijkheid over de verwachte opbrengsten van deze gewassen. De huidige opbrengstschattingen zijn gebaseerd op slechts enkele kleinschalige veldproeven op een beperkt aantal plaatsen in de wereld. De verwachte opbrengst van deze biomassa-gewassen is echter de sleutelfactor in de evaluatie van de mogelijkheden van deze gewassen als duurzame energiebron. (Wanneer de verwachte opbrengst hoog is zijn er meer mogelijkheden dan wanneer deze laag is). Uit de literatuur is bekend dat de opbrengsten behaald in veldproeven geen goede schatting zijn voor de opbrengstmogelijkheden van een gewas wanneer het op grotere schaal verbouwd wordt. Er zijn voorbeelden bekend van het feit dat de opbrengst op grote schaal nog niet de helft was van die behaald in een veldproef. Ook recente gegevens van opbrengsten van wilg in Zweden vertonen dit beeld: in veldproeven zijn opbrengsten van 12 ton drogestof ha^{-1} behaald, terwijl de opbrengstcijfers van de praktijkpercelen minder dan 6 ton drogestof ha^{-1} bedragen.

In de nu bekende evaluatiestudies naar de mogelijkheden van biomassa als energiebron wordt de opbrengst van een gewas als een constante factor beschouwd. De bijdrage van biomassagewassen aan de energieproductie wordt in dat geval berekend door het beschikbare areaal te vermenigvuldigen met de verwachte opbrengst. Uit landbouwkundig onderzoek is echter bekend dat er grote regionale verschillen in opbrengsten kunnen optreden.

Voor een goede evaluatie van de mogelijkheden van biomassa als energiebron is het daarom van belang de huidige opbrengstschattingen te verbeteren.

In dit rapport wordt een methode beschreven voor het schatten van opbrengsten van biomassa-gewassen onder verschillende groeiomstandigheden in diverse regio's. Er worden drie verschillende productieniveaus onderscheiden, te weten: de potentiële productie (de groei van een gewas wordt alleen bepaald door de gewaskenmerken, de globale straling en de temperatuur; er is voldoende water, nutriënten zijn niet beperkend en het gewas heeft geen last van ziekten, plagen en onkruiden). De potentiële productie is een maat voor wat gewassen kunnen produceren onder optimale groeiomstandigheden. In goede veldproeven (met irrigatie) kunnen dergelijke productieniveaus gehaald worden. Het tweede productieniveau is de water-gelimiteerde productie. De productie wordt bepaald door de gewaskenmerken, de temperatuur, globale straling en de hoeveelheid beschikbaar water, de nutriëntenvoorziening is optimaal en het gewas ondervindt geen hinder van ziekten en plagen of van onkruiden. De water-gelimiteerde productie kan gezien worden als maat voor de productiemogelijkheden van individuele boeren. Nutriënten-tekorten en schade door het optreden van ziekten en plagen kunnen (in principe) worden voorkomen door juiste toepassing van bemesting en het gebruik van pesticiden (goed boeren). Voor irrigatie zijn echter vaak infrastructurele aanpassingen op regionale schaal nodig die individuele boeren niet kunnen realiseren. Zowel de potentiële en de water-gelimiteerde productie zijn een maat voor de productiemogelijkheden in de toekomst en zijn van belang in studies naar de toekomstige mogelijkheden van deze energiebron. Naast de toekomstige productiemogelijkheden is het ook van belang te weten wat er onder de huidige omstandigheden aan opbrengsten van deze gewassen verwacht kan worden. Met andere woorden: de opbrengsten die door boeren gehaald kunnen worden wanneer ze op dit moment biomassa-gewassen gaan verbouwen (de actuele productie).

De in dit verslag ontwikkelde methode is gebaseerd op de lineaire relatie tussen de hoeveelheid geabsorbeerde straling en de geproduceerde bovengrondse biomassa. Deze lineaire relatie is gevonden voor een zeer uiteenlopend scala van gewassen: van landbouwgewassen tot en met wilg, populier en Eucalyptus in korte rotatie. Om de productie van een willekeurig gewas uit te rekenen moet de hoeveelheid geabsorbeerde straling tijdens het groeiseizoen bekend zijn. Deze hoeveelheid kan worden afgeleid uit de ontwikkeling van het bladoppervlak tijdens het groeiseizoen en bij veel gewassen is deze ontwikkeling afhankelijk van de luchttemperatuur.

Voor vijf gewassen die regelmatig genoemd worden als potentiële biomassa-gewassen (wilg, populier, Eucalyptus, Miscanthus en Sorghum) werd de ontwikkeling van het bladoppervlak gedefinieerd aan de hand van een temperatuursom. De benodigde informatie werd afgeleid uit veldproefgegevens van deze gewassen. Wanneer het verloop van de temperatuur en de globale straling in een gebied bekend zijn, kan de ontwikkeling van het bladoppervlak van de diverse gewassen in dat gebied afgeleid worden, en met dit verloop van het bladoppervlak kan vervolgens de hoeveelheid geabsorbeerde straling worden berekend, waaruit de potentiële productie kan worden afgeleid.

De water-gelimiteerde productie werd berekend met behulp van een bodemwaterbalans. Hiermee kan worden berekend of er voldoende water beschikbaar is in de bodem om potentiële productie mogelijk te maken. Wanneer dit niet het geval is wordt de groei geremd. Voor het berekenen van de water-gelimiteerde productie zijn neerslaggegevens van het gebied nodig. In veel gebieden in Europa is de water-gelimiteerde productie aanzienlijk lager dan de potentiële.

Binnen de Europese Unie (12) werden 58 regio's onderscheiden (de zogenaamde NUTS 1 regio's), voor elke regio werden weersgegevens (temperatuur, globale straling en neerslag) verzameld. Hiermee werden potentiële en water-gelimiteerde producties van de vijf biomassa-gewassen berekend.

Van landbouwgewassen is bekend dat er grote verschillen bestaan tussen de water-gelimiteerde productie en de opbrengsten die momenteel gehaald worden. Er bestaat geen reden om aan te nemen dat dit verschil bij biomassa-gewassen niet zou optreden. Het bestaande verschil tussen water-gelimiteerde productie en actuele productie van landbouwgewassen werd als uitgangspunt genomen voor het berekenen van de actuele productie van de biomassa-gewassen. Voor alle 58 Europese regio's werd met de boven beschreven methode de water-gelimiteerde productie van tarwe uitgerekend; deze productie werd vergeleken met de huidige opbrengstgegevens van dit gewas. De verhouding tussen actuele en de water-gelimiteerde productie werd gebruikt als maat voor de ontwikkeling van de landbouw in een regio. Door deze verhouding vervolgens toe te passen op water-gelimiteerde productie van de diverse biomassa-gewassen kon een schatting van de productie van deze gewassen onder huidige omstandigheden worden gemaakt. De kwaliteit van deze schattingsmethode werd geëvalueerd door de opbrengsten van landbouwgewassen in een aantal regio's in Nederland te schatten. Het bleek dat met deze methode opbrengsten met een nauwkeurigheid van meer dan 90% geschat konden worden. Deze afwijking is aanzienlijk kleiner dan die welke verkregen wordt wanneer opbrengsten van veldproeven gebruikt worden als schatting voor de productie op een grotere schaal.

De potentiële productie van wilg, populier en Miscanthus varieerde van 12 ton drogestof ha^{-1} in Noord Europa tot meer dan 40 ton ha^{-1} in sommige gebieden in Zuid Europa; Eucalyptus en Sorghum kunnen alleen in Zuid Europa groeien omdat ze slecht tegen vorst en/of lage temperaturen kunnen. De potentiële productie van Eucalyptus lig in veel gebieden boven de 50 ton ha^{-1}, die van Sorghum is lager: 20-25 ton ha^{-1}. De verschillen tussen regio's in water-gelimiteerde opbrengsten waren aanzienlijk kleiner: wilg, populier en Miscanthus 12-15 ton ha^{-1}, Eucalyptus 25-40 ton ha^{-1} en Sorghum 15-23 ton ha^{-1}.

De verschillen tussen regio's in de actuele opbrengsten waren nog veel kleiner: voor heel Europa varieerde de schatting van de actuele productie tussen de 5 en 10 ton ha^{-1}.

De verschillen tussen de diverse gebieden in Europa werden veroorzaakt doordat in het zuiden van Europa de temperaturen hoger zijn; hierdoor is het groeiseizoen langer en wordt er meer straling opgevangen waarmee een hogere productie gehaald kan worden. Het groeiseizoen van Eucalyptus duurt zelfs het hele jaar, aangezien dit gewas z'n bladeren niet verliest. In Noord Europa valt er genoeg regen om droogte te voorkomen en zijn potentiële en water-gelimiteerde producties aan elkaar gelijk. De neerslag in Zuid Europa is echter niet voldoende om potentiële productie mogelijk te maken; in dit gebied is de water-gelimiteerd productie aanzienlijk lager dan de potentiële (het verschil tussen Noord en Zuid Europa wordt hierdoor kleiner).

Binnen Europa zijn er ook grote verschillen in de verhouding tussen actuele en water-gelimiteerde producties. In Noord Europa ligt deze verhouding boven de 0.5 terwijl in sommige gebieden van Portugal de actuele productie nog geen 10% van de water-gelimiteerde productie is (de verschillen in actuele productie binnen Europa worden hierdoor klein).

Tot nu toe is alleen de productie van biomassa-gewassen in ton ha^{-1} besproken. Voor een energiegewas is de netto energie-opbrengst ook van belang. De netto energie-opbrengst van een gewas is het verschil tussen de energie in het geoogste product (energie-output) en de energie die nodig was om het gewas te verbouwen en te oogsten (energie-input). De energie-input hangt af van de gebruikte teeltmethode (gebruik van irrigatie, pesticiden en meststoffen) en de gebruikte teeltmethode heeft weer invloed op de opbrengst (energie-output). Om een indruk te krijgen van deze netto energie-opbrengst van biomassa in verschillende productiesystemen werd de energie-input van 5 verschillende productiesystemen voor populier berekend. Voor alle handelingen tijdens de teelt van populier (planten, wieden, bemesten, irrigeren, oogsten etc.) werd bepaald hoeveel energie en tijd daarvoor nodig waren. Daarnaast werd van elke toevoeging (kunstmest, pesticiden) bepaald hoeveel energie er nodig was voor de productie ervan (de energie-inhoud).

Het eerste systeem is de potentiële productie van populier in Noord-West Europa (opbrengst 12 ton ha^{-1}). In dit gebied is er voldoende neerslag om watertekorten te voorkomen en deze productie kan gehaald worden zonder irrigatie. In dit productiesysteem wordt gewasbescherming en bemesting toegepast. Het tweede systeem is de productie in dezelfde regio, maar nu zonder het gebruik van gewasbeschermingmiddelen. De productie van dit systeem ligt lager omdat er opbrengstderving door ziekten en plagen plaatsvindt (10 ton ha^{-1}). Het derde bestudeerde systeem is dat van de potentiële productie in Portugal waar opbrengsten van 43 ton ha^{-1} kunnen worden verwacht, maar om dit productieniveau te halen is irrigatie noodzakelijk evenals bemesting en gewasbeschermingsmaatregelen. Het volgende systeem is de water-gelimiteerde productie in Portugal (dus zonder irrigatie), maar met bemesting en het toepassen van gewasbeschermingsmiddelen (28 ton ha^{-1}). Uiteindelijk werd ook nog een laag-'input'-systeem in Portugal bestudeerd met een opbrengst van 5 ton ha^{-1}. In dit systeem wordt niet bemest, niet geïrrigeerd en er worden geen gewasbeschermingsmaatregelen getroffen. Voor alle vijf de systemen werd de benodigde energie input (GJ) en arbeidsinput (uren) uitgerekend en de netto energie-opbrengst bepaald. Het geïrrigeerd systeem in Portugal had de hoogste netto energie-opbrengst (692 GJ ha^{-1}) maar had de laagste efficiëntie, zowel voor de energie (8 GJ GJ^{-1}) als voor de arbeid (24 GJ hr^{-1}). Het laag-input-systeem had de hoogste energie efficiency (22 GJ GJ^{-1}) maar de netto opbrengst was laag (86 GJ ha^{-1}). De andere drie systemen waren vergelijkbaar in hun efficiënties (15 GJ GJ^{-1} en 40 GJ uur^{-1}). Er wordt geconcludeerd dat de verbouw van biomassa-gewassen met behulp van irrigatie niet realistisch is, aangezien de hoeveelheid energie en arbeid die nodig zijn voor het irrigeren te hoog zijn. De berekende water-gelimiteerde opbrengsten moeten daarom gezien worden als opbrengstpotenties van de energiegewassen in de toekomst. Deze water-gelimiteerde opbrengsten liggen in de orde van grootte van 12-30 ton ha^{-1} voor de verschillende regio's van de EU. De opbrengsten op korte termijn zullen echter veel lager liggen omdat met name in de zuidelijke regio's van Europa nog grote verschillen bestaan tussen opbrengstpotenties en actuele opbrengsten.

De berekende opbrengsten zijn de opbrengsten van gewassen met de kenmerken van de nu gebruikte rassen; door veredeling is het mogelijk deze opbrengsten te verhogen. Voor wilg is nagegaan welke veredelingsopties het meest voor de hand liggen en wat voor opbrengstverhogingen hiervan te verwachten zijn. Door verlenging van het groeiseizoen (verandering van de temperatuursom) blijken opbrengstverhogingen van 10 ton ha^{-1} mogelijk te zijn voor het midden en noorden van Europa, in het zuiden zijn de verhogingen veel kleiner (5 ton ha^{-1}).

In vergelijking met de huidige voedselgewassen is de arbeidsinzet voor de teelt van biomassa-gewassen bijzonder laag (aardappel: 53 uur jr-1 ha-1, populier in korte rotatie: 2 uur (jr-1 ha-1). Dit heeft tot gevolg dat wanneer boeren over stappen van de teelt van voedselgewassen op de teelt van biomassa-gewassen er een grote afname van de arbeidsbehoefte zal plaatsvinden; dit kan leiden tot een afname van het aantal arbeidsplaatsen op het platteland.

Summary

The European energy supply is mainly based on combustion of fossil fuels. The use of these fossil fuels as major energy sources implies that large quantities of CO_2 are emitted to the atmosphere; CO_2 is a greenhouse gas and increasing CO_2 levels in the atmosphere are likely to affect global climate. Besides the need to reduce CO_2 emissions, the non-renewability of the fossil fuel reserves also implies a necessity to look for renewable energy sources. One of the renewable energy sources frequently mentioned is biomass: the use of crops as feedstock for electricity production. Due to the increased productivity of agriculture the acreage required for food production has declined. These surplus agricultural grounds could be used for growing energy crops.

In studies on the possibilities of biomass crops as an energy source the yield per hectare of these crops emerges as a key factor. The expected yield per hectare determines whether the use of crops for energy supply is a realistic option or not. The crops that are mentioned as biomass crops are presently not grown on a large scale and large uncertainties exist with respect to their yield potentials. The yield estimates presently used are based on the yields obtained in a few small-scale field experiments. However, from literature it is known that yields in field experiments are not suitable as estimates for yields obtained on larger scales. In order to evaluate the contribution biomass crops can make to the energy supply, it is essential that the existing methods for determining yield potentials are improved.

In this report methods are developed to estimate yield potentials of biomass crops in various regions within the European Union (EU-12). Three different production levels are considered; firstly, the potential production level that can be realized when the crop is optimally supplied with water and nutrients and free from pests, diseases and weeds. Crop growth is only determined by crop characteristics, temperature and solar radiation. The potential yield of a crop in a region is a measure for what can be obtained under optimal growing conditions in this region. In well-designed field experiments (with irrigation) this yield level can be reached. Secondly, the so-called water-limited production level is recognized. In the water-limited situation, nutrients are in optimal supply and the crop is free of pests, diseases and weeds, but yield is limited by the availability of water. This water-limited yield is accepted as the attainable yield level by individual farmers. The effects of nutrient shortages and damage caused by pests and diseases can be reduced by good crop management (fertilization and application of crop protection measures). Irrigation, however, often implies investments on regional scale which cannot be established by individual farmers.

Potential and water-limited yields are measures for yield potentials in the future; with respect to biomass crops also the yield under actual conditions is of interest. Therefore, also the actual yield level was estimated. The method used to determine the various production levels is based on the linear relation between intercepted radiation and the above-ground biomass production as has been found for a wide range of (agricultural) crops. For several biomass crops (short rotation forestry of willow, poplar and Eucalyptus, Miscanthus and Sorghum) intercepted radiation was determined in 58 regions of the EU (12) and potential yield was derived from this value. Through introduction of a soil water balance the production under rain-fed conditions could be determined in the regions of interest. Based on the presently existing yield gap between actual and water-limited yields of agricultural crops estimates were made for the actual biomass yields in the 58 regions under study.

The potential yields of the biomass crops calculated with the method varied from 12 ton ha^{-1} y^{-1} in northern parts of Europe to over 40 ton ha^{-1} y^{-1} in the southern regions. The differences in water-limited yields were smaller: in northern parts 12 ton ha^{-1} y^{-1} and in Southern Europe 30 ton ha^{-1} y^{-1}. For the estimated yields under actual circumstances differences were very small: for the whole of Europe the estimated actual yields varied between 5-10 ton ha^{-1} y^{-1}.

Besides the yield in ton ha^{-1} y^{-1} the net energy yield (output-input) of biomass crops is also of importance. To obtain an impression of this net energy yield, the input requirements of five different poplar production systems were determined. Firstly, the potential production in North-Western Europe, with an annual yield of 12 ton ha^{-1}. In this part of Europe the annual precipitation is enough to prevent water shortage and potential production can be achieved without irrigation. In this production system crop protection measures are taken.

The second system is the production in the same region but no crop protection measures are applied, and a yield reduction as result of damage caused by pests and or diseases is accounted for. The third system is the potential production of poplar in Portugal which is estimated to be 43 ton ha^{-1} y^{-1}, but to obtain this production level irrigation is required. The fourth system is water-limited production in Portugal. Finally, a low input system is recognized; the yield of this system was set at 5 ton ha^{-1} y^{-1}, similar to the estimates of present biomass yields in Southern Europe. For all of these systems the energy inputs and labor inputs were quantified. It was shown that the irrigated system in Southern Europe was less efficient than the other systems, both energy and labor efficiencies of this system were low. The low-input system had the highest energy efficiency, but labor efficiencies were low and the net yields per hectare were too small (GJ) to be of use as an energy source. The other systems were similar in their efficiencies. It was concluded that the growing of biomass crops under irrigation is not a realistic option (due to the low efficiency). The water-limited yields must be accepted as future yield potentials for biomass crops which will lay in the order of magnitude of 12-30 ton ha^{-1} y^{-1} for the various regions within Europe. The yields on the short term will be much lower since in most parts of the EU large yield gaps exist between yield potentials and actual yields.

The labor requirements for growing biomass crops are much smaller than for growing agricultural crops. This implies that when farmers change from growing food crops to growing energy crops, a large reduction of labor requirements will occur, which may lead to loss of jobs in rural areas.

1. Introduction

The European energy supply is mainly based on combustion of fossil fuels: 23% of natural gas, 38% oil and 24% coal (Hall *et al.,* 1993). The use of these fossil fuels as major energy sources implies that large quantities of CO_2 are emitted to the atmosphere; CO_2 is a greenhouse gas and increasing CO_2 levels in the atmosphere are likely to affect global climate. The IPCC report on global change (Houghton *et al.,* 1990) estimated that under the 'business as usual scenario' (the present annual increase of CO_2 emissions is retained) the atmospheric CO_2 concentration will reach the 700 ppm level by the year 2050, which may have serious effects on global climate. Many countries have made a commitment under the United Nations Framework Convention on Climate Change to take action to reduce greenhouse gas emission.

Besides the need to reduce CO_2 emissions, the non-renewability of the fossil fuel reserves also implies a necessity to look for renewable energy sources. The present global energy use is about 300 EJ per year (1 EJ = 10^{18} J). Large differences in energy use per capita exist between industrialized countries (250 GJ y^{-1}, 1 GJ = 10^9 J) and developing countries (35 GJ y^{-1}). This means that 25% of the worlds population uses 66% of the total energy. Due to the expected increase of the population in the developing countries and increase of their economic development (which leads to increased energy use per capita) the global energy requirements will rise enormously in the coming decades. Assuming that all (present) 5 billion people on earth will use 250 GJ y^{-1} the global energy use will increase from 300 to 1250 EJ.

About half of the global energy requirements are fulfilled with oil and natural gas, the reserves of these fossil fuels are estimated on 20 10^3 EJ (WRR, 1994). Based on present energy use the oil and natural gas reserves will be depleted within 132 years and based on an energy consumption of 250 EJ per person already within 32 years. The coal reserves will last another 100 years but are also finite, so there is a strong need to develop and introduce new energy sources to sustain future energy supply.

Presently, the price of energy obtained from non-fossil energy sources like windturbines is much higher than energy from fossil fuels and the contribution of these renewables to present energy supply is therefore very limited. The depletion of presently accessible oil and gas reserves will lead to higher energy prices because oil has to be gained from less accessible oil fields. The rise in fossil fuel prices makes renewables more competing and their share in energy supply will increase. In a scenario developed by Shell (Kassler, 1994) it is even estimated that in 2060 over 50% of the global energy requirements will be obtained from renewable energy sources including wind turbines, photovoltaic cells and biomass.

The interest in use of crops for energy production is not new. Wood has always been used as an energy carrier for heating and cooking. Presently, in developing countries still 38% (= 31 EJ) of the energy need is fulfilled by biomass (including wood, crop residues and dung) (Hall *et al.,* 1993). The energy density of biomass is low: only 17 GJ ton^{-1} dry matter (compare coal: 35 GJ ton^{-1}), which makes biomass inconvenient as an energy source. Moreover, it is much easier to transport a GJ of oil than a GJ of biomass. To be of use in modern society biomass has to be converted into a more efficient energy carrier. During the oil crises in the seventies in several countries programs where started on the use of agricultural products for energy supply. Examples are the Pro Alcool program in Brazil where sugar cane was used to produce ethanol and the program in the US where maize was used as basis for ethanol production. In 1985

11.8 10^9 liters of ethanol were produced in Brazil and 3 10^9 liters in the US. Smaller programs were running in Sweden (20 10^6 liters) and France (0.2 10^6 liters). In Brazil the program was initiated at the moment that world market price for sugar cane was low and the oil price high. By producing their own energy from sugar cane, expensive oil imports could be reduced. When the oil price dropped at the end of the eighties, the interest in this subject was lost: the price of the energy produced by crops was higher than the price of energy based on fossil fuels. In 1990, e.g., the cost price of ethanol was \$20 GJ^{-1} while the price of gasoline was only \$4 GJ^{-1} (Elliott & Booth, 1990).

In 1992 a report was published on the possibilities of growing energy crops in the Netherlands (Lysen *et al.,* 1992). They calculated the net energy yield of energy crops, which was defined as the energy contents of the end product (for instance ethanol) diminished with the energy required for growing of the crop (diesel for tractors etc.), and transportation of the harvested material and the energy requirements for production of the end product. In that report various crops and conversion methods were studied like wheat and sugar beet for ethanol production, rapeseed for biodiesel, and biomass crops (poplar, Miscanthus) for electricity production. It was concluded that the use of so-called biomass crops for electricity production was the most promising option. The other options (sugar beet or wheat for ethanol, or rapeseed for biodiesel) were assessed as being not realistic because the energy involved in production of the energy carrier was large and the net output is too small. However, in the present situation electricity from biomass crops is still more expensive than the electricity based on fossil fuels. Electricity based on poplar costs 12.6 ct kWh^{-1}, based on gas 7.3 ct kWh^{-1} and on coal 7.1 ct kWh^{-1}. However, when the price of fossil fuels rises and/or CO_2 emissions are taxed, electricity from poplar can compete with fossil fuels.

The efficiency (J electricity/J solar radiation) of the process in which solar radiation is converted, via biomass, into electricity is very low (about 2%). The efficiency of photovoltaic cells is much higher: 10% under field conditions at the moment, and with a theoretical limit of 30% (Kelly, 1993), but the price per kWh is much higher: electricity from biomass costs 15 ct/kWh while electricity from solar cell costs 200 ct/kWh (Lysen *et al.,* 1992). The low efficiency of crops implies that for 'growing' electricity large areas of land are needed. In principle, these large areas are available, since due to increased productivity of agriculture the acreage of land needed for food production has declined. It has been calculated that within the EU (12) in the coming decades up to 80 million hectares of agricultural land may become available for other purposes than food production (WRR, 1992). Assuming a biomass yield of 10-15 ton ha^{-1} y^{-1}, on the 80 million ha surplus land 1600 TWh (TWh = 10^{12} Wh) of electricity may be produced, which nearly covers present annual electricity requirements of the EU(12): 1800 TWh. The cultivation of biomass crops on surplus agricultural land and the combustion of the harvested plant material for electricity generation has therefore a large potential as a renewable energy source within the EU(12).

All plants produce biomass, but not all biomass produced by plants is suitable as feedstock for electricity generation. For being useful as a biomass crop, the crop should have the following attributes (Goudriaan *et al.,* 1991):

1. A high growth rate, this growth rate should be maintained over a long period.
2. Biomass production should be above ground, harvesting below-ground products requires too much energy.
3. A low nutrient concentration in harvested product. The production of fertilizer nitrogen requires a lot of energy, which reduces the net energy yield.

4 Perennial crop, this reduces the (energy) costs of annual plowing and sowing. The crops should not be susceptible to frost.
5 It should have a long growing season starting early in spring and senesce late in autumn, nutrients should flow back to the remaining plant biomass (see 3).
6 It should be possible to harvest the biomass (relatively) dry, moisture in the product increases the transportation costs and extra energy is needed for drying.
7 The crop should not be susceptible to pathogens, the necessity to spray against fungi or pests involves the use of energy, which lowers the net energy output, and spraying of tall crops (poplars) causes technical problems.
8 It should be a strong competitor against weeds. Also for this purpose the crop should start to grow early in the season.
9 The crop should have a low water use.

The attributes mentioned above are directed to high yields and low costs for cultivation. The presently used agricultural crops are grown and selected for food production; they are generally not suitable as energy crops. Potato and sugar beet, for instance, produce their biomass below ground, the growing season of maize is short, etc. The attributes of poplar in short rotation and Miscanthus seem to fit well. It is also likely that new crops will be found with the above-mentioned features. In various countries research is done on suitability of wild growing species for biomass production (Long *et al.,* 1990)

1.1 The importance of reliable estimates of regional biomass crop yields

The suitability of biomass as an energy source is strongly determined by the yield potentials per unit of area and expected yields of these crops are key factors in evaluation studies. When food crops like wheat and sugar beet are used as an energy source the yields of these crops are easy to determine since detailed agricultural statistics exist. From these statistics (FAO, 1993; LEI, 1992) data on crop production in various regions of the world can be derived. For crops like willow, Miscanthus and poplar, which are frequently mentioned as candidate biomass crops, this regional yield information is lacking. In recent studies (Hall *et al.,* 1993; Lysen *et al.,* 1992) on possibilities of using crops as an energy source the yield of biomass crops is assumed to be the same for all regions: for instance 20 ton ha^{-1}. This yield estimate is based on yield data of a few small-scale field experiments. The contribution of these crops to the total energy requirements is calculated by multiplying available acreage of land by the estimated yield (see example before). However, yields obtained in field experiments have proven not to be reliable estimates for yields that can be obtained in practice on a larger scale; Cannell (1989) compared results of field experiments on tree growth from all over the world. It was shown that in many experiments serious inaccuracies in the set-up of the experiments existed. Major errors were poor sampling (caused by the relatively low density of trees in comparison with agricultural crops), serious bias due to border effects and poor definitions of yield (were leaves, branches and/or roots included?). An example was given where annual growth rates of 25-30 ton ha^{-1} were determined for poplar stands in small plots in Wisconsin and growth rates of only 10 ton ha^{-1} in large plots in the same area. Earlier work on growth rates of annual C3 crops done by Monteith in 1978 gave the same picture. He showed that extremely high growth rates mentioned in literature were due to errors varying from simple typing mistakes to errors in the design of the experiments (for instance absence of border rows, through which the amount of light intercepted by the crops was underestimated); Cannell (1989) therefore concludes that: 'published data on plant and tree production may be used to indicate likely differences (between sites, life forms, etc.) and upper limits of production only when several independent well-reported data sets are corroborative'. These 'several independent well-reported data sets' are lacking for most biomass crops.

The assumption that biomass yields are the same all over the world, as is done in the presently existing studies, is too simple. From agricultural crops it is known that large differences occur in crop yields obtained in various regions. The wheat yield in Spain, for instance, is only one quarter of the wheat yield obtained in The Netherlands (FAO, 1993). It is rather likely that such yield differences will occur also for biomass crops.

Since energy from biomass crops is an option for future energy supply, the present yields are of limited importance; the potentials in the nearby and distant future are of greater interest. Agricultural yields have nearly doubled over the last 30 years and a further yield increase is expected. Similar developments can be expected for biomass crops.

To obtain more insight into the possibilities of using biomass from crops as a future energy source the presently existing yield estimates have to be improved: variation in yield between regions must be accounted for and yield potentials in the future must be determined. These yield estimates should not be based on data of field experiments solely.

Questions with respect to yield potentials in the future and regional yield differences also play an important role in research into the world food supply. In agricultural research, methods have been developed to determine production possibilities of food crops in various regions of the world. Several survey studies exist on production possibilities of various food crops in different regions of the world. In these studies often various production levels are distinguished (Rabbinge & De Wit, 1989). Firstly, the potential production level in which the crop is optimally supplied with water and nutrients and free from pests, diseases and weeds. Crop growth is only determined by crop characteristics, temperature and solar radiation. The potential yield of a crop in a region is a measure for what can be obtained under optimal growing conditions in this region. In well-designed field experiments (with irrigation) this yield level can be reached.

Secondly, the so-called water-limited production level is recognized. In the water-limited situation, nutrients are in optimal supply and the crop is free of pests, diseases and weeds, but yield is limited due to the availability of water. This water-limited yield could be accepted as the attainable yield level by individual farmers, since the effects of nutrient shortages and damage done by pests and diseases can be reduced by good crop management (fertilization and application of crop protection measures). Irrigation, however, often implies investments on regional scale which cannot be established by individual farmers.

Large differences exist between various regions of the world in potential and water-limited yields (WRR, 1994), but also large variations between regions exist in the differences between actually obtained yields and the attainable yield in that region (yield gap) (WRR, 1992).

In this report a method to estimate yield potentials of biomass crops in various regions of the EU is described. This method is based on procedures used in agricultural research to determine yield potentials of agricultural crops. The knowledge on biomass crops is very limited in comparison to information available on well-studied food crops like wheat. The procedures used for agricultural crops are therefore not entirely suitable for biomass crops and adaptations in existing methods had to be made (2.1-2.3).

For all candidate biomass crops the crop-specifics information required to calculate yield potentials is collected from literature (3.2). Within the EU 58 regions are distinguished, and growing conditions for crops in these regions are quantified (3.3). Yield potentials of several candidate biomass crops are estimated for all regions under study (4.2-4.6).

In contrast to food crops, yields of biomass crops under present circumstances are not known, because these crops are not yet grown on a large scale. Since it is also of interest what yields can be expected on a short term, a method to estimate actual yields of biomass crops is developed (2.3), and the estimates of present yields of biomass crops in the 58 EU regions are given in 4.1-4.6.

With respect to energy supply the yield of dry matter is not of interest, but the net energy yield of the crop. This net yield depends on the harvested dry matter, but also on the energy required for growing the crop (energy for harvesting etc.). Five biomass production systems are compared, the (energy) input requirements of these techniques are determined (2.4) and the net yield of these systems is calculated (4.7). Finally, a comparison is made between growing food crops and growing energy crops with respect to required labor inputs and economic returns.

2. Method

2.1 Calculation of the potential production

In 1977 Monteith provided a framework to analyze crop production based on three easy measurable factors: amount of solar radiation intercepted by the crop, the efficiency for conversion of this radiation into structural plant material and the harvest index (the fraction of the total biomass that is finally harvested). Since then for various crops growing under different conditions values for light use efficiency (LUE) have been determined. Values of 1.2-1.4 g MJ^{-1} were found for both agricultural crops and trees growing under optimal growing conditions (well watered and fertilized). Under less favorable growing conditions light use efficiencies were lower. In the paper of Monteith (1977) higher values were mentioned for C4 crops growing at higher temperatures, but only for maize such higher values have actually been found (1.8 g MJ^{-1}; Kiniry *et al.,* 1989), while for other C4 crops like Sorghum and Miscanthus LUE remained below 1.4 g MJ^{-1} (Kiniry *et al.,* 1989; van der Werf *et al.,* 1993).[1)]

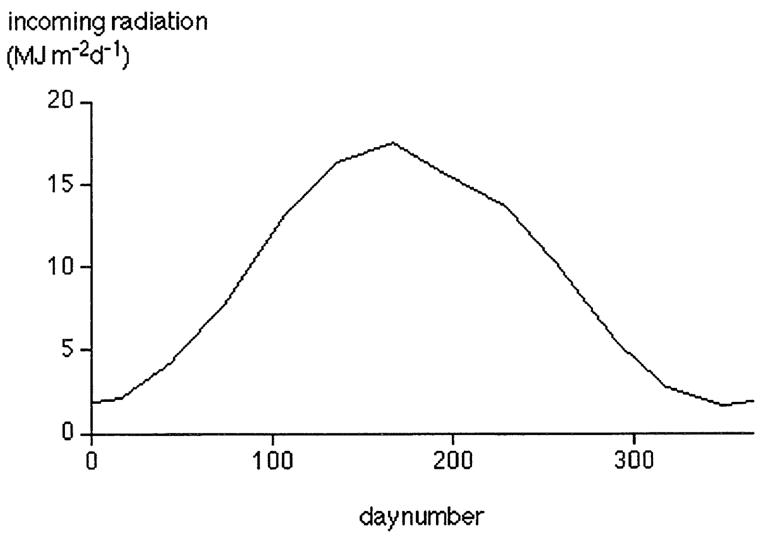

Figure 2.1 The course of the daily total incoming global radiation (MJ m^{-2} day^{-1}) during the year in Wageningen, The Netherlands

The incoming radiation varies between sites and shows a sinusoidal curve over the year (Fig. 2.1). This incoming solar radiation determines the upper limit of primary production in a region. Large differences in the amount of radiation intercepted during the growing season exist between crops. Conifers and Eucalyptus can intercept annual radiation throughout the

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1) *In the literature different definitions of LUE are used which lead to different values than the 1.4 g MJ^{-1} mentioned above. Some authors define LUE on basis of photosynthetic active radiation (PAR), which accounts for 45-50% of the total incoming short wave radiation. This definition leads to doubled LUE values (2.8 g MJ^{-1}). Further, some authors calculate LUE on basis of total biomass produced which includes roots. Assuming that the roots account for 10% of the total biomass this leads to a value of 3.1 g MJ^{-1} for a LUE. For a detailed discussion on deviations occurring in LUE values the reader is referred to Gallo et al. (1993). Here, LUE is based on intercepted global radiation and on above-ground biomass (dry matter) produced.*

year, since they keep their 'leaves' in winter; annual crops and deciduous trees only intercept radiation during a part of the year. Through multiplying the intercepted radiation by the light use efficiency, the total above-ground biomass production can be calculated. In general only a part of the plant is harvested, for instance from potato only the tubers, from sugar beet only the root and from trees only the stems. Leaves remain in the field. The fraction of the total biomass that is harvested is called the harvest index and is crop specific (0.45 for wheat and 0.7 for potato etc.).

To calculate potential production of a crop on a specific site the following information is required: the incoming radiation during the year on that site, the fraction of that radiation that is intercepted by the crop, the LUE of this crop under optimal growing conditions and its harvest index.

Since the LUE value of 1.4 g MJ^{-1} is found for a very wide range of crops grown under optimal conditions (from willow (Cannell *et al.,* 1987) to Sorghum (Kiniry *et al.,* 1989) it is not unrealistic to assume that crops presently not used will use solar energy with the same efficiency (when grown under optimal circumstances). Thus for all crops above ground production is calculated through by intercepted radiation during the growing season with 1.4 g MJ^{-1}.[2)]

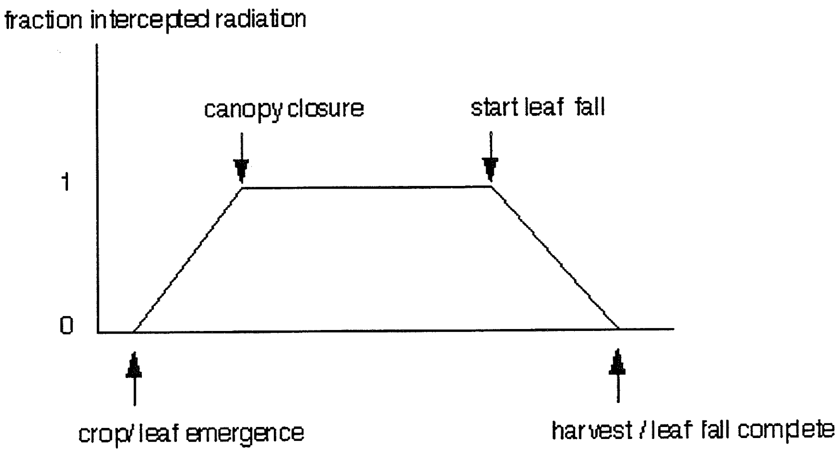

Figure 2.2 The fraction intercepted radiation of a crop during the various phases of its growing season

The amount of radiation intercepted by a crop varies between regions. So for all crops, in all regions, the fraction of the light that is intercepted by the crop has to be determined. In the growing season three phases are distinguished: from leaf appearance or crop emergence to formation of a closed canopy, the period of the season that a closed canopy exists, and the leaf fall or ripening period in which leaves are dropped or the crop dies. The fraction of the solar radiation that is intercepted in these periods is shown in Figure 2.2. Some crops (sugar beet for instance) are harvested when there is still a closed canopy; for those crops the period of leaf fall is missing. Finally, the harvest index must be known to calculate the harvested biomass. This value is crop specific and has to be derived from literature. Thus growth of a crop is defined by only 5 data: 4 data on development of the canopy and its harvest index. Determination of these data is described per crop individually in 3.2.1- 3.2.6.

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2) *The value of 1.2-1.4 g MJ^{-1} is only applicable to crops that produce mainly carbohydrates. The production of other plant materials like proteins or oils requires much more energy (Penning de Vries et al., 1974). A lower value for the LUE must be used to calculate the production potential of crops like sunflower and rapeseed. Candidate biomass crops do not produce these 'energy expensive' plant materials, so that a LUE of 1.4 g MJ^{-1} is appropriate for estimation of their yields.*

Example
Sugar beet in The Netherlands are sown in April, crop emergence is around May 1st and crop closure June 20th, the crop is harvested in November (PAGV, 1986). Assuming a linear increase of the amount of intercepted light between May 1st and June 20th and an interception of all incoming radiation from June 20th to November 1st, the total amount of intercepted light is 1928 MJ m^{-2}. Multiplication by 1.4 g MJ^{-1} leads to a total above-ground biomass of 2700 g m^{-2}. The harvest index of a sugar beet crop is 0.8, which leads to a potential yield of 21.6 ton ha^{-1} (dry matter).

2.2 Calculation of the water-limited production

In the previous paragraph a method is described to determine the potential production: the yield under optimal conditions (ample supply of water and nutrients and in the absence of pests, diseases and weeds). To maintain potential growth crops need sufficient water for transpiration. When water shortage occurs stomata are closed and photosynthesis and growth are reduced (de Wit, 1958), so that a strong correlation exits between available water and crop growth. The water required for transpiration has to be taken up by the roots. To determine the water-limited production the amount of water available for uptake by the roots has to be calculated. Here, this amount of water is calculated with a simple soil water balance. The soil is represented as a container with a given capacity (mm), water enters the container as precipitation and leaves it through uptake by the roots for transpiration and drainage (Fig. 2.3).

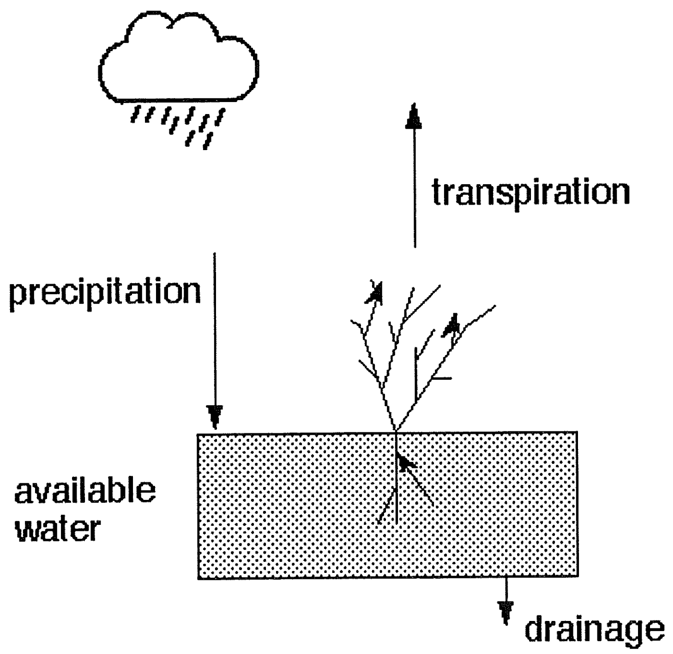

Figure 2.3 A schematic representation of the soil water balance used in the simulation model

The container represents the available water holding capacity of the profile (the amount of water between field capacity and wilting point). The capacity of the container depends on soil type and crop (rooting depth). When the container is full, all surplus water is lost (drainage out of the profile). In this concept crops have no access to groundwater tables etc.

Transpiration of a crop ($T_{pot.}$ (mm)) is determined by the weather conditions and can be calculated according the Makkink equation (Makkink, 1957):

$$T_{pot} = 0.65 \frac{s}{s+\gamma} \frac{K}{\lambda} \qquad 2.1$$

where s is the slope of the saturation water vapor temperature curve (mbar K^{-1}), γ is psychrometric constant (mbar K^{-1}), K the global radiation (J m^{-2}) and λ is the latent heat of vaporization of water (J kg^{-1}).

The transpiration calculated with eq. 2.1 is the transpiration of a well-watered closed canopy. In the part of the growing season that the crop canopy is not (yet) closed the transpiration is lower. Therefore the transpiration (T_{pot}) is multiplied by the fraction of the light that is intercepted (F, see Figure 2.2), and the actual transpiration (T_{act}) of the crop is calculated by:

$$T_{act} = T_{pot} \times F \qquad 2.2$$

The actual transpiration is calculated on a daily basis. When the amount of water required for transpiration is available in the soil profile, it is removed from the profile and growth occurs at potential rate (1.4 g MJ^{-1}). When not enough water is left in the profile to meet the transpiration requirements transpiration becomes 0 and growth stops. When water is added to the profile by precipitation growth starts again. Data on global radiation and precipitation are required to calculate water-limited production.

2.3 Calculation of the actual yields

The calculated potential and water-limited production levels are measures for future production possibilities. With respect to biomass crops it is also interesting to know what yields of these crops would be when they are grown under present conditions, i.e. the yields that farmers can expect when they start to grow biomass in the very near future with current management practices. From agricultural research it is known that a large gap exits between potential and water-limited yields and the regionally averaged yields obtained in practice (de Koning & van Diepen, 1992). This gap is caused by nutrient shortages and/or occurrence of pests and diseases. To determine the magnitude of the gap the effects of nutrient shortages and damage caused by pests and diseases on crop yields have to be quantified individually. Even for well studied agricultural crops like wheat this is not yet possible on a regional scale due to lack of information. Therefore it is unlikely that for the rather unknown biomass crops this kind of information will become available in the coming years. To obtain an indication of the magnitude of the present yield gap another method than quantifying individual yield-limiting or -reducing factors is introduced here.

The gap between potential and actual yield in a region can be interpreted as a measure for 'development' of agriculture in that region, since effects of nutrient shortages and pests and diseases can be eliminated by good management of the crop (applying fertilizers, etc.). In high-input agriculture the gap will be smaller than in low-input agriculture. For food crops the actual production can be derived from the agricultural statistics, the potential production can be calculated with the method described in previous paragraphs and the magnitude of the yield gap can be determined. Here, the ratio between actual (Y_a) and potential production (Y_p) is called the Regional Yield Factor (RYF):

$$RYF = \frac{Y_a}{Y_p} \qquad 2.3$$

Assuming that the RYF value is a measure for development of agriculture in a region, the RYF values derived from yield data from one crop can be used to estimate actual yield of other crops. This assumption is based on the idea that when farmers are able to reach certain yield levels for one crop, because nutrients are supplied sufficiently and pesticides are used to reduce damage caused by pests, it is very likely that they will apply this knowledge to other crops too. The actual yield of any other crop (Y_{ex}) can therefore be estimated by:

$$Y_{ex} = RYF \times Y_{px} \qquad 2.4$$

where RYF is determined in eq 2.3, and Y_{px} is the potential yield as calculated with the method described in previous paragraphs. The quality of this yield estimation procedure can be evaluated by comparison of actual obtained yields of agricultural crops and the estimated yields via the RYF value. This was done for two regions in The Netherlands. The RYF values were determined on the basis of the actual and potential potato yields in these regions, and these RYF values were used to estimate yields of wheat, maize and sugar beet in these regions:

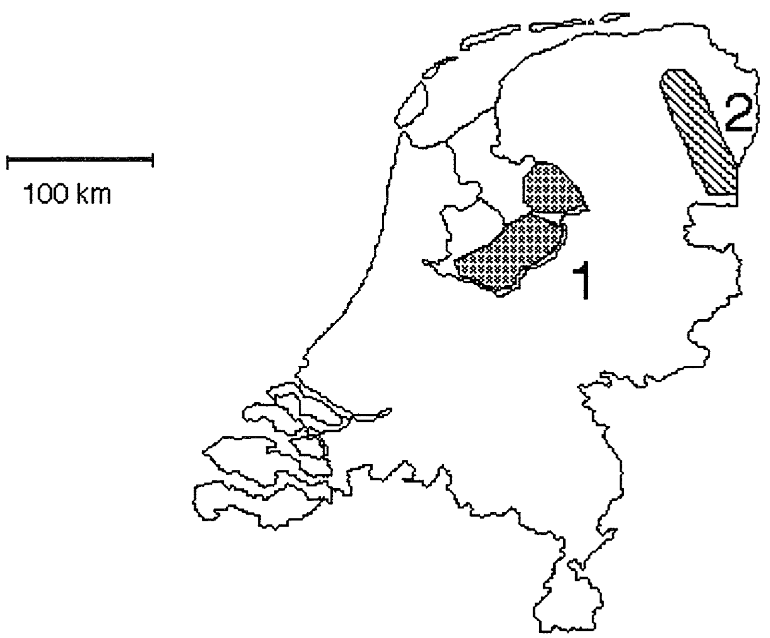

Figure 2.4 The location of the Dutch regions mentioned in the text (region 1: Flevoland, region 2: Veenkoloniën)

In The Netherlands potatoes are planted in April and the crop is harvested in September (de Jong, 1985a). The total amount of global radiation intercepted by the crop is about 1400 MJ m^{-2}, which leads to a potato yield of 15.0 ton ha^{-1} (HI of a potato crop is 0.75). In 1992 the actual potato yield in Flevopolders (region 1, Figure 2.4) was 10.6 ton ha^{-1} (dry matter) and in Veenkoloniën (region 2, Figure 2.4) it was 8.6 ton ha^{-1} (dry matter) (PAGV, 1995). Applying eq. 2.3 results in RYF for region 1 (RYF1) of 0.71 and for region 2 (RYF2) of 0.56. Potential yields of winter wheat, sugar beet and maize in The Netherlands are 10.8. 21.3 and 20.6 ton ha^{-1} (dry matter), respectively (Nonhebel, 1995). The estimates for actual yields based on these data are given in Table 2.1 together with the actually obtained yields. Table 2.1 shows that actual yields of various crops in The Netherlands can be estimated with a deviation of less than 13%. It is concluded that the method described above is a useful tool to estimate actual yields of various crops.

Table 2.1 Comparison between actual yields (Ya) of agricultural crops and estimated yields (Ye) for two different regions with RYF1 = 0.71 and RYF2 = 0.56. Deviation (dev in % of Ya) is also given. Yields (harvestable biomass) in ton dry matter ha^{-1}.

	Region 1			Region 2		
Crop	Ye	Ya	dev.	Ye	Ya	dev.
winter wheat	7.6	7.3	4%	6.1	5.4	13%
sugar beet	15.1	15.4	2%	12.3	12.0	3%
silage maize	14.6	15.4	5%	11.9	13.2	10%

The average regional yield is affected by various factors: physical ones such as climate and soil conditions, but also by factors like knowledge of the farmers and infrastructure in the region (availability of irrigation water). Here, the effects of all these different factors on yield were not determined individually, only the overall effect on yield was derived by introducing the RYF. Climate and soil conditions remain more or less constant over the years, but the other factors will change in time, so that the RYF is time-dependent. In 1960, for instance, the average wheat yield in The Netherlands was 4.25 ton ha^{-1} (dry matter) leading to a RYF of only 0.39. When this RYF value is used to determine potato yield in 1960 a value of 5.85 ton ha^{-1} (dry matter) is calculated, which is in accordance with the average potato yield for 1960 (5.68 ton ha^{-1}).

In the Netherlands crops are grown in a crop rotation system on farms, and potato, winter-wheat, sugar beet and silage maize are each grown on about 20% of the area of arable land. This implies that they are grown under more or less the same growing conditions, so that the RYF value determined from potato data is suitable to estimate yields of wheat and sugar beet. For most regions within the EU this is not the case. Some regions are more or less specialized in one crop, for instance Ile de France where nearly 50% of the arable land is used for wheat production and only 0.9% of the land for potato (de Koning & van Diepen, 1992). It is realistic to assume that farmers in this region have less experience in growing potato than growing wheat and that the RYF value determined on the basis of the wheat yields is likely to be different from the RYF value based on the potato yields in that region.

It should be realized that in some parts of Europe crops are irrigated. Yields of irrigated crops are higher than yields of the same crops under rain-fed conditions, so that the RYF values determined on the basis of irrigated yields are higher than RYF values determined on rain-fed yields.

To estimate actual yields of biomass crops in Europe, it is not possible to determine the RYF value on basis of yields of just any agricultural crop and apply this to the biomass yields. It is essential that yield data from an agricultural crop grown under more or less the same growing conditions as biomass crops are used. Here, yield data of wheat were used. Since in most regions in Europe wheat is grown on about 20% of the arable land under rain-fed conditions (de Koning & van Diepen, 1992). The data on actual wheat yields in the various European regions were also obtained from de Koning & van Diepen (1992), and refer to average yield data from 1983-1986. Since RYF values are time-dependent, the values for RYF calculated here are likely to be lower than when present yields are used. But these present yields were not yet available on a European scale.

The derivation of the phenological data of wheat required to calculate potential and water-limited yields for the various European regions is described in section 3.2.6.

Further it was decided to determine the RYF value on the basis of the water-limited production instead of on the potential production as was done in the example given above.

The water-limited yield is accepted as the attainable yield level for individual farmers. In North-Western Europe the difference between potential and water-limited production is small, so that the potential yield is nearly the same as the attainable yield. In Southern Europe, water is an important limiting factor and potential yield deviates substantially from the attainable yield (sometimes over 10 ton ha^{-1}). For biomass production it is more realistic to compare production possibilities within the EU on the basis of the water-limited production (= attainable yield) than on basis of the potential production. Thus, for all European regions the RYF values were derived from water-limited wheat yields and the actual wheat yields. The RYF values were used to estimate the actual yields of various biomass crops.

2.4 Input requirements for biomass production

2.4.1 Energy input in five different production techniques

To evaluate the possibilities of biomass crops as an energy source not the yield in ton ha^{-1} is of interest but the net-energy yield of these crops, i.e. the energy content of the harvested material minus the energy required to produce this material. This implies that the energy requirement of the cultivation has to be quantified, which is the amount of energy involved in production and application of nutrients and pesticides and energy used during planting, weeding and harvesting of the crop. These amounts depend on the production techniques used. When a crop is grown under low-input conditions the energy input is likely to be lower than under high-input production techniques, but yields in ton ha^{-1} obtained in both situations are different too. In this paragraph several production systems of biomass crops will be distinguished and net energy yield will be determined. The method used is based on de Koning *et al.* (1992), where various production techniques for agricultural crops were defined.

The systems studied are based on growing poplar species in a short rotation of 4 years. Every fourth year the crop is harvested by coppicing and is chipped at the same moment. After a harvest the crop resprouts and is harvested again four years later. It is assumed that the plantation has a total lifespan of 20 years, so that 5 harvests can take place. The yield is the same for all years, the lower yields in the starting years of the rotation that have been found in practice are ignored. The results of the simulation model for potential and water-limited production for various European regions were used as starting point.

To get an impression of the energy requirements and energy ratios of poplar production, five different systems of poplar production were compared. Firstly, the potential production of poplar in North-Western Europe, with an annual yield of 12 ton ha^{-1} (Chapter 4). In this part of Europe the annual precipitation is enough to prevent water shortage and potential production can be achieved without irrigation. In this production system crop protection measures are applied. The second system is the poplar production in the same region but no crop protection measures are applied, and a yield reduction as a result of damage done by pests and or diseases is assumed to be 20%. The yield in this system is 9.6 ton ha^{-1} y^{-1} (= 80% of potential). The third system is the potential production of poplar in Portugal which may yield 43 ton ha^{-1} y^{-1}, but to obtain this production level irrigation is required. The fourth system is water-limited production in Portugal. Finally, a low-input system is recognized; the yield of this system is estimated at 5 ton ha^{-1} y^{-1}, similar to the estimates of present biomass yields in Southern Europe (Chapter 4). It is assumed that this yield can be obtained without irrigation and use of pesticides. Since yields are low, nitrogen export is small (5000 * 0.005 = 25 kg ha^{-1}). This quantity is of the same order of magnitude as the annual N deposition due to 'acid rain', so that no extra nitrogen is required. Only in the first year some nitrogen is applied for the nitrogen in the leaves.

For each of the production systems described the energy inputs were quantified for the whole rotation of 20 years based on the assumptions mentioned below. The number of working hours required for the measures distinguished were also calculated.

2.4.2 Nutrients

The production of biomass must be sustainable. This implies that minerals in the harvested material that are removed from the site have to be replaced by fertilization, to prevent a decline of the fertility of the soil. The amount that has to be replaced depends on the yield and on the nutrient concentration in the harvested material. Here, only nitrogen is considered, since in comparison with other nutrients a large quantity is required and secondly because the energy content of nitrogen is high (production of nitrogen requires 65 MJ kg^{-1}, of phosphate 15 MJ kg^{-1} and of potassium 8.6 MJ kg^{-1}; Eriks *et al.,* 1991). The application of nitrogen has therefore a large effect on the energy balance. The energy involved in potassium and phosphate is only 10% of the energy in nitrogen.

Based on Nilson & Eckersten (1983) and Eckersten & Slapokas (1990) it is assumed that the nitrogen contents of the leaves of poplar is 4% and of the stem 0.5%. The nutrients in the roots are ignored.

In the first year of the rotation the nitrogen in the leaves is also applied to the system, the leaves are dropped at the end of the year and nitrogen in them is recycled and used for production of leaves in the following years (no losses are assumed).

Not all nitrogen applied to the soil is available to the crop. The fraction that is taken up depends on the soil type and the crop. Here, the recovery factor (the fraction of the nitrogen that is taken up by the crop) is assumed to be high and the same as grass (0.85, de Koning *et al.,* 1992), based on the fact that the rooting system remains intact after a harvest. The amount of nitrogen required to replace harvested nitrogen in the stems (N_S) is calculated with equation 2.5, in which W_S is the weight of the stems in kg dry matter ha^{-1}.

$$N_S = \frac{W_S \times 0.005}{0.85} \qquad 2.5$$

In the first year also nitrogen in the leaves (N_l) must be applied (W_l is weight of the leaves in kg dry matter ha^{-1}):

$$N_l = \frac{W_l \times 0.04}{0.85} \qquad 2.6$$

Data on the weight of the stems and the weight of the leaves are derived from the simulation results from the various regions.

It is assumed that nitrogen is applied every year. This may cause practical problems since the crop can reach heights of over 4 meters and use of presently existing machines would not be possible. The other option, application of the nitrogen once every four years after harvesting will lead to large nitrogen losses in the northwestern parts of the Europe. During the first years not all nitrogen applied can be taken up by the crop, and in the following winter period this unused nitrogen will be subject to leaching. In parts of Europe with high potential yield levels the amount of nitrogen that has to be applied becomes too high. To give an example: when potential yield (stems) is 40 ton ha^{-1} y^{-1} the amount of nitrogen that is removed from the field at harvest after 4 years is 800 kg (4*40 ton ha^{-1} at 0.5% nitrogen = 800 kg). When nitrogen in the leaves is also considered as well as the losses, the total nitrogen that has to be applied in the first year becomes nearly 2000 kg ha^{-1}. When such amounts of nitrogen are given in one application this will cause osmotic damage to the crop. Therefore, it is assumed the nitrogen is given at amounts of 300 kg ha^{-1} at a time. The energy required for a nitrogen application (diesel for the tractor) is derived from Eriks *et al.* (1991), and set at 0.25 GJ ha^{-1} per application of 300 kg. Each application requires 0.25 hours of labor per ha.

2.4.3 Crop protection measures

Two production techniques are considered: with and without the use of biocides. When no crop protection measures are applied a yield reduction of 20% is assumed, based on de Koning *et al.* (1992). In that case the assumption is made that the biomass crop is not planted as a monoculture of one clone but as a mixture of clones.

Since most biomass crops reach heights of over 4 meters the application of biocides with a conventional sprayer will cause technical problems. For application of biocides use of aircrafts might be necessary. Since no literature on energy costs of spraying from aircrafts was found, data were estimated on basis of field data. In Dutch conditions (data from: Aero Service, Lelystad) about 60 ha of agricultural crops can be sprayed from the air in about one hour. The aircraft uses about 200 liters of fuel (37 MJ l^{-1}) per hour, so on an average 3 liters per ha, which results in an energy use of 120 MJ ha^{-1}. Eriks *et al.* (1991) mention 150 MJ ha^{-1} for spraying from the ground with a tractor, thus both application methods require similar amounts of energy.

Initially it is assumed that the crop protection agent is applied 3 times per year and each time 1 kg of active ingredient is used. The production of the pesticides requires 0.2 GJ kg^{-1} and the application itself 0.2 GJ ha^{-1} and each application requires 0.5 hours (spraying with a tractor) (Pimentel, 1980; Eriks *et al.,* 1991).
In the first years after planting or after coppicing the removal of weeds is essential. It is assumed that in years 1, 5, 9, 13 and 17 weeds are removed mechanically two times; according Eriks *et al.* (1991) this requires 0.35 GJ ha^{-1} each time and 1.5 hour ha^{-1}.

2.4.4 Irrigation

In some regions of Europe the annual precipitation is not enough to achieve the potential production level. Potential yields can only be attained when extra water is applied to the crops. The amount of extra water that is required (I in mm, see eq. 2.7) can be derived from the simulation results as the difference between water used in the potential (T_{pot}, in mm) and water-limited production (T_{wl} in mm) levels. Not all irrigation water applied can be taken up by the crop and a field application efficiency of 0.6 is used based on de Koning *et al.* (1992).

$$I = \frac{T_{pot} - T_{wl}}{0.6} \qquad 2.7$$

The energy required for irrigation depends on the distances over which water has to be transported. Stanhill (1981) mentions values of 0.13-7.7 MJ m^{-3} (1 MJ m^{-3} = 10 MJ mm^{-1} ha^{-1}). The 7.7 value concerns water that has to be pumped vertically over 100 m; this value is used here. Based on de Koning *et al.* (1992) it is assumed that water is applied in quantities of 15 mm at a time and that it requires 0.5 hour ha^{-1} per irrigation.

2.4.5 Harvest

The energy required for harvest and chipping is based on data from Hall *et al.* (1993), where values of 0.6 GJ ton^{-1} dry matter are mentioned.

The (energy) costs for transportation of the harvested material to a power station are not taken into account, since they depend on the distances that have to be covered and large regional differences may occur. This should be studied on a smaller scale.

3. Input requirements of the model

3.1 The sensitivity of the model

The simulation result is determined by the values of the input parameters used. The crop data include information on phenology, harvest index and rooting depths, and site specific information as available water holding capacity of the soil and weather data. The gathering of this type of information for various regions in Europe implies a lot of work. To prevent that a lot of effort is made to collect data for which the model is not sensitive, the sensitivity of the model to various input values is studied. In this paragraph the sensitivity of the model is evaluated for a hypothetical crop with the following parameters: growing season (phenology) is defined by following data: 120-150-270-300, harvest index is 0.7, rooting depth is 1.00 meter. Two sites are studied Wageningen in The Netherlands and Avignon in southern France. The soil is assumed to have an available water holding capacity of 200 mm m^{-1}.

3.1.1 Phenology

The effect of a deviation of 15 days in various phenological data was studied; the effect is shown in Figure 3.1. The results are given in Table 3.1. The standard crop yields 20.2 ton ha^{-1} in Wageningen and 21.0 ton ha^{-1} in Avignon. Earlier start of the growing season, earlier canopy closure and later start of leaf fall and later end of growing season lead to higher yields and the opposite to lower yields. The effect of a deviation of 15 days is relatively small (less than 6%). In Wageningen there is a difference between the effect of deviations early in the growing season and the effect of deviations at the end.

Table 3.1. The effect of a deviation of 15 days in phenological data on simulated water-limited yield (ton ha^{-1}) for two sites in Europe: Wageningen and Avignon (Dev, is deviation in percentage from the standard)

Growing season				Yield Wag.	Dev.	Yield Avig.	Dev.
120	150	270	300	20.2		21.0	
105	150	270	300	21.3	6	22.1	5
135	150	270	300	19.0	-6	20.2	-3
120	135	270	300	21.3	6	21.9	5
120	165	270	300	18.9	-6	20.6	-2
120	150	255	300	19.6	-3	20.1	-4
120	150	285	300	20.6	2	21.8	4
120	150	270	285	19.7	-2	20.2	-4
120	150	270	315	20.5	2	21.7	3

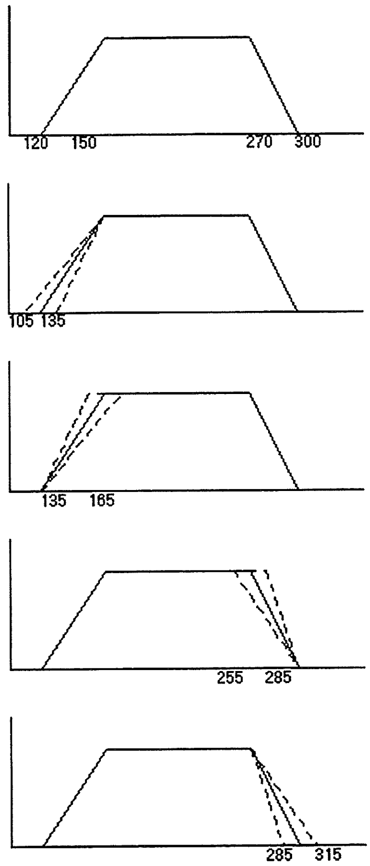

Figure 3.1 Light interception during the growing season and the effect of a deviation of 15 days in the start or end of various phases

3.1.2 Harvest index (HI)

The harvest index is the fraction of the above-ground biomass that is harvested. The simulated above-ground biomass is multiplied by this fraction to determine the yield; therefore deviations in this fraction have a large effect on simulated yield as is shown in Table 3.2: a 10% deviation in HI results in a 10% deviation in simulation result.

Table 3.2 The effect of a 10% deviation in harvest index on simulated yields of the standard crop with an above-ground biomass production of 28.8 ton ha^{-1}

Harvest index	Yield	Deviation
0.7	7	
0.77	22.2	10%
0.63	18.1	- 10%

3.1.3 Rooting depth/available water holding capacity

The amount of water in the soil that is available for uptake by the crop is determined by the rooting depth of the crop and by the available water holding capacity of the soil (AWC). On a sandy soil AWC can be less than 200 mm m^{-1}, while on a clay soil it can be 350 mm m^{-1}. A crop with a rooting depth of 50 cm has 100 mm available on a sandy soil and 175 on a clay soil. For the model there is no difference whether water comes from a deep profile with a low AWC or from a shallow profile and a high AWC. In this paragraph the effect of differences in available water (AW) as a whole is studied. Results are given in Table 3.3. In Southern Europe the effects of the deviation in the AW value used are large, while in Wageningen no effect on simulated yields is observed.

Table 3.3 The effect of deviations in available water (AW in mm) to the crop on simulated water-limited yields (ton ha^{-1}) for two sites (Dev. = deviation (%) from 200 mm crop)

AW	Yield Wageningen	Dev.	Yield Avignon	Dev.
200	20.2	0	21.0	
100	20.2	0	15.9	-24%
300	20.2	0	26.0	24%

3.1.4 Climatic data

The amount of incoming radiation during the growing season of a crop differs from year to year, and so does the amount of precipitation. This implies that the simulated yield differs from one year to another. In this study we are not interested in the yield in a particular year, but in the average yield over several years. This average yield can be obtained via two routes: through simulation of the yields in several years by using the weather data of these years and average the obtained yields, or through using averaged weather data over the years under study and simulate the yield for this average weather situation. From literature it is known that both ways can lead to different results (Nonhebel, 1994). The simulated yields for the standard crop using daily weather data from Wageningen and Avignon over 20-30 years are given in Figure 3.2. Large yield differences are observed between years. The average yield and the yield simulated with climatic data (monthly averages over the years studied) are given In Table 3.4.

Table 3.4 The average yield (ton ha^{-1}) simulated with daily weather data over several years and the yield simulated with the climatic data for Wageningen and Avignon

Data	Wageningen	Avignon
Weather data	20.2	22.7
Climatic data	20.2	21.0

For Wageningen, the use of average weather data (climatic data) does not result in a different simulation result, for Avignon climatic data resulted in a yield decline of 1.7 ton ha^{-1} (7.5%). The use of climatic data implies an enormous reduction in the amount of data required to run the model. Daily data over 20 years involves a data set of 20*365 = 7300 values per variable, while the data set with climatic data only consists of 12 values per variable.

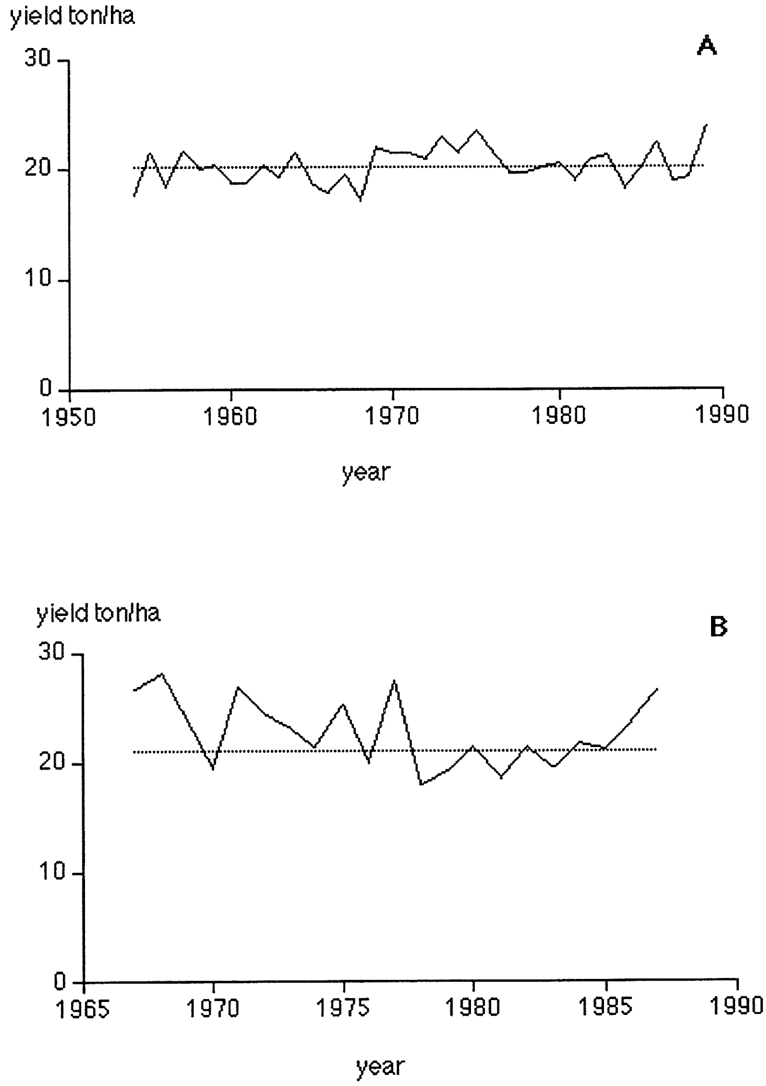

Figure 3.2 The simulated water-limited yields of the standard crop when daily data and climatic data (dotted line) of Wageningen (A) or Avignon (B) were used as input

3.2 Determination crop specific information

As mentioned in paragraph 2.1, a crop is defined by 5 parameters. Four determining the growing season and a value for the harvest index. The harvest index of a crop is crop-specific and is assumed to be the same for all regions. Growing season, however, differs between regions. The leaf appearance of the poplar clone I214 occurs at the end of April in The Netherlands, in the beginning of April in Spain and at the end of March in Hungary (van Haaren, 1987; Tóth & Erdös, 1988; Padro Simarro, 1993). In Italy Miscanthus starts to grow in the first half of April, while in Ireland it starts only in the beginning of May (Pers. comm. E. van den Heuvel, European Miscanthus Network). This implies that the growing season parameters of a crop are different in the various regions. Since most of the biomass crops are not yet grown in the regions under study, this information cannot be obtained from field experiments. Further large differences in start of the growing season have been found between years; in a cold spring leaf appearance can be 3 weeks later than in a warm one (van Haaren, 1987). Available data on growing seasons of biomass crops only refer to one or two years. When these data are used to define growing seasons in various regions it is possible that leaf appearance in a cold spring in France is compared with leaf appearance information obtained in a warm spring in Scotland, which would give a unrealistic picture of the growing seasons. Here, information on the 'average' growing seasons are required. Therefore, for each crop growing season was defined as a function of air temperature based on information from literature. Since air temperatures in various regions are known, the growing season of the crop in each region can be calculated.

Crops frequently mentioned as potential biomass crops are studied: willow, poplar, Miscanthus, Eucalyptus and Sorghum.

The water available to the crop differs from site to site, since large variation in soil types exist (with different values for the AWC), but also large differences in depth of the profile occur within short distances. In this study it is assumed that on all sites for all crops available water was 200 mm (3.1.3). On individual sites the situation can deviate considerably from this value, in northern parts of Europe this deviation has no effect on simulated water-limited production because water is not a limiting factor, in southern parts of Europe considerable deviations in simulation results can be expected.

3.2.1 Willow spp.

Willow spp. are grown as short rotation coppice in the northern regions of Europe (United Kingdom (Porter *et al.,* 1993), Ireland (McElroy & Dawson, 1986) and Sweden (Christersson *et al.,* 1993). The crop is harvested every fourth year by cutting the above-ground biomass in the winter period (only stem and branches are harvested, leaves are not available in this part of the year). The crop resprouts after coppicing and is harvested again 4 years later. Several willow clones are in use (Sennerby-Forsse, 1985). Research is going on to optimize planting densities and harvesting rotation (Willebrand & Verwijst, 1993). Willow species and varieties show differences with respect to development of the crop canopy; differences of several weeks in leaf emergence and leaf fall have been observed.

Therefore a standard willow crop was defined on the basis of data from Porter *et al.* (1993), Cannell *et al.* (1987), Nilson & Eckersten (1983) and Elowson & Rytter (1988). Light interception starts at temperature sum 150 Cd, calculated from January 1st onwards with base temperature of 5°C. Sixty days after the start of the growing season a closed canopy is formed, leaf fall starts on September 21st (day length of 12 hours) and on day 300 (November 1st) the crop has lost all leaves. The harvest index is assumed to be 0.72, based on data from Cannell *et al.* (1987).

A light use efficiency of 1.38 g MJ^{-1} has been found by Cannell *et al.* (1987), which agrees with the assumptions made in Chapter 2.

3.2.2 Poplar spp.

Poplar is the most-investigated biomass crop. It is mainly grown for the paper industry. Detailed experiments have been conducted in the United States (Ceulemans *et al.*, 1992a), United Kingdom (Milne *et al.*, 1992), Belgium (Ceulemans *et al.*, 1992b), France (Barigah *et al.*, 1994) and Spain (Ciria *et al.*, 1994). Generally, rotation length of the crop is 4-7 years and a planting density of 2500-4000 per hectare is used, but trials with annually harvested woodgrass (planting density of 25000 per hectare; DeBell *et al.*, 1993) also exist.

Several species and clones are used and large differences in start of leaf growth (20-30 days) are found with respect to leaf area development etc. (van Haaren, 1987; Ceulemans *et al.*, 1992a). In comparison with most willow species light interception starts later in the year and stops earlier (Cannell *et al.*, 1988).

Based on canopy development data from several sites in the world (Landsberg & Wright, 1989; Rogers *et al.*, 1989; Ceulemans *et al.*, 1992a; Cannell *et al.*, 1988; Ceulemans *et al.*, 1992b) a standard poplar crop is defined: light interception starts at temperature sum 200 Cd (from January 1st onwards with base temperature of 5°C). Sixty days after the start of the growing season a closed canopy is formed, defoliation starts at September 1st and trees have lost all leaves by October 1st. Harvest index is assumed to be 0.70, based on data from Cannell *et al.* (1998), Ceulemans *et al.* (1992b) and Impens *et al.* (1990).

Several authors determined light use efficiency values of poplar clones. Values of 1.0 -1.5 g MJ^{-1} have been found for above-ground biomass (Cannell *et al.*, 1988; Ceulemans *et al.*, 1992b) which agree with the assumptions made in Chapter 2.

3.2.3 Miscanthus (*Miscanthus sinensis* var. Giganthus)

Miscanthus is a perennial C4 crop which can be used for fiber and fuel production. It is not yet grown on a farm scale and only data from a limited number of field experiments exists.
The crop is planted at a density of 10000 plants ha^{-1} in spring. In the first growing season it remains low and produces mainly leaves, in the second year stems are formed and the crop reaches heights of 3 meters. In the third year it reaches full production (Darwinkel *et al.*, 1994). The crop is sensitive to frost and the above-ground biomass dies when temperatures drop below zero. In cold winters sometimes even roots are affected by the low temperatures and the whole plantation is lost. The growing season runs roughly from the last frost in spring until first frost in autumn.

The above-ground biomass dies at the first frost in autumn and remains in the field during the winter period. In this period the stems dry, so that the biomass harvested in spring has a low moisture content (15%; van der Werf *et al.*, 1993). But during the winter period leaves and stem tops are lost, they break in windy periods, so that dry matter harvested in spring is less than the standing biomass in October when the crop died. It is not yet known what is more profitable a high (wet) yield in autumn with large costs involved to dry the product or a lower yield with lower drying costs when the crop is harvested in spring. Here, it is assumed that the crop is harvested in spring and that at that moment only stems are left which account for 73% of the above-ground biomass produced in the previous growing season (harvest index = 0.73) (van der Werf *et al.*, 1993).

It is assumed that light interception starts as soon air temperature rises above 13°C, a closed canopy is formed 650 Cd after the start of the growing season (based on data from van der Werf *et al.,* 1993) (Tbase is 0°C). At day 300 growth and interception stop.

LUE values of 2.6 g MJ^{-1}, based on PAR, have been found (= 1.3 g MJ^{-1} based on global radiation) in The Netherlands (van der Werf *et al.,* 1993), which agree with values assumed in Chapter 2.

3.2.4 Sweet Sorghum (*Sorghum bicolor* L. Moench)

Sorghum is an annual C4 crop, mainly grown in tropical climates. For detailed information on growing practices the reader is referred to Purseglove (1972). It reaches heights of 0.5 -6.0 meters.

Various authors mention Sweet Sorghum as a potential energy crop, based on the fact that its biomass can be transformed into ethanol, fiber and electricity. In Europe some experiments with Sweet Sorghum have been conducted in Italy (Petrini *et al.,* 1993; Belletti *et al.,* 1991) and southern France (Kiniry *et al.,* 1989). In the Po valley Sweet Sorghum yields of 13-19 ton ha^{-1} dry matter were obtained under rain-fed conditions.

Although high growth rates are expected since this C4 crop is growing in warm regions, the measured values of LUE are not high (1.4 g MJ^{-1} by Rachidi *et al.* (1993) and Kiniry *et al.,* (1989); 1.1 g MJ^{-1} by Ferraris & Charles Edward (1986) and 1.2 g MJ^{-1} by Muchow & Coates (1986)). All authors mention that they expected higher values based on Monteith (1978) but that differences between C3 and C4 did not appear to be as distinct as previously thought. The LUE values mentioned in the literature are determined under high temperatures (average day temperature over 20°C), under cooler circumstances values may be lower.

With respect to the phenology of the crop, it is mentioned that the crop requires a temperature sum of 1500-2000 Cd (base 10°C) to finish its growing cycle (Petrini *et al.,* 1993; van Heemst 1988; Muchow & Coates, 1986).

The following boundary conditions were assumed: average temperature during the growing season must be above 20°C and growing season must be long enough to reach a temperature sum of 1500 Cd (base 10°C). This implies that in most parts of Europe climatic conditions are not suitable for growing Sorghum; only in southern France, Italy, Greece, and most parts of Spain and Portugal temperatures are high enough for growing Sorghum.

In the regions suitable for growing Sweet Sorghum the following growing season was assumed: sowing of the crop takes place when average temperature rises above 15°C, start of the light interception is 30 days after sowing; 30 days after start of the interception a closed canopy is formed and the crop is harvested 120 days after sowing.

Harvest index is assumed to be 0.95 (identical to the harvest index of silage maize (de Jong, 1985b)).

3.2.5 Eucalyptus spp.

Eucalyptus spp. originate from Australia and currently about 500 species are recognized (Chipendale, 1988). Eucalyptus was introduced in Europe in the middle of the last century and it is mainly grown for the paper and pulp industry in short rotations (Pereira *et al.,* 1989). It is an evergreen tree, so that its growth potentials are higher than these of deciduous trees and annual crops. However, Eucalyptus spp. are susceptible to frost and their growing regions are limited to southern parts of Europe (Portugal, Spain, Italy and Greece). Research is going on with respect to freezing mechanisms and frost hardiness of various Eucalyptus species (Scarascia-Mugnozza *et al.,* 1989; Hallam *et al.,* 1989). Since it is an evergreen tree, light interception occurs year-round and growing seasons in various regions do not have to be determined. However, since the tree is susceptible to frost, the regions in which Eucalyptus may grow have to be determined. For some species temperatures just below freezing point can be lethal and care must be taken in definition of suitable regions. The available climatic data are limited to average minimum temperatures over several years and it is known that daily values can deviate considerably from this average value. It was therefore decided that only regions in which average minimum temperatures remain above 4°C are suitable for growing Eucalyptus. The harvest index was assumed to be 0.7, based on data from Pereira & Miranda (1992). Pereira *et al.* (1992) determined a light use efficiency of 0.8 g MJ^{-1}.

3.2.6 Wheat

In this study yields of wheat are simulated to determine the value of the Regional Yield Factor (RYF). The data on the growing season were obtained from Boons-Prins *et al.* (1993). In their report flowering date and date of maturity of wheat in various regions of the EU are given. Based on information on LAI, development data during the growing season of wheat are also given in that report. It is assumed that light interception of wheat starts 90 days before flowering, that a closed canopy is formed 30 days before flowering and that this closed canopy remains until 30 days before maturity and light interception is 0 at maturity. The harvest index of wheat is 0.45 (de Jong, 1986).

3.3 Regions studied and weather stations used

In section 3.1.4 it has been shown that the use of climatic data instead of daily weather data had hardly any effect on the simulated output of the model so that climatic data could be used as input in the model. The big advantage of being able to use climatic data is that the number of locations from which these data are available is much larger than the number of sites from which daily data are available. It was therefore possible to run the model for a very large number of locations in the EU.

Within the EU (12) 58 administrative regions are recognized (Fig. 3.3). These are the so-called NUTS1 regions and from these regions average yield data can be obtained from agricultural statistics. Climatic data from a weather station located in each of the regions of interest were used as input in the model. The regions and stations used are given in Table 3.5. The data are obtained from the weather data set of the AB-Met database (Stol, 1994) (in this data set daily data for several years are only available from 6 locations in Europe). From all stations climatic monthly averages were available for minimum and maximum air temperatures, daily total global radiation and average monthly precipitation (1960-1980).

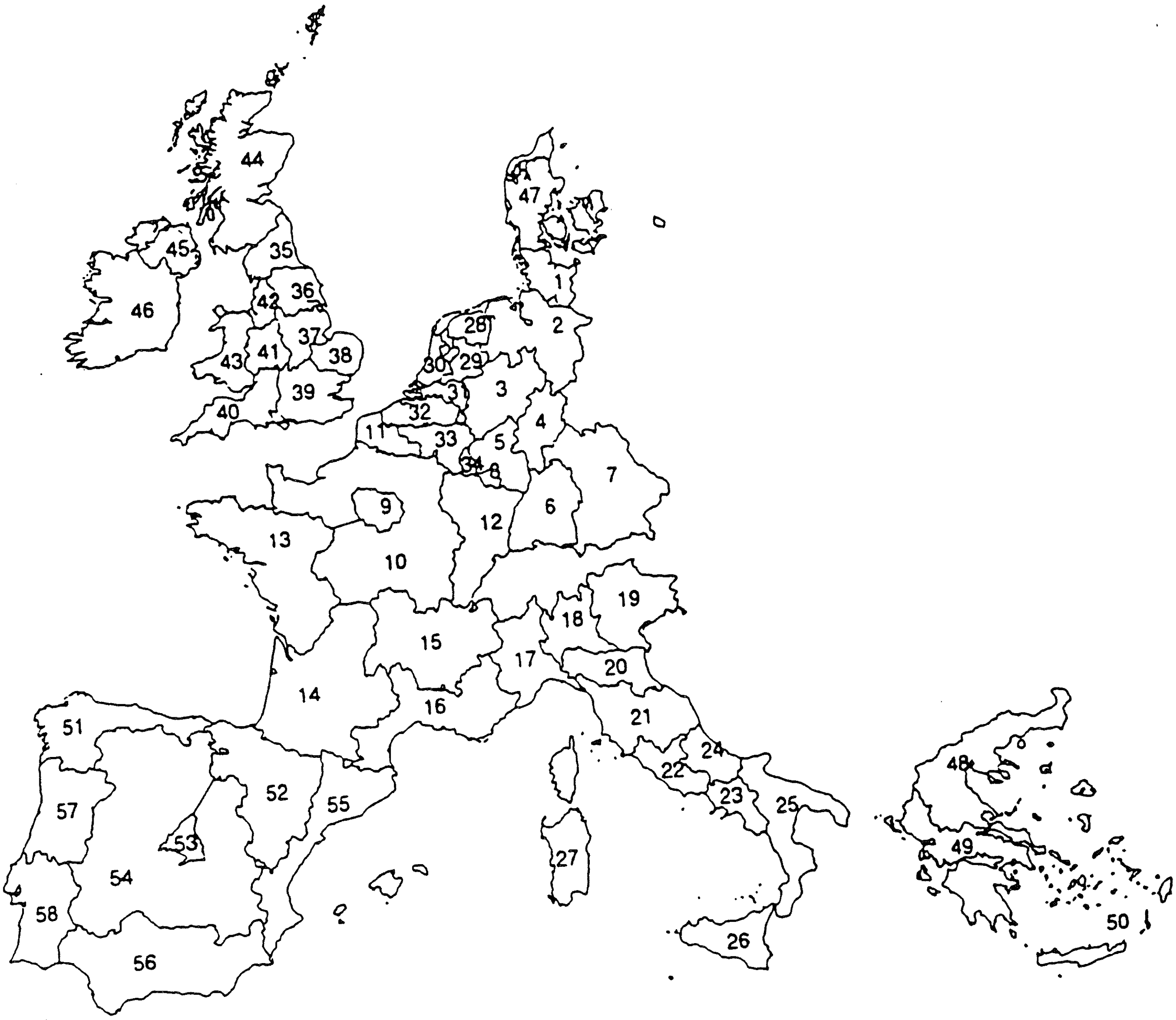

Figure 3.3 NUTS1 regions under study (for names of the regions see Table 3.5)

Table 3.5 Weather stations used in various European regions (NUTS-1 regions)

NUTS-1 Nr	Region	Weather station	Latitude	Longitude	Altitude (m)
1	Schleswig-Holstein	Schleswig	54 32 N	09 33 E	48
2	Niedersachsen	Hamburg	53 38 N	10 00 E	16
3	Nordrhein-Westfalen	Essen	51 24 N	06 58 E	161
4	Hessen	Frankfurt	50 07 N	08 39 E	103
5	Rheinland-Pfalz	Trier	49 45 N	06 40 E	265
6	Baden-Württemberg	Stuttgart	48 50 N	09 12 E	311
7	Bayern	Munich/Riem	40 08 N	11 42 E	529
8	Saarland	Trier	49 45 N	06 40 E	265
9	Ile de France	Paris/Le Bourget	48 58 N	02 27 E	65
10	Bassin-Parisien	Orleans	47 59 N	01 45 E	125
11	Nord Pas de Calais	Lille	50 34 N	03 06 E	44
12	Est	Nancy/Essey	48 41 N	06 13 E	217
13	Ouest	Rennes	48 04 N	01 43 W	35
14	Sud-Ouest	Bordeaux/Merignac	44 50 N	00 42 W	61
15	Centre-Est	Lyon/Bron	45 43 N	04 57 E	201
16	Mediterranee	Nimes/Courbessac	43 52 N	04 24 E	62
17	Nord-Ovest	Torino	45 05 N	07 40 E	238
18	Lombardia	Milano	45 28 N	09 11 E	121
19	Nord-Est	Padova	45 24 N	10 51 E	14
20	Emilia-Romagna	Bologna	44 30 N	11 21 E	60
21	Centro	Perugia	43 07 N	12 21 E	493
22	Lazio	Roma	41 54 N	12 29 E	17
23	Campania	Napoli	40 53 N	14 17 E	110
24	Abruzzi-Molise	Pescara	42 28 N	14 12 E	13
25	Sud	Taranto	40 28 N	17 14 E	15
26	Sicilia	Palermo	38 06 N	13 19 E	31
27	Sardegna	Cagliari-Elmas	39 15 N	09 03 E	7
28	Noord Nederland	Wageningen	51 58 N	05 40 E	7
29	Oost Nederland	Wageningen	51 58 N	05 40 E	7
30	West Nederland	Wageningen	51 58 N	05 40 E	7
31	Zuid Nederland	Wageningen	51 58 N	05 40 E	7
32	Vlaams-Gewest	Brussels	50 48 N	04 21 E	100
33	Region-Wallone	Brussels	50 48 N	04 21 E	100
34	Luxembourg	Luxembourg	49 37 N	06 03 E	330
35	North	Tynemouth	55 01 N	01 25 W	33
36	Yorkshire/Humberside	Kingston upon Hull	53 45 N	00 16 W	2
37	East-Midlands	Waddington	53 10 N	00 31 W	70
38	East-Anglia	Cromer	52 56 N	01 17 E	54
39	South-East	London/Gatwick Arpt	51 09 N	00 11 W	62
40	South-West	Plymouth/Mountbatte	50 21 N	04 07 W	27
41	West-Midlands	Birmingham Airport	52 27 N	01 44 W	80
42	North-West	Manchester Intl	53 21 N	02 16 W	77
43	Wales	Cardiff-Wales Airport	51 24 N	03 21 W	67
44	Scotland	Edinburgh	56 00 N	03 24 W	35

Table 3.5 Continued

NUTS-1 Nr	Region	Weather station	Latitude	Longitude	Altitude (m)
45	Northern Ireland	Belfast/Aldergrove	54 39 N	06 13 W	81
46	Ireland	Shannon Airport	52 42 N	08 55 W	20
47	Danmark	Tylstrup	57 11 N	09 57 E	13
48	Voreia-Ellada	Thessaloniki	40 37 N	22 57 E	25
49	Kentriki-Ellada	Patrai	38 15 N	21 44 E	1
50	Nisia	Hiraklion	35 20 N	25 11 E	39
51	Noroeste	Orense	42 20 N	07 52 W	127
52	Noreste	Zaragoza	41 40 N	01 01 W	258
53	Madrid	Madrid	40 24 N	03 42 E	657
54	Centro	Salamanca	40 58 N	05 40 W	805
55	Este	Valencia	39 29 N	00 23 W	13
56	Sur	Sevilla	37 24 N	06 00 W	30
57	Norte do Continente	Porto	41 08 N	08 36 W	95
58	Sul do Continente	Beja	38 01 N	07 52 W	247

4. Results

4.1 Regional Yield Factors

The RYF values based on average and simulated wheat yields from 1983-1986 are given in Figure 4.1. Large differences in RYF values were observed. Regions 44 and 29 had values over 0.6, while for all other regions much lower values were calculated. In Portugal, parts of Spain, Sardine, and Southern Italy the RYF values were even below 0.2. This implies that presently only 20% of the water-limited yields are actually achieved in these regions.

4.2 Willow

The simulated potential yields for the standard willow crop are given in Figure 4.2. Large differences in potential yields were simulated between various regions in Europe. The lowest yield of 12 ton ha^{-1} was simulated for Scotland (region 44) and the highest yield of 45 ton ha^{-1} in region 57 (Northern Portugal). For the United Kingdom, Benelux, Germany and Denmark simulated yields lay between 10-20 ton ha^{-1}. For France, Cornwall, Northern Italy and central Spain yield potentials varied between 20 and 30 ton ha^{-1}. In Southern France, large parts of Spain and Greece and Southern Italy potentials lay between 30-40 ton ha^{-1} and in Southern Spain, Portugal, Sicily and Greece between 40 and 50 ton ha^{-1}.

The differences in simulated water-limited yields between various European regions were smaller than the differences in potential yield and varied between 12 and 31 ton ha^{-1} (Fig. 4.3. In the northern parts of Europe there was no difference between potential and water-limited yields. In Southern Europe a large yield reduction (sometimes even 15 ton ha^{-1}) in comparison with the potential production was simulated.

The estimated actual production of the standard willow crop showed a quite different picture (Fig. 4.4): in general yields were between 6-10 ton ha^{-1}, in some regions in Southern Europe even below 6 ton ha^{-1}. Only for region 10 the simulated actual willow yield was higher than 10 ton ha^{-1}: 11.5 ton ha^{-1}.

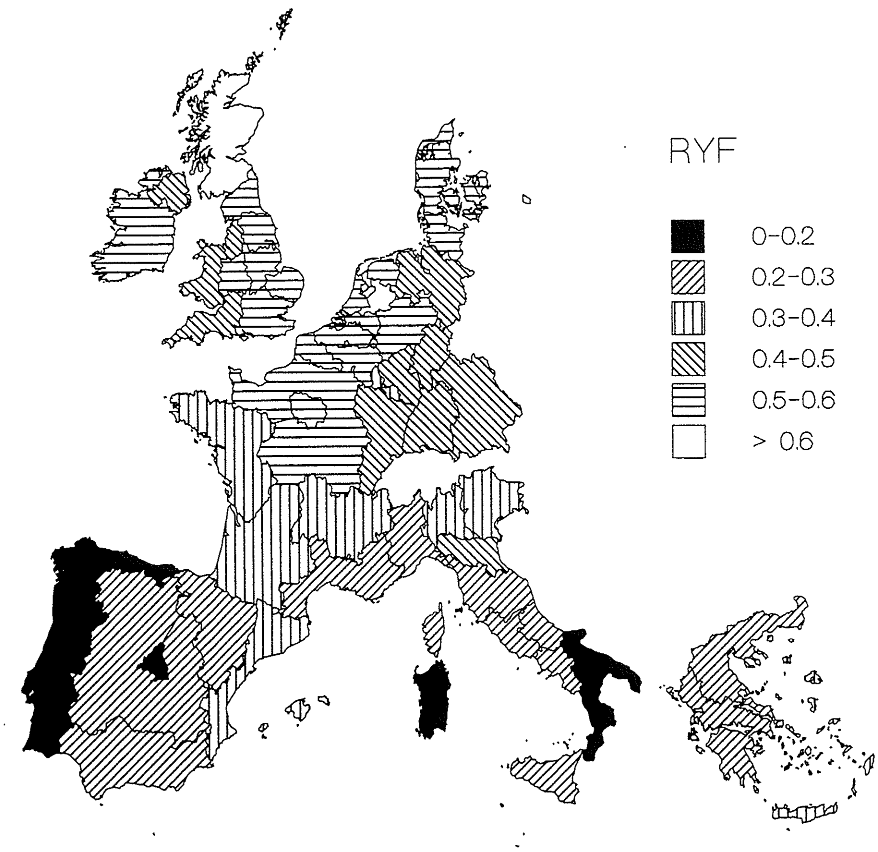

Figure 4.1 RYF values in the various European regions

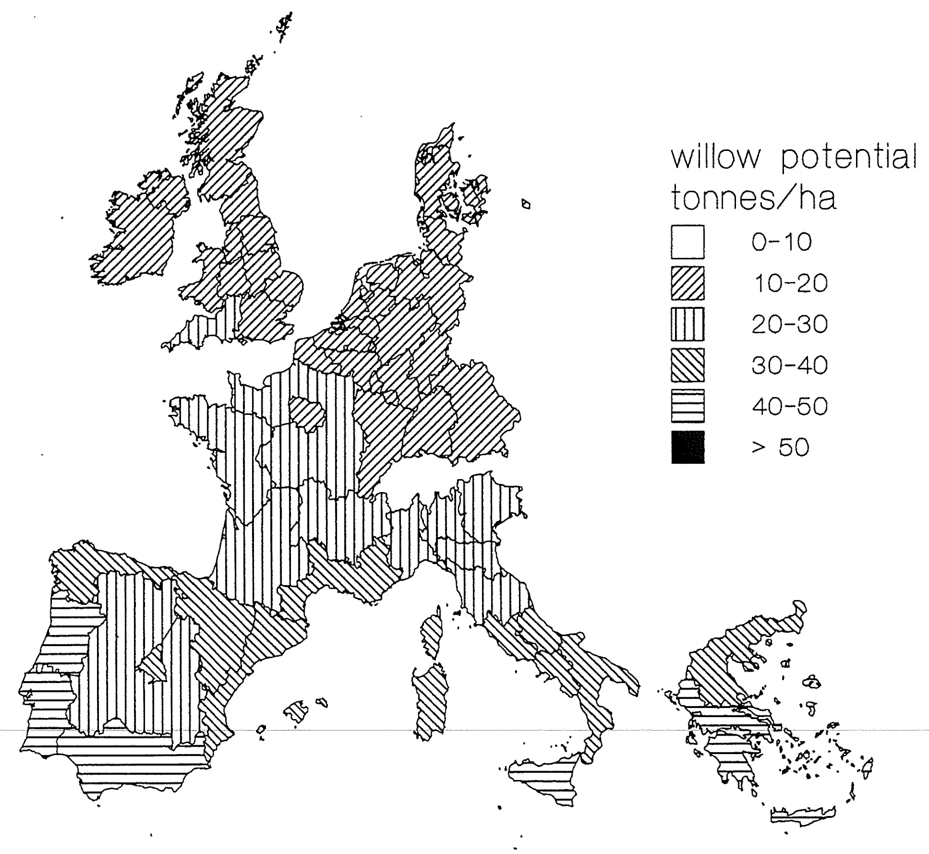

Figure 4.2 Simulated potential willow yield (ton ha^{-1} y^{-1}) in various regions of the EU

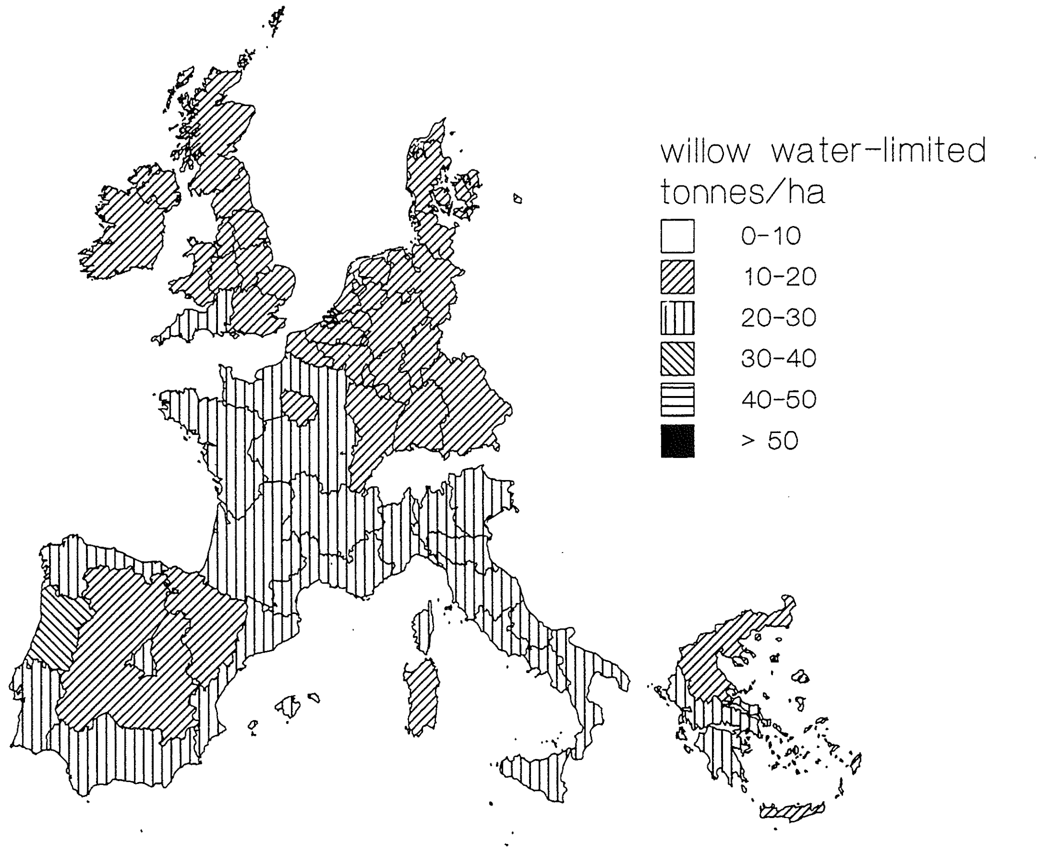

Figure 4.3 Simulated water-limited willow yield (ton ha^{-1} y^{-1}) in various regions of the EU

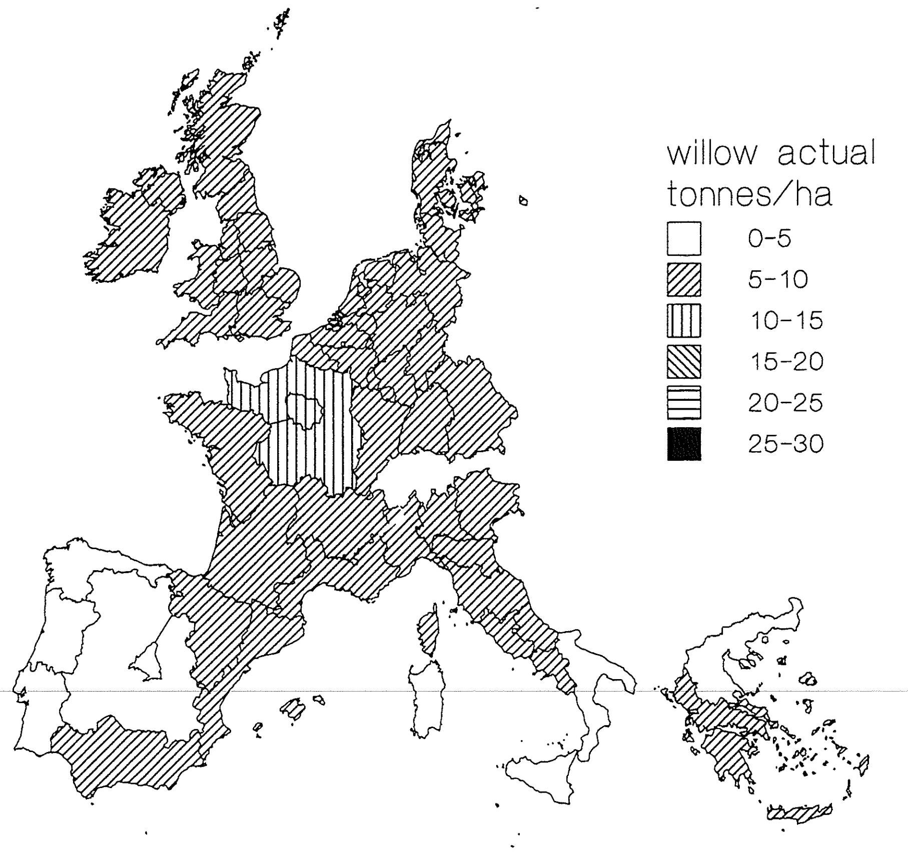

Figure 4.4 Estimated actual willow yield (ton ha^{-1} y^{-1}) in various regions of the EU

4.3 Poplar

In general potential poplar yields were lower than yields calculated for willow (Fig. 4.5). Lowest poplar yield was calculated for Scotland (9.8 ton ha^{-1}) and highest in region 57: 43 ton ha^{-1}. In comparison with the potential production of willow the border of the various yield classes moved 1-2 regions to the south (cf. Figure 4.2).

For water-limited yield similar effects as for willow were found: in northern parts of Europe there was no difference between potential and water-limited production, while in Southern Europe a yield reduction by 10-15 ton ha^{-1} was simulated (Fig. 4.6). In region 50 (Nisia) simulated yield dropped from 43 to 17 ton ha^{-1} due to water shortage.

The estimated actual production gave the same picture as was found for willow. In Southern Italy actual yield even dropped below the 5 ton ha^{-1} level (Fig. 4.7).

4.4 Miscanthus

Potential Miscanthus yields varied between 10.6 ton ha^{-1} in Scotland and 51.3 in region 50 (Nisia) (Fig. 4.8). The north to south gradient in yields was not as distinct as was found for willow and poplar (Figs. 4.2 and 4.6). Two regions in Germany and the Po valley in Italy had yields in different yield classes than their neighboring regions. These differences were caused by the choice of the category classes. In Germany simulated yields in regions 5 and 7 were 19.4 and 18.9 ton ha^{-1} while for region 6 20.4 ton ha^{-1} was calculated. A similar effect occurred in Italy (see also appendix I). Yield levels of Miscanthus were of the same order of magnitude as simulated for willow, and thus higher than those of poplar.

The simulated water-limited production gave similar results as found for willow and poplar: in Northern Europe there was no difference between potential and water-limited yields, while for Greece a yield reduction of 30 ton ha^{-1} due to water shortage was simulated (Fig. 4.9).

The actual yields for the larger part of Europe were between 5-10 ton ha^{-1} (Fig. 4.10). For some regions, such as parts of the Netherlands, Belgium, France and Italy, yields over 10 ton ha^{-1} were calculated.

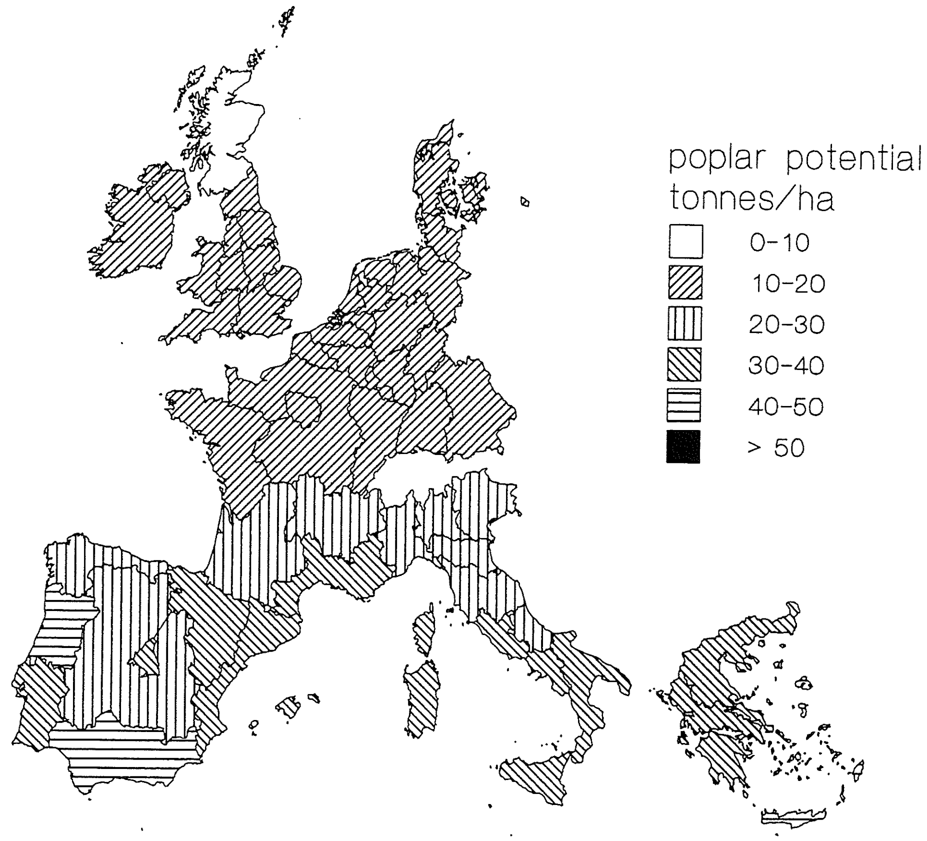

Figure 4.5 Simulated potential poplar yield (ton ha^{-1} y^{-1}) in various regions of the EU

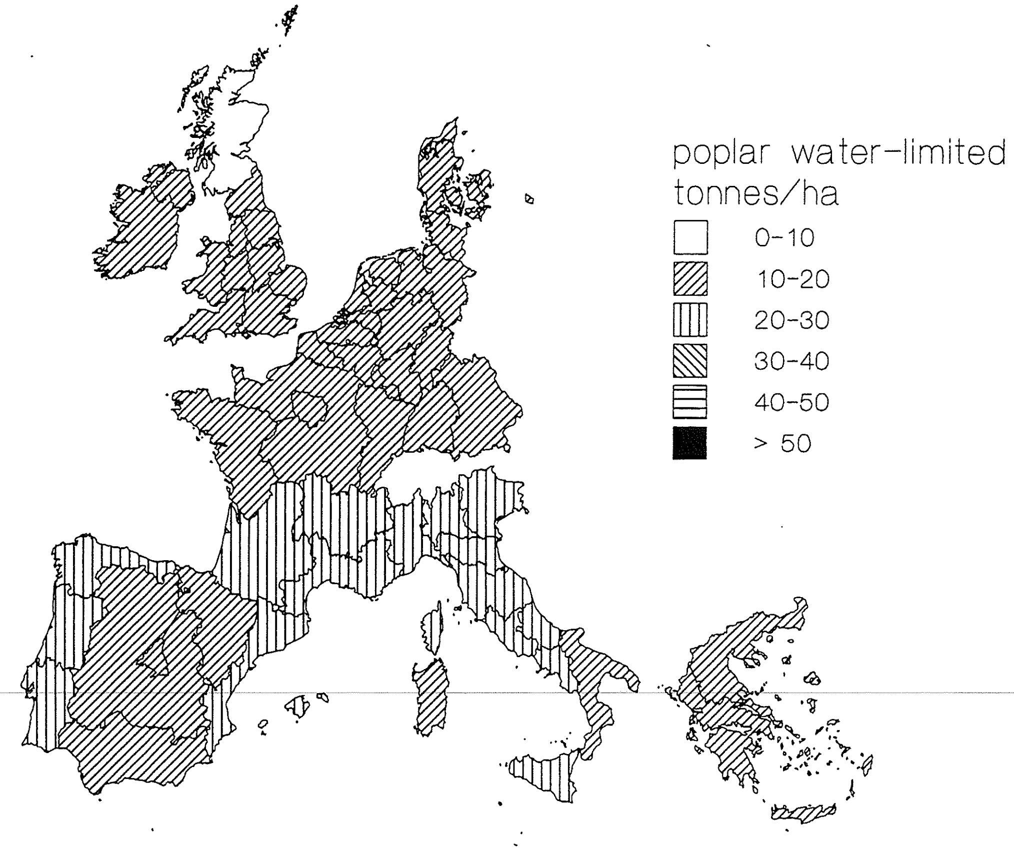

Figure 4.6 Simulated water-limited poplar yield (ton ha^{-1} y^{-1}) in various regions of the EU

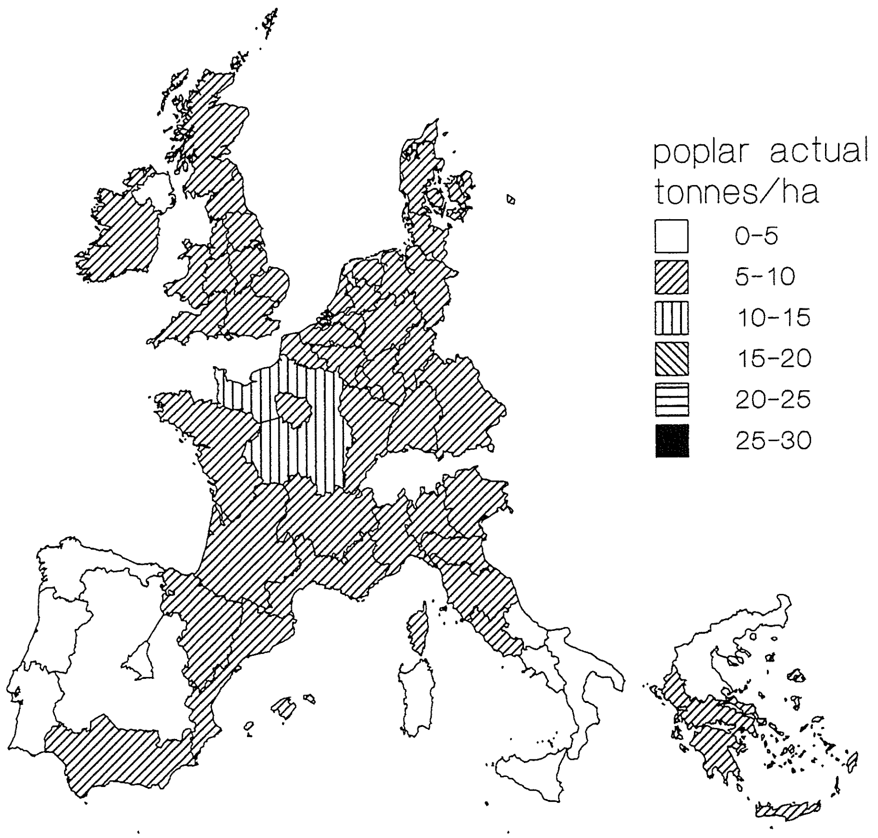

Figure 4.7 Estimated actual poplar yield (ton ha^{-1} y^{-1}) in various regions of the EU

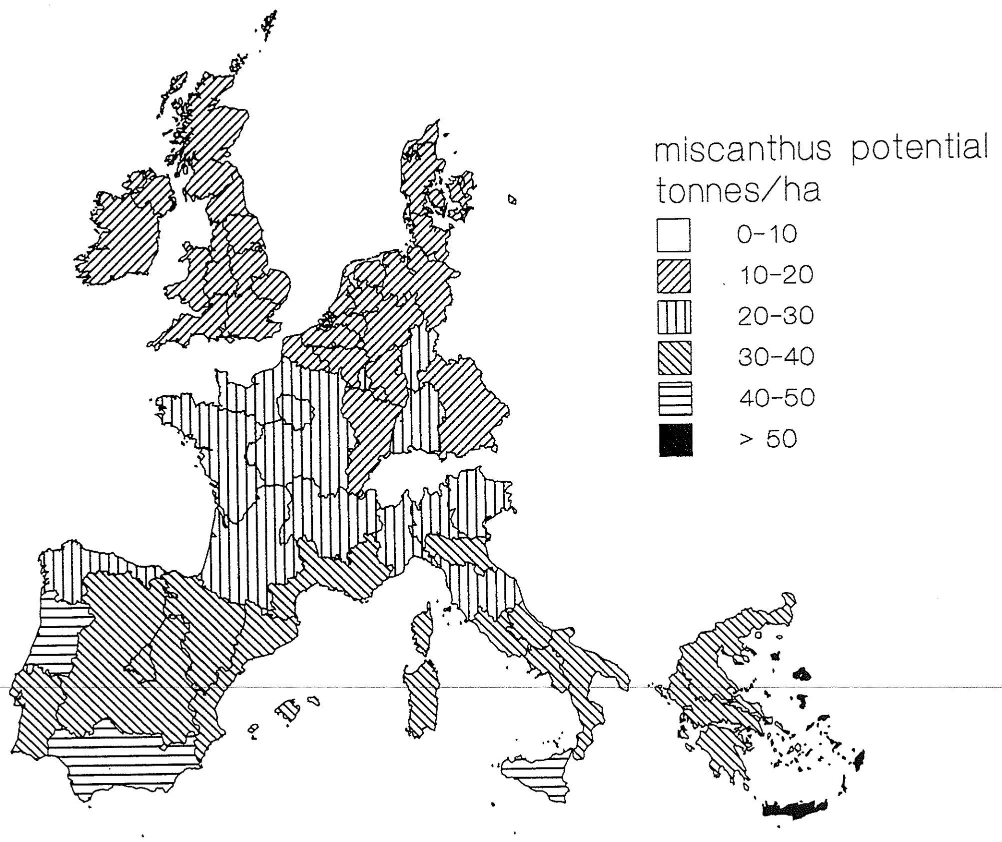

Figure 4.8 Simulated potential Miscanthus yield (ton ha^{-1} y^{-1}) in various regions of the EU

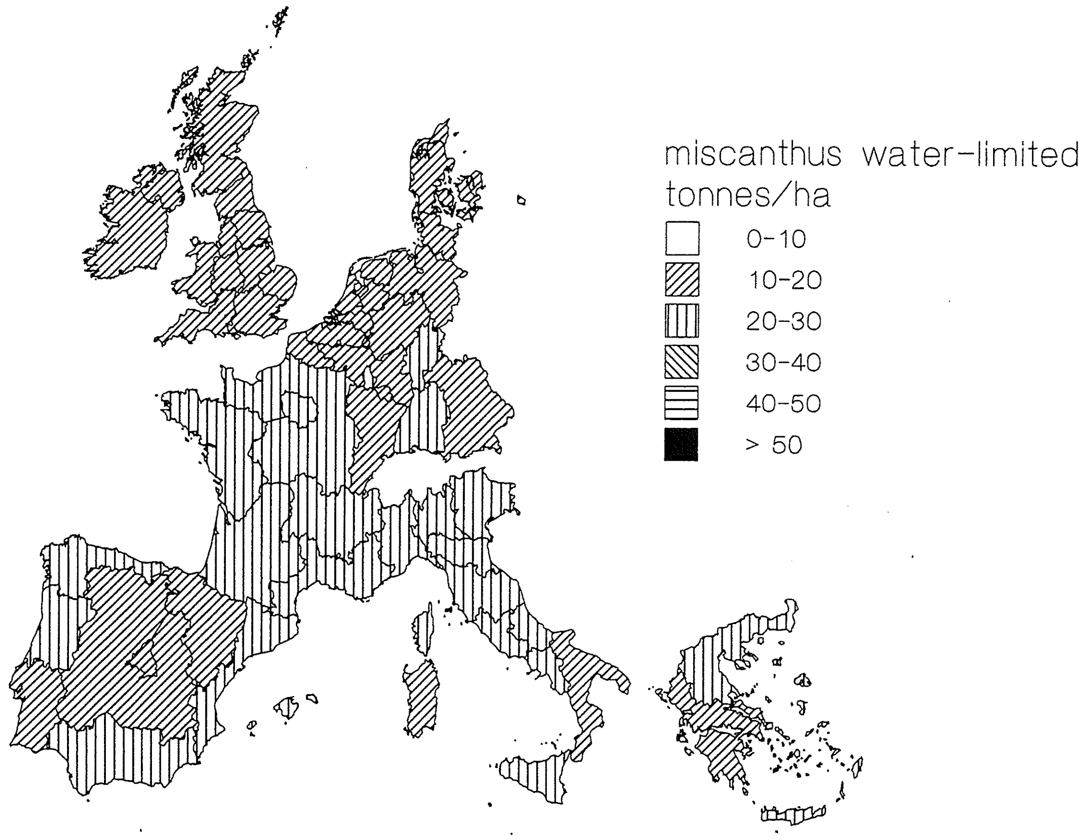

Figure 4.9 Simulated water-limited Miscanthus yield (ton ha^{-1} y^{-1}) in various regions of the EU

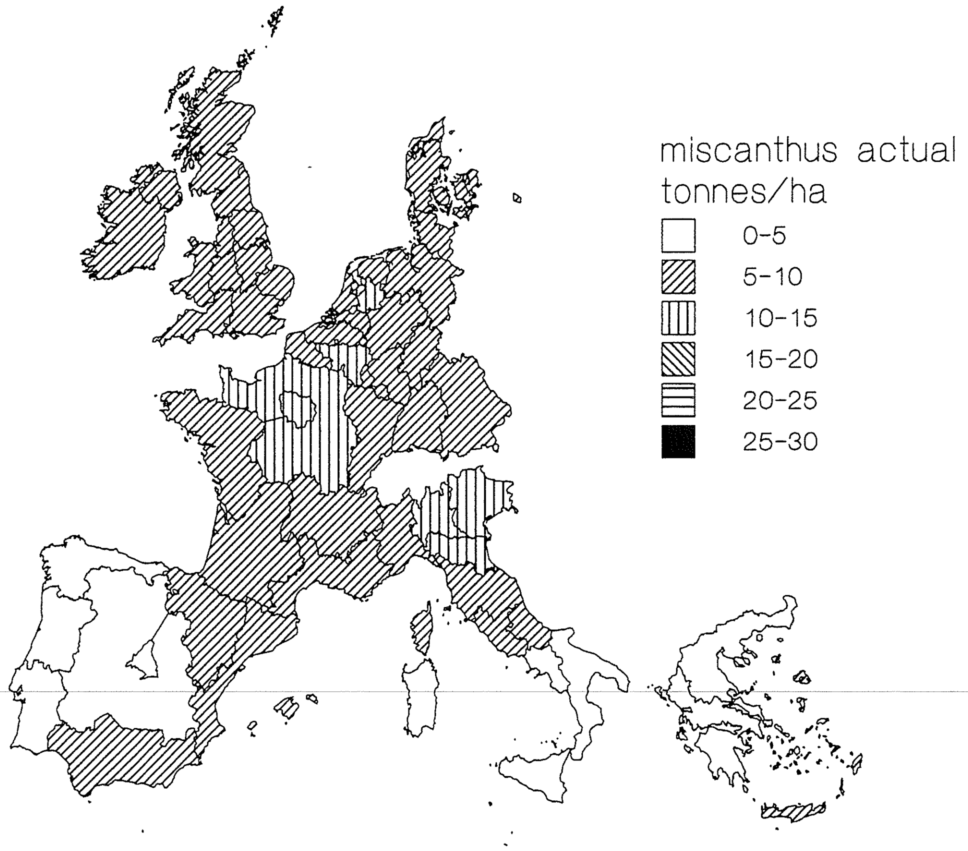

Figure 4.10 Estimated actual Miscanthus yield (ton ha^{-1} y^{-1}) in various regions of the EU

4.5 Sorghum

The area suitable for growing Sorghum was larger than the area suitable for growing Eucalyptus, although most parts of Europe still turned out to be not suitable for growing Sorghum (Fig. 4.11). In regions that were suitable for Sorghum growing potential yields of 20-30 ton ha^{-1} were simulated. The effect of water shortage on crop production was relatively small: yields dropped by 5-10 ton ha^{-1}. In Northern Spain, Southern France and Northern Italy Sorghum yields were similar to those of willow; in other regions they were lower than the water-limited willow yield (Fig. 4.12). In about half of the regions estimated actual yields were less than 5 ton ha^{-1} (Fig. 4.13).

4.6 Eucalyptus

The potential yields of Eucalyptus in the regions suitable for growing this crop are given in Figure 4.14. Large parts of Europe turned out to be not suitable for growing Eucalyptus because temperatures were too low. In regions suitable for growing Eucalyptus potential yields were much higher than yields of other biomass crops (cf. Figure 4.2, 4.5, 4.8 and 4.14; note that class distribution is different from previous figures). Potential yields of over 50 ton ha^{-1} were simulated (even up to 60 in region 57). The effect of water shortage was smaller than simulated for willow and poplar (Fig. 4.15); yields dropped by 10-15 ton ha^{-1}. Actual yields of over 10 ton ha^{-1} were estimated in Southern Spain. In other regions estimated actual yields were 5-10 ton ha^{-1} (Fig. 4.16).

4.7 Input requirements of several production systems for poplar

4.7.1 Energy requirements

A summary of the input requirements for five production systems (2.4.1) is given in Table 4.1. The calculations for the whole rotation are given in appendix I. Large yield differences occurred between the systems distinguished: 5-43 ton ha^{-1} y^{-1}, but the input requirements also showed large differences (4-82 GJ ha^{-1} y^{-1}). Nitrogen fertilization, irrigation and harvest were the largest energy consumers of the production. The efficiency (energy field/energy requirements) in Portugal of the low input system was highest (22) and the energy efficiency of the irrigated system was lowest (8); the other systems were similar with energy ratios between 14 and 15. The net energy yield per ha of the least efficient system, however, was highest: 692 GJ ha^{-1} y^{-1} and of the most efficient system lowest: 86 GJ ha^{-1} y^{-1}.

4.7.2 Labor requirements

The production systems studied also differed in their labor requirements as is shown in Table 4.2. Irrigated system 3 required nearly 29 hours ha^{-1} y^{-1}, while the low-input system 5 required only 2.6 hours ha^{-1} y^{-1}. Irrigation requires the largest labor input followed by harvesting.

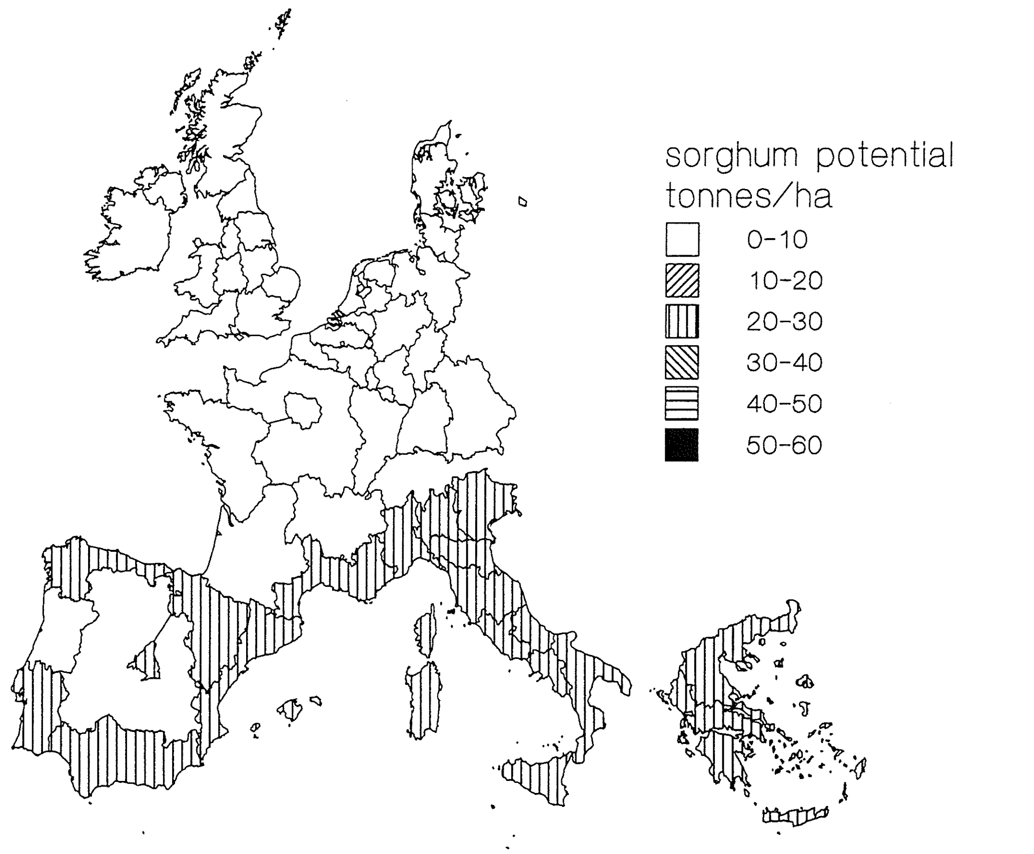

Figure 4.11 Simulated potential Sorghum yield (ton ha^{-1} y^{-1}) in various regions of the EU

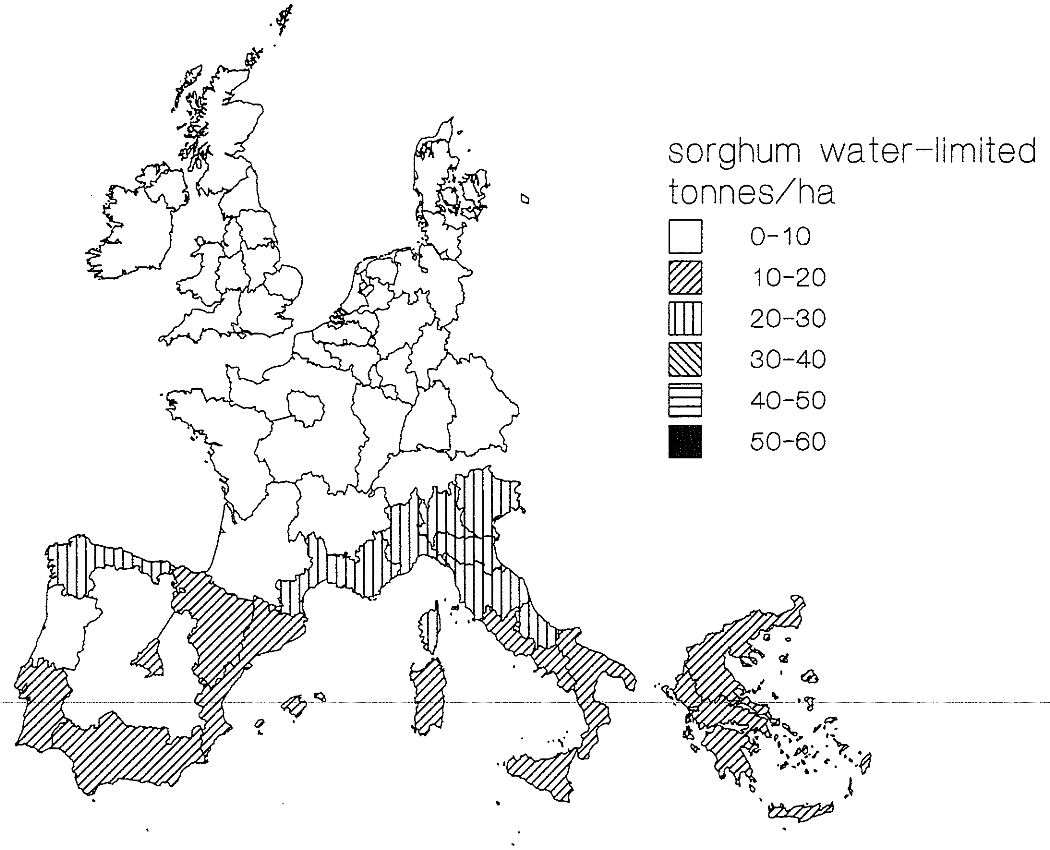

Figure 4.12 Simulated water-limited Sorghum yield (ton ha^{-1} y^{-1}) in various regions of the EU

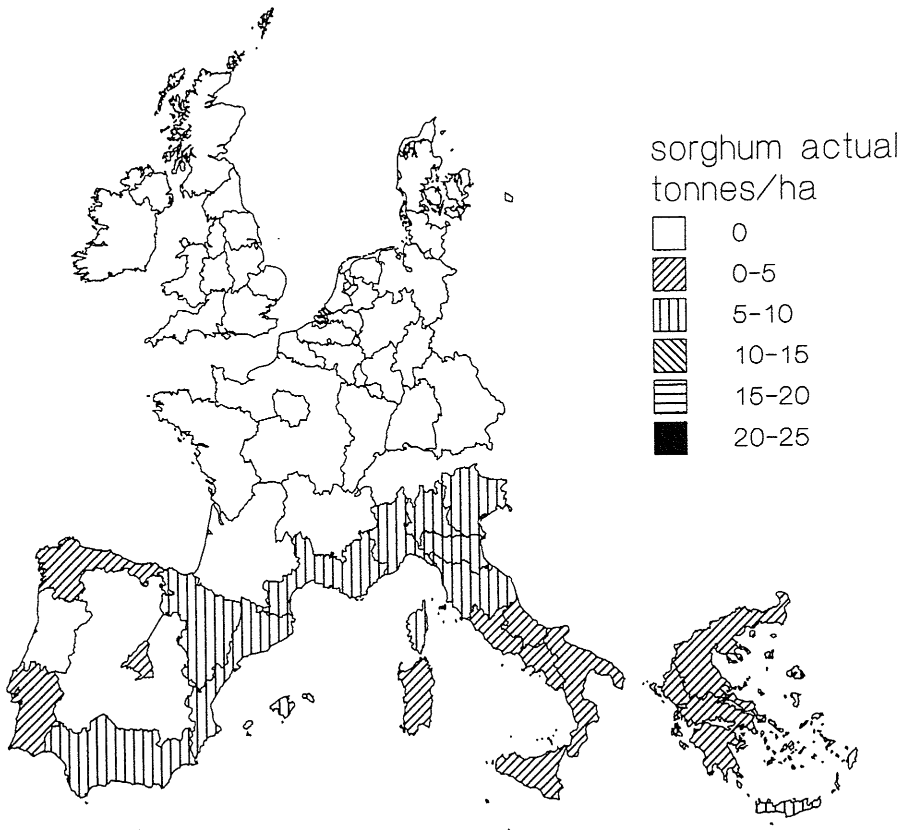

Figure 4.13 Estimated actual Sorghum yield (ton ha^{-1} y^{-1}) in various regions of the EU

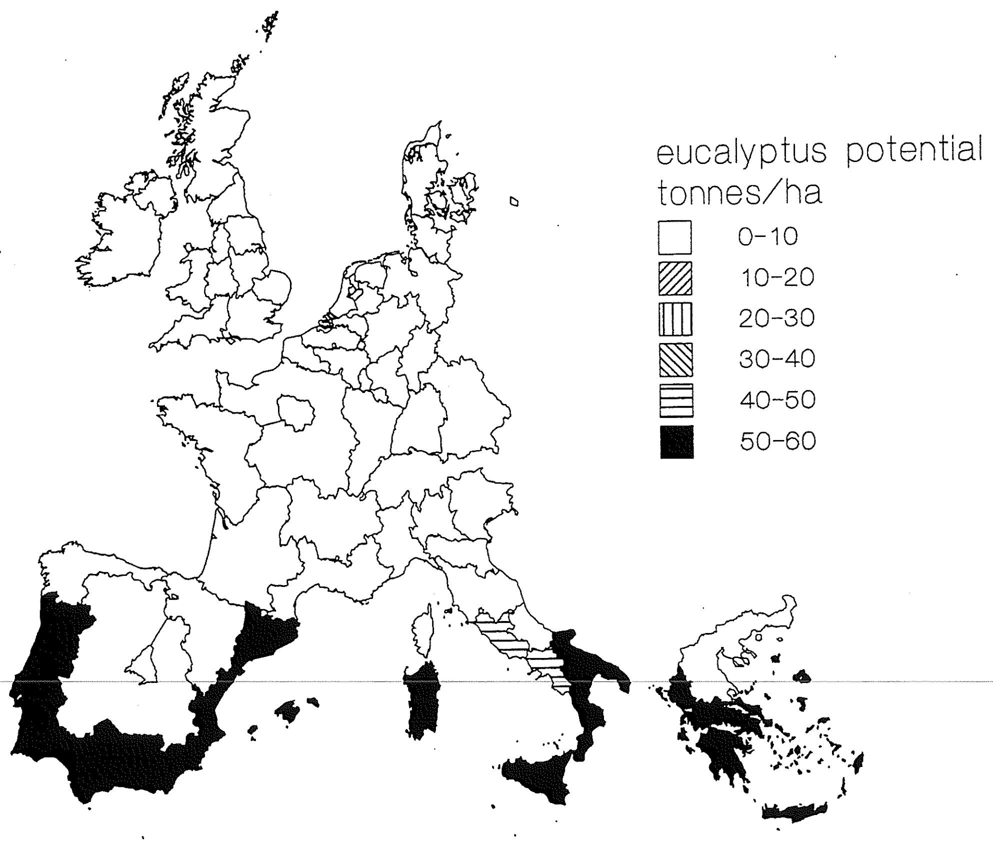

Figure 4.14 Simulated potential Eucalyptus yield (ton ha^{-1} y^{-1}) in various regions of the EU

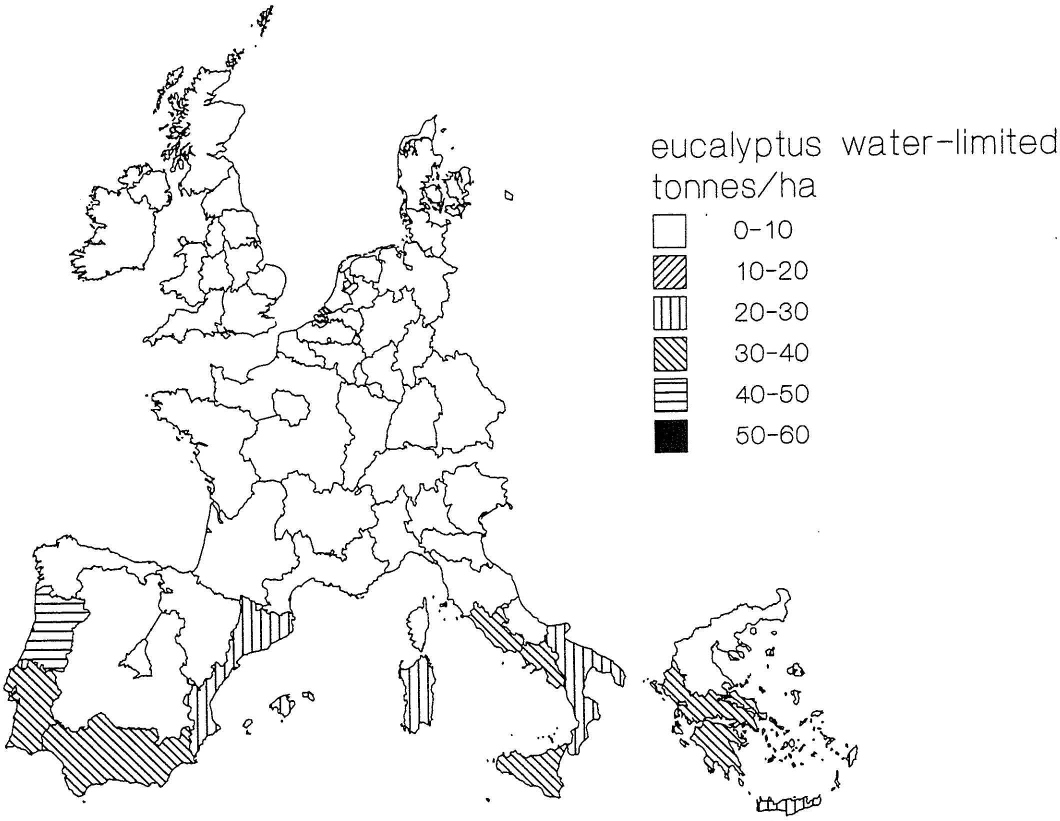

Figure 4.15 Simulated water-limited Eucalyptus yield (ton ha^{-1} y^{-1}) in various regions of the EU

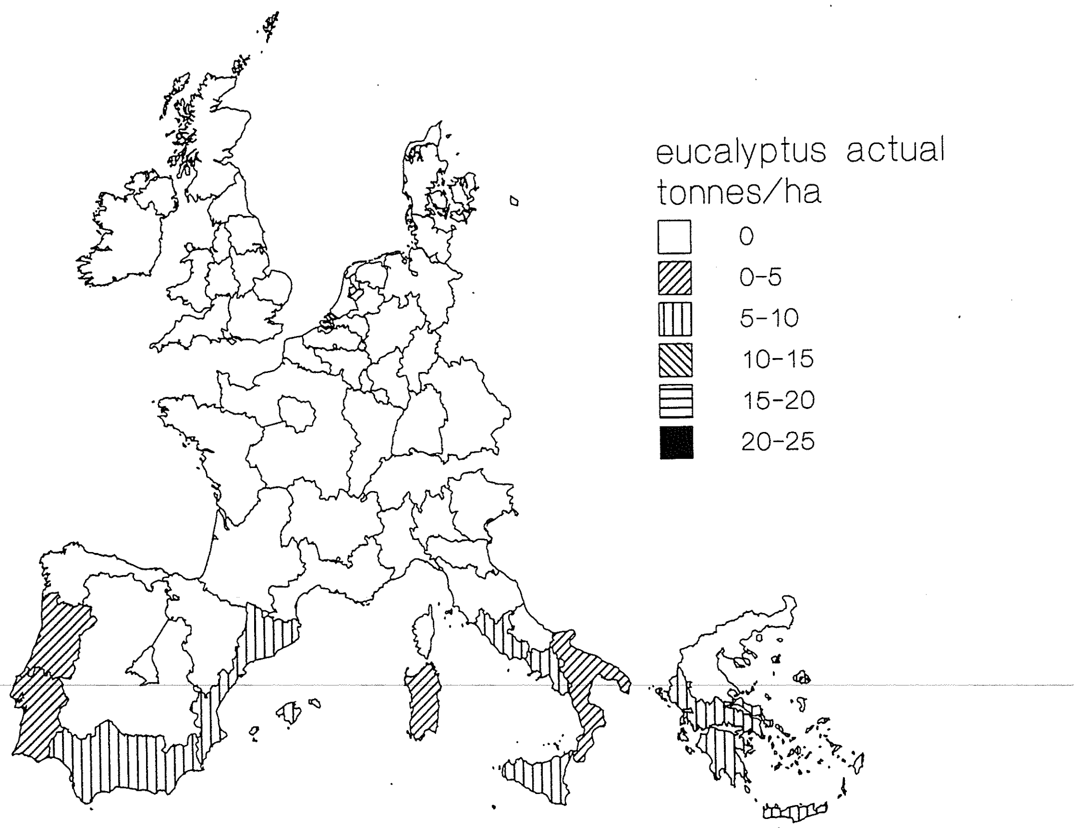

Figure 4.16 Estimated actual Eucalyptus yield (ton ha^{-1} y^{-1}) in various regions of the EU

The rain-fed system in Portugal (4) produced most GJ per working hour (51 GJ h^{-1}) and the irrigated system in Portugal the lowest amount (24 GJ h^{-1})

Table 4.1 Energy inputs of five biomass production systems for poplar

System	1	2	3	4	5
Yield (ton ha^{-1} y^{-1})	12	9.6	43	28	5
Heating value (GJ ton^{-1})	18	18	18	18	18
Gross energy yield (GJ ha^{-1} y^{-1})	216	173	774	504	90
Energy requirements (GJ ha^{-1} $20y^{-1}$)					
Planting	6	6	6	6	6
Fertilizer	112	91	425	256	8
Crop protection	24	0	24	24	0
Weeding	3.5	3.5	3.5	3.5	3.5
Irrigation	0	0	665	0	0
Harvest	144	115	516	336	60
Total energy req. (GJ ha^{-1} $20y^{-1}$)	290	215	1640	626	78
Energy req. (GJ y^{-1})	14	11	82	31	4
Net yield (GJ ha^{-1} y^{-1})	202	162	692	473	86
Efficiency (GJ GJ^{-1})	14	15	8	15	22

Table 4.2 Labor inputs of five biomass production systems for poplar

System	1	2	3	4	5
Yield (ton ha^{-1} y^{-1})	12	9.6	43	28	5
Heating content (GJ ton^{-1})	18	18	18	18	18
Gross energy yield (GJ ha^{-1} y^{-1})	216	173	774	504	90
Labor requirements (hr ha^{-1} $20y^{-1}$)					
Planting	17	17	17	17	17
Fertilizer	10	10	12	11	1
Crop protection	30	0	30	30	0
Weeding	15	15	15	15	15
Irrigation	0	0	323	0	0
Harvest	48	38	172	112	20
Total labor input (hr ha^{-1} $20y^{-1}$)	120	80	569	185	53
Average labor input (hr ha^{-1} y^{-1})	6	4	28	9	3
Net yield (GJ ha^{-1} y^{-1})	202	162	692	473	86
Efficiency ($GJ^{-1}hr^{-1}$)	34	40	24	51	33

5. Discussion

5.1 Simulation model

The model BIOMASS developed and used in this report is very simple, and with a very limited amount of data crop production was estimated for various crops in several regions in Europe. Production of the crops was only determined by amount of intercepted light by the crop and availability of water. All other processes that may affect crop growth were ignored: for instance the effect of air temperature on photosynthesis and the loss of water from the soil profile by evaporation from the soil surface. It is therefore to be expected that the BIOMASS model will overestimate production in comparison with more detailed models. To get an impression of the order of magnitude of this overestimation wheat yields simulated with BIOMASS were compared with wheat yields simulated with the WOFOST model (van Diepen *et al.,* 1988). The WOFOST model was used to evaluate production of agricultural crops in the 58 NUTS1 regions of the EU (de Koning & van Diepen, 1992). The simulation results of both models are given in Figure 5.1. As expected, the yields simulated with BIOMASS were higher than those simulated with WOFOST. The yield differences were to 2-3 ton ha^{-1} and were more or less constant for all regions. WOFOST requires about 150 crop specific data to simulate crop growth. For the biomass crops studied here, these data will not become available in the coming years, so that the use of a more detailed crop growth model for simulating crop production will not be possible in the very near future. The use of the BIOMASS model is therefore a suitable temporary solution, but it should be realized that the model tends to overestimate yields in comparison with more detailed models.

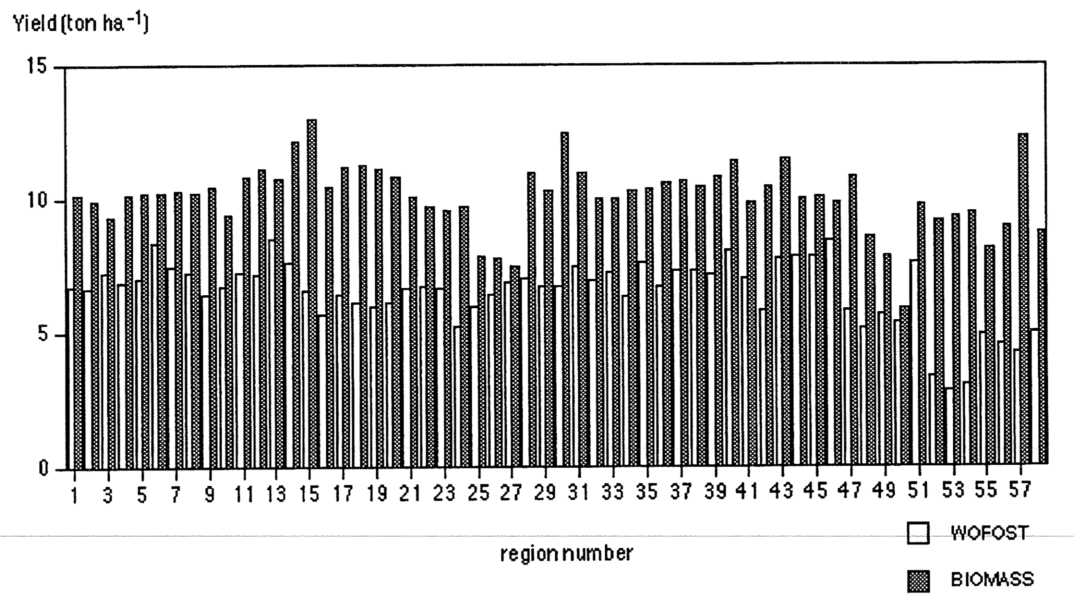

Figure 5.1 Comparison between the water-limited wheat yields simulated with the WOFOST model and wheat yields simulated with the model BIOMASS for 58 European regions

5.2 The application of RYF values in various regions of Europe

Since large differences exist between crop production potentials and the yields obtained presently, the production potential of a crop has little to do with the yields that can be obtained in the nearby future (coming decade). For an appropriate evaluation of the possibilities of using biomass crops as energy source in the nearby future, the present yield gap has to be taken into account. In recent studies on this subject this yield gap is ignored, and estimated biomass yields are identical to production potentials. Since biomass crops are not yet grown on a large scale, the actual yield is difficult to determine. The introduction of the Regional Yield Factor is an attempt to estimate this actual yield. It is, however, a black box method and should be applied with great care. As mentioned in 2.3 it is essential that yield data of crops grown under similar circumstances (bio-physical and management) are used to estimate the RYF values. When this boundary condition is met the results of the method are promising: yields of agricultural crops were estimated with an inaccuracy of ca. 10% (Table 2.1). This inaccuracy is much smaller than the difference between potential and actual yields.

In none of the regions under study the RYF method could be tested for biomass crop yields, since no yield data were available on a regional scale. To validate the RYF method, data from Sweden were used, where over 200 hectares of willow in short rotation have been planted in the last 6 years and yield data after 4 years of growth have become available recently (NUTEK, 1994). The average yield over these 200 hectares in Southern Sweden was used as indication of the regional yield.

The simulated water-limited wheat yield in this region was 10.5 ton ha^{-1}; the actual yield is 6 ton ha^{-1} (FAO, 1993), which leads to a RYF value of 0.6. The simulated water-limited willow yield for this region was 10.8 ton ha^{-1}, application of RYF on this yield leads to an estimated actual willow yield of 0.6 * 10.8 = 6 ton ha^{-1} y^{-1}. In general, the yield of a willow plantation in the starting year is low (Mitchell *et al.,* 1992). When no yield is assumed in the first year, and with normal growth in years 2-4, total expected yield after 4 years would be 3 * 6 = 18 ton ha^{-1}.

The average yield obtained on the 200 hectares was 19 ton ha^{-1} over 4 years (NUTEK, 1994). This information shows that the application of the RYF method gives a better estimation of the present yield levels than the yield potentials of that crop which would result in a yield estimate of 3 * 10.8 = 31.4 ton ha^{-1}.

5.3 Simulation results

5.3.1 Growing season

The potential production of a crop is determined by the amount of radiation intercepted by this crop. In this study the fraction of the daily incoming radiation that is intercepted is determined by the air temperature: for most crops start of the light interception is determined by a temperature sum or by air temperature itself (3.2.1 - 3.2.6). Only for Eucalyptus the growing season runs from January 1st till December 31st, but only in regions where the risk of frost is small, which is also determined by air temperature values (see 3.2.5). Since temperature requirements differ between crops and since air temperatures and radiation levels differ between regions, differences in production were simulated. In Figure 5.2 the course of the temperature and the daily global radiation is given for 5 regions from north to south over Europe: UK: Scotland (44), The Netherlands: Noord (28). France: Bassin-Parisien (10). Mediterranean (16) and Spain: Sur (56). Both air temperature and global radiation show a sinusoidal curve over the year for all regions but the average levels differ. In region 56 temperatures never drop below 10°C in winter, and in summer average temperatures are above 25°C, while in region 44 winter temperatures are very near to 0°C and summer temperatures hardly reach 15°C. Global radiation levels give the same picture: high values in the southern regions and low values in northern regions.

As a result of these differences in temperature, the simulated fraction intercepted radiation differed between these regions as is shown in Figure 5.3 for the standard willow crop. The start of the light interception of this crop was defined at temperature sum 150 (3.2.1). Since temperatures differed between various regions, temperature sum 150 was reached at different moments in the year. In Southern Spain start of light interception of willow was simulated on day 27 (end of January), while in Scotland light interception only started on day 137 (second half of May). For willow the start of leaf fall and complete defoliation were defined on day 245 and 300 respectively, for all regions, so that no regional differences at the end of the growing season were observed. The shift of the growing season of crops from north to south over Europe is also observed in the literature (section 3.2).

Start of light interception was defined differently for various crops (3.2), so that the fraction of the light intercepted in one particular region differed between crops as is shown in Figures 5.4 and 5.5. In Scotland light interception of willow started on day 137, for poplar on day 146 and for Miscanthus on day 166. Also differences at the end of the growing season were observed, caused by differences in definition of the leaf fall. Due to the low temperatures in region 44, this region was not suitable for growing Sorghum and Eucalyptus. In Southern Spain duration and timing of the growing season of various crops was different from Scotland; in general the growing season was longer. In region 56 it was possible to grow Sorghum and Eucalyptus.

The growing season of Sorghum was rather short in comparison with the other crops: it only lasted 100 days. Eucalyptus intercepted all annual incoming radiation.

5.3.2 Potential production

Since the light interception differed between regions and crops, differences in above-ground biomass production were observed (note: to obtain the yield the above-ground biomass must be multiplied by the value for the harvest index of the particular crop). For the growing seasons discussed in the previous paragraph the simulated above-ground biomass during the year is given in Figures 5.6, 5.7 and 5.8. A longer growing season led to a higher production. Willow had the longest growing season in region 56 (Fig. 5.3) resulting in an above-ground biomass of nearly 60 ton ha^{-1} at the end of the growing season (Fig. 5.6). The shortest growing season was in Scotland and the simulated above-ground biomass in this region was only 16 ton ha^{-1}. Similar effects were found for the differences between crops in one region: the crop with the longest growing season was generally yielding highest. The highest above-ground biomass was simulated for Eucalyptus in region 56 for which a production of 80 ton ha^{-1} was simulated (Fig. 5.8).

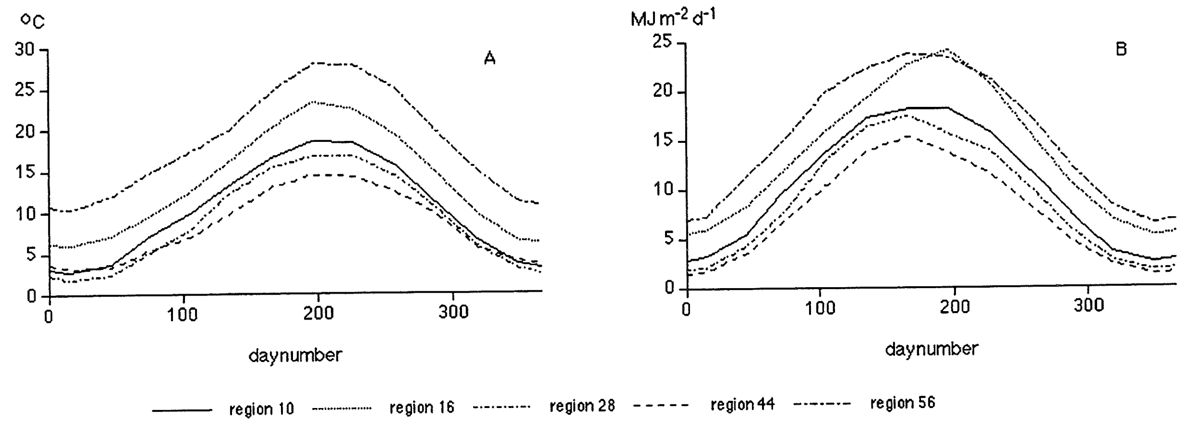

Figure 5.2 Course of the average air temperature in °C (A) and total daily global radiation in MJ m^{-2} d^{-1} (B) in 5 European regions during the year

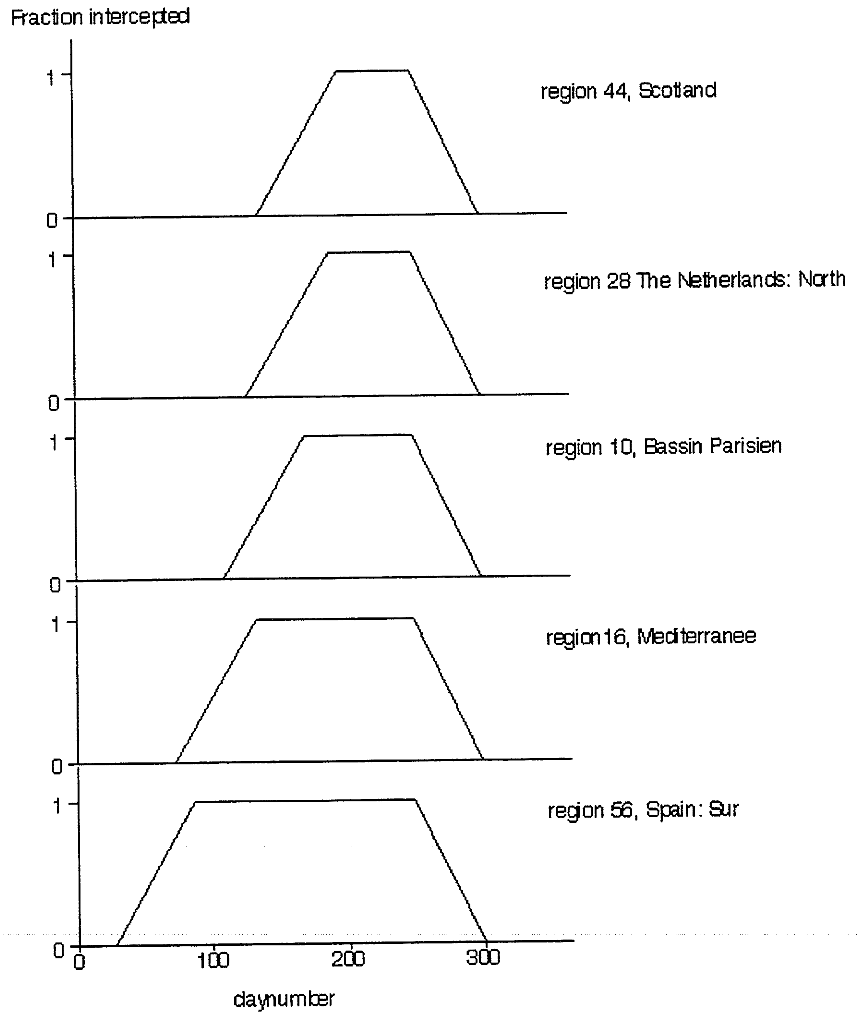

Figure 5.3 Fraction of the incoming radiation intercepted during the year by a standard willow crop in five different regions

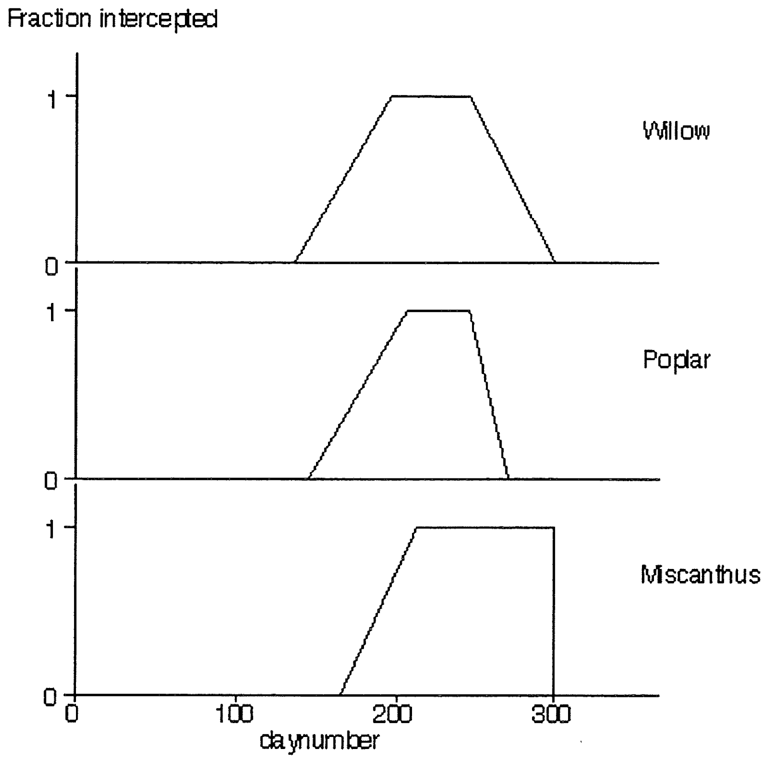

Figure 5.4 Fraction of the incoming radiation intercepted during the year by three different crops in

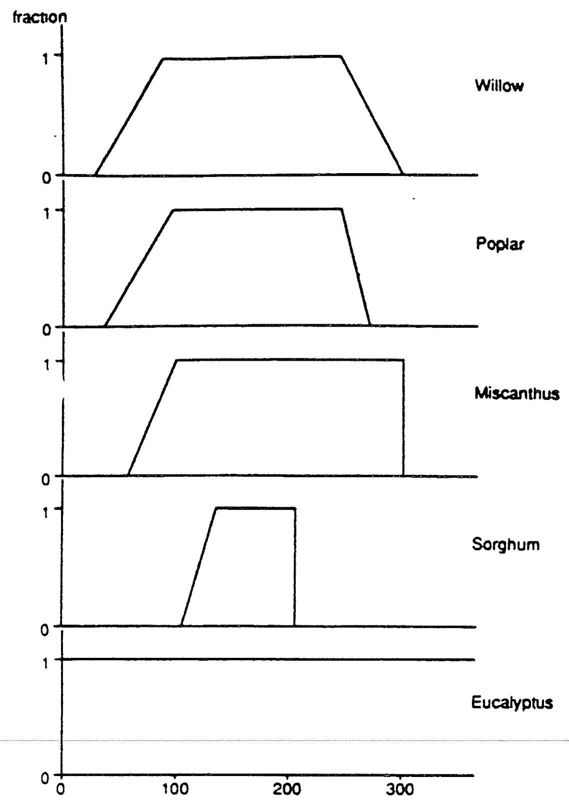

Figure 5.5 Fraction of the incoming radiation intercepted during the year by five different crops in region 56 (Spain: Sur)

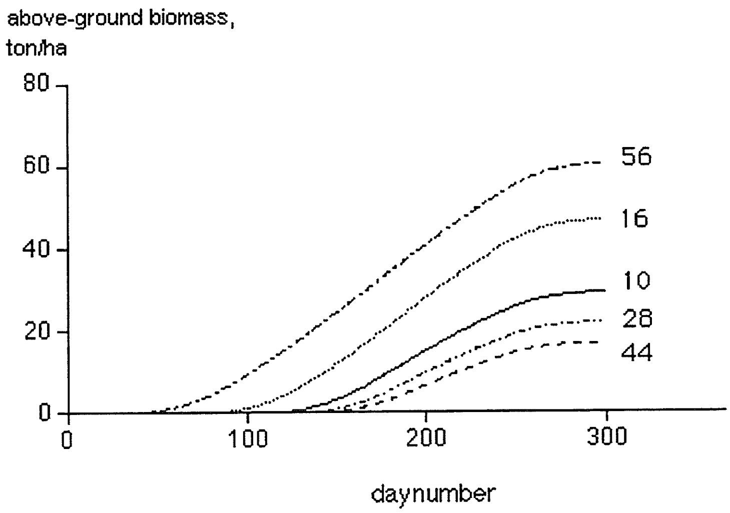

Figure 5.6 The above-ground potential biomass production of a standard willow crop as simulated for five different regions

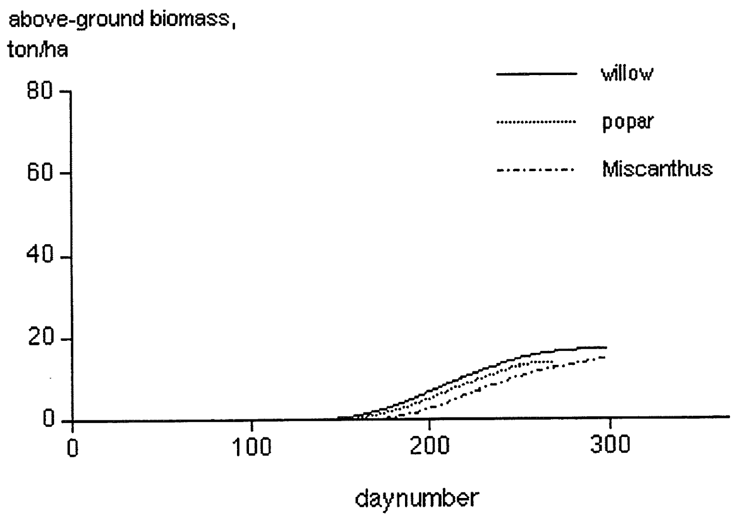

Figure 5.7 The above-ground potential biomass production of three different crops as simulated for region 44: Scotland

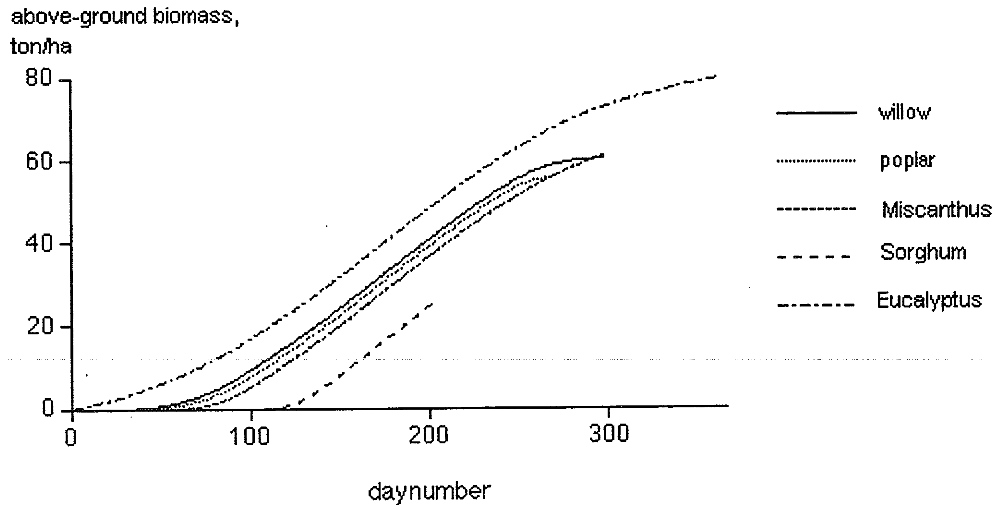

Figure 5.8 The above-ground potential biomass production of five different crops as simulated for region 56: Spain: Sur

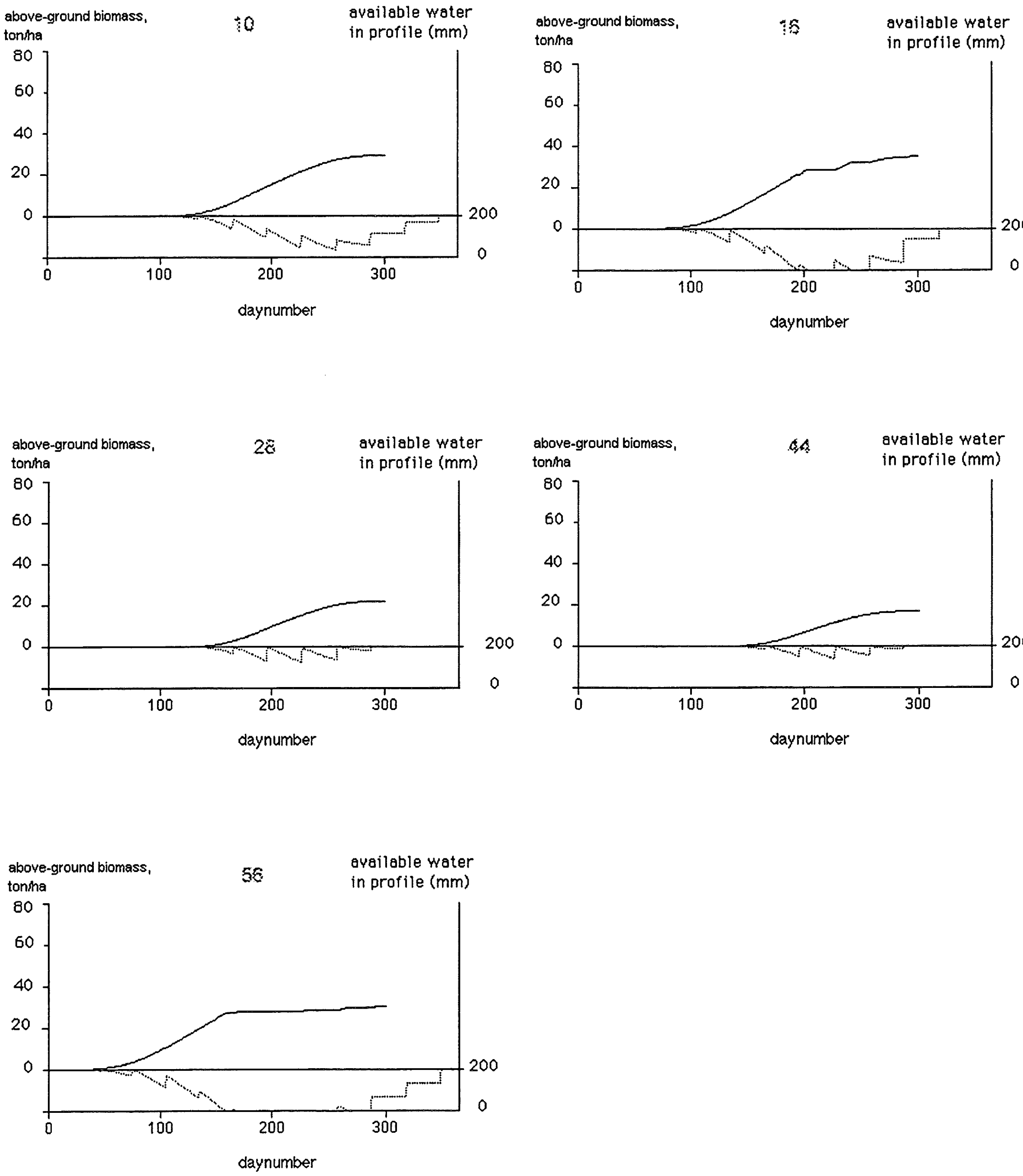

Figure 5.9 The simulated above-ground water-limited biomass production (——) and the available water in the soil profile (·······) for willow in five different regions

5.3.3 Water-limited production

The potential growth rate of a crop can only be maintained when there is enough water in the rooted profile to sustain the transpiration requirements of the crop. In the BIOMASS model the available water for transpiration during the growing season was calculated with a soil water balance (2.2). In Figure 5.9 the water-limited production of willow is shown for five regions together with available water for transpiration during the year at these locations.

For all regions the amount of water in the profile started to drop as soon as growth started. At monthly intervals water was added to the profile (precipitation), which led to a kind of sawtooth pattern. In regions 30 and 44 the monthly precipitation was enough to bring the profile to field capacity (200 mm) again; in the other regions the amount of water during the growing season gradually decreased. In regions 16 and 56 the available water was depleted halfway the growing season (available water = 0), and biomass production ceased. In these regions a difference between potential and water-limited production was observed. In region 10 the profile got dryer during the growing season but the amount of available water remained enough for crop production and no difference between potential and water-limited production was observed. In all regions precipitation in autumn made sure that at the end of the year (Dec. 31st) the profile was saturated again (200 mm).

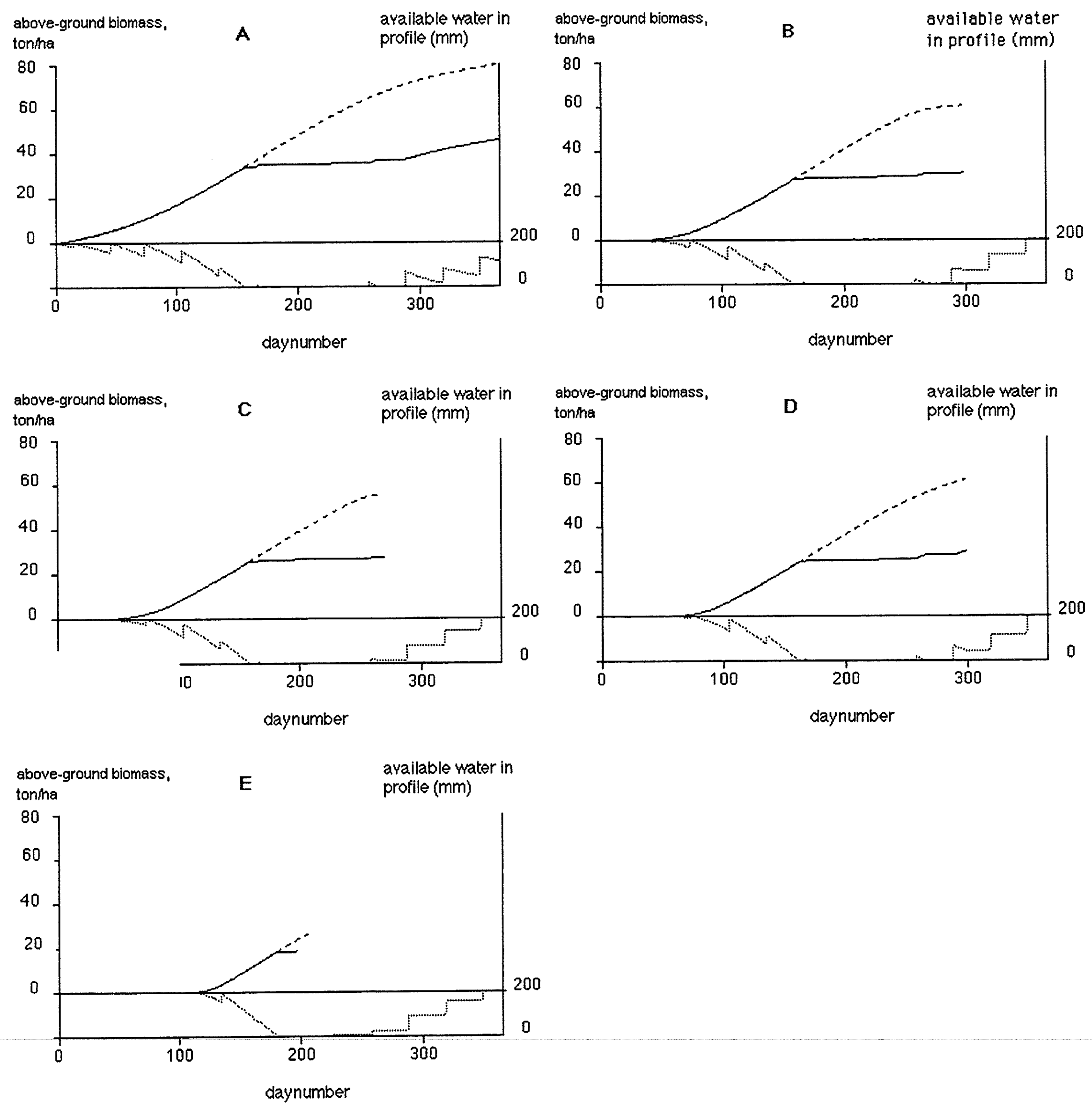

Figure 5.10 Simulated above-ground biomass (both potential (----) and water-limited (—)) and the available water in the soil profile (·······) for five different crops in region 56 (Spain: Sur). A = Eucalyptus, B = willow, C = poplar, D = Miscanthus and E = Sorghum.

The water requirements differed between crops, which is shown for five crops in region 56 in Figure 5.10. All crops suffered from water shortage in the summer months and differences between potential and water-limited production were observed. For Sorghum this difference was about 5 ton ha^{-1}, while for Eucalyptus it was nearly 40 ton ha^{-1}. Eucalyptus was the only crop that benefited from the autumn precipitation: its growth started again in November (when water came available). The other crops had already lost their leaves at that moment . Figure 5.10 shows that for Eucalyptus the soil profile was not at field capacity again at the end of the year.

Compared to the potential production the differences between regions in water-limited production were much smaller (lowest = 10 ton ha^{-1}, highest = 30 ton ha^{-1}). This was caused by the differences in distribution of the rainfall between various regions. In the northern part of the Europe precipitation is distributed more ore less regularly over the year with about 60-70 mm $month^{-1}$. In Southern Europe most of the precipitation falls in autumn and winter and summer is very dry (10 mm $month^{-1}$). For crops growing in spring and summer in these regions this implies that the amount of water in the profile is not replenished by precipitation during their growing season and their water-limited production is small. Eucalyptus can grow year-round, so that this crop makes a much better use of the annual precipitation, which is shown in Figure 5.10.

5.4 Energy and labor input requirement of various systems

5.4.1 Energy input requirements

When energy ratios of various systems are compared, the ratio of the no-input systems was highest: 22. The fossil energy used in this system was used most efficiently. The net yield of this system was low in comparison with the other systems. This implies that the acreage required to produce feedstock for electricity generation increases, and so are the costs for transport of the biomass. The energy content of biomass is low, which implies that transportation costs per MJ are high. In future research the transportation costs should be included to be able to determine the most efficient energy production system. The irrigated system in Portugal was producing the highest net energy yield ha^{-1}. The energy ratio of this system was low. Thus only when the number of hectares is the limiting factor this system may be an option, but in that case other energy producing systems (solar cells) may be more appropriate. The non-irrigated systems (1.2 and 4) were similar in their energy use efficiencies.

As is shown in section 4.7, the largest energy consumers during cultivation of poplar were nitrogen fertilization and harvest. The energy requirements of both actions were strongly related to the expected yields. A high yield required a high energy input, and the energy efficiencies were more or less the same at different yield levels. This is a major difference with other studies on energy efficiencies of biomass crops. In Lysen *et al.* (1992) estimated energy inputs were independent of the yield levels, so that a yield increase resulted in an increase of the energy efficiency (the ratio increased from 10-16). In Hall *et al.* (1993), the energy required for harvesting was related to the yield, but energy in fertilizers remained constant and the energy ratio increased from 15 to 18 when the expected yield increased from 11 to 18 ton ha^{-1}.

It is not likely that an increase efficiency can be obtained with higher yields. Increase of the efficiencies can only be expected when the harvesting system requires less energy, or when nitrogen from other sources is used. Such options are not taken into account in this study.

5.4.2 Labor requirements of the production systems

The five production systems considered differed in their labor input (Table 4.2). Irrigation required the largest labor input and the efficiency per hour was lowest in the irrigated system (24 GJ hr^{-1}). Since the energy efficiency of this system was also low it is not likely that biomass crops will be grown under irrigation. The low input system 5 required the smallest labor input (3 hr y^{-1}), but the efficiency of this labor was lowest (33 GJ hr^{-1}), while its energy efficiency was highest (see previous paragraph).

For the rain-fed systems harvesting required the largest labor input and this input was related to the size of the yield. Crop protection measures also required a relative large labor input. This input can, however, be reduced through spraying by aircraft instead of by tractor. When an aircraft is used for the application of the pesticides, the total number of hours involved in crop protection measures will be reduced to one in the whole growing cycle of 20 years. Since the application of pesticides by plane or by tractor requires the same amount of energy (2.4.1) the labor efficiency will increase in the 'plane-sprayed' systems 1, 3 and 4 to 44, 26, 60, respectively.

In contrast to the energy efficiency, the labor efficiency increased with increasing yields. This is caused by the fact that only harvesting was yield-related whereas the labor inputs for the other actions were independent of the yield. The highest yielding system (4) has therefore the highest efficiency per hour.

5.5 Possibilities of using biomass as a renewable energy source

The estimated actual biomass production on a regional scale, for all regions within Europe, varies roughly between 5-10 ton ha^{-1} y^{-1} (Figs 4.4, 4.7, 4.10, 4.13, 4.16). These yield estimates are much lower than mentioned in other studies (Hall *et al.,* 1993; Lysen *et al.,* 1992). Based on the estimates made here, the contribution of biomass to present energy requirements seems to be limited. When biomass crops are grown on the 80 million ha of potential surplus agricultural land it would yield about 500 TWh of electricity, which is only 30% of the present electricity requirements of the EU and only 11% of the total energy requirements (electricity is 30% of total energy consumption). However, it is realistic to assume that these yields will increase in the coming decades. Based on the method used in this study yield increases can be obtained via two routes: through a change in the value of the RYF (improvement of the agricultural management practices) or through a change in the crop characteristics (breeding).

5.5.1 Development of the RYF value with time

As mentioned in Section 2.3, the RYF value is time-dependent. To give an impression of the development of the RYF values with time, the RYF values calculated on the basis of wheat yields over the last 30 years in The Netherlands and in Spain are given over in Figure 5.11. In The Netherlands RYF values increased from 0.30 in the fifties to 0.60 in the nineties; in the same period RYF values in Spain increased from 0.08 to 0.18. So for the whole of Europe large discrepancies between actual yields and the attainable production possibilities exist. Especially in the southern parts of Europe large increases in yields are possible through improvement of the present agricultural practices. Figure 5.11 shows that the rate of increase of the RYF value has been more or less linear over the last 30 years: 0.01 y^{-1} in the Netherlands and 0.003 y^{-1} in Spain. The future increase rate of the RYF value is difficult to predict; it is not realistic to presume that it remains linear since this would imply that in 2030 the average production in The Netherlands would be above the water-limited yield levels, since RYF would reach values above 1.0. It is also very unlikely that a RYF value of 1.0 will be ever possible, since this would mean that in the whole region production is not affected by yield-limiting factors. On individual fields this may be possible, but in a region lower-yielding areas will always exist, which will reduce the regional average.

The linear increase in RYF values in Spain would imply that only in 2135 crop production in Spain will reach the current production levels in The Netherlands (RYF = 0.6). Through improvement of the infrastructure in the region and training of farmers the increase rate of RYF can be enhanced so that RYF values of 0.6 can be achieved earlier. Whether this will actually happen depends on political decisions.

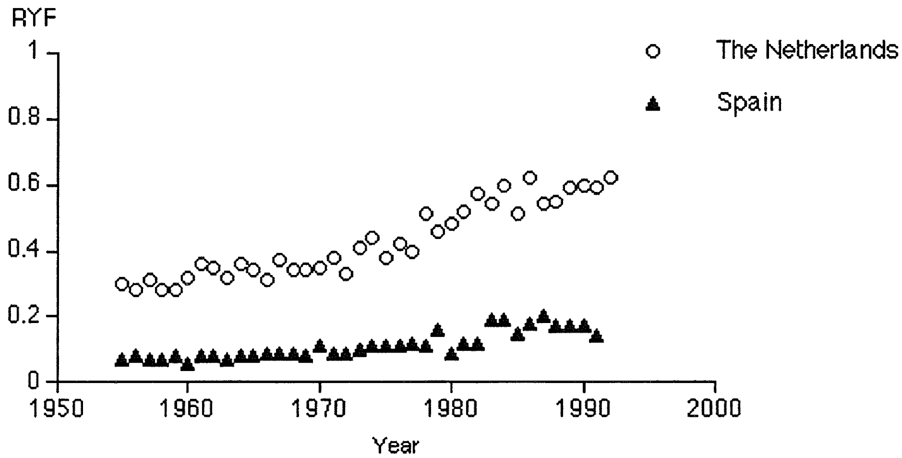

Figure 5.11 Course of the regional yield factor (RYF) over the last 30 years in The Netherlands and in Spain

5.5.2 Breeding possibilities

Another possibility to improve yields is through change of the crop characteristics. In this study a crop is defined by only 5 parameters. The effects of breeding on yield potentials can be studied through changes in these parameters, thus a change in harvest index or a change in phenological characteristics. Yield improvement through change in the harvest index has been observed for several agricultural crops. An example is given in Table 5.1 for wheat. During the last century the total above-ground biomass of the wheat varieties remained the same, but since they have become shorter the fraction of the total biomass that was harvested (harvest index) increased which resulted in higher yields.

Table 5.1. Characteristics of winter wheat varieties introduced in different time periods (data from Austin *et al.,* 1989)

Period of introduction	Above-ground biomass (ton ha^{-1})	Grain yield (85% dm) (ton ha^{-1})	Harvest index	Height ear base (cm)
1830-1900	15.0	6.0	0.34	145
1900-1920	15.5	6.6	0.36	134
1950-1970	14.8	7.9	0.45	96
1980-1985	15.9	9.5	0.51	78

Table 3.2 shows for biomass crops that changes in the harvest index value led to changes in the simulated yield. The harvest index for the biomass crops under study is already high in comparison with some agricultural crops (willow: 0.7, wheat: 0.5). From short rotation forestry only stems are harvested; the leaves and small branches remain in the field. When the harvest index is increased in this type of crop the fraction leaves becomes smaller, which will result in a smaller light interception during the season leading to a lower total biomass. The specific leaf weight of poplar leaves is about 55 g m^{-2} (Ceulemans *et al.,* 1992b; Isebrands & Nelson, 1982). To intercept all incoming radiation a leaf area index (m^2 leaf m^{-2} ground) of at least 5 is required, which corresponds to about 3 ton leaves ha^{-1}. This value increases further since leaves have a limited life span (Ceulemans *et al.,* 1992a; Porter et al, 1993), so that during the growing season a larger amount of leaves has to be produced than 5 times the soil surface. A stem yield of 10 ton ha^{-1} and a harvest index of 0.7 means that 4 ton leaves are produced per hectare. In this situation hardly any improvement of yields can be expected through increase of the harvest index. In higher yielding regions (stem yields of 20 ton ha^{-1}) a harvest index of 0.7 means a leaf production of 8 ton ha^{-1}, in which some reduction seems to be possible. However, the high yields are the result of a longer growing season, and since the life span of leaves is limited, in a longer growing season more leaves have to be formed than in a shorter growing season. The possibilities to improve yield through an increase of the harvest index for willow and poplar are therefore limited.

For Miscanthus there is another option. Presently this crop is harvested in spring. During winter about 30% of the biomass is lost, so that a harvest index of 0.7 is used for this crop (Section 3.2.3). When this crop is harvested in autumn this winter loss can be prevented and the harvest index increases to 0.95 resulting in a yield increase of nearly 30%. However, the moisture content of the autumn-harvested crops is much higher than of the spring harvested crops, which requires extra energy inputs for drying.

The other option to change production is by changing phenology during the growing season of the crop. For willow and poplar large differences in leaf emergence and leaf fall are observed between different varieties and clones. Differences of over one month are observed in various European countries (van Haaren, 1987; Tóth & Erdös, 1988; Padro Simarro, 1993). Thus a large genetic variation exists and it must be possible to select varieties or clones with longer growing seasons than the standard ones used in this study. Theoretically, the highest yield can be expected of a crop that intercepts all annual incoming radiation (like Eucalyptus in southern parts of Europe). In northern regions of Europe only conifers intercept all radiation, but these trees are not suitable for biomass production, since their light interception per gram needle is too small and they do not resprout after coppicing (for further discussion on conifers the reader is referred to Cannell (1989)). To get an impression of the yield that can be obtained from a crop that intercepts all radiation, a hypothetical crop was defined which had a harvest index of 0.8 and which intercepted all annual incoming radiation in all regions.

The water-limited production of this hypothetical crop is given in Figure 5.12. The yields varied between 24 ton ha^{-1} in region 52 and 49 ton ha^{-1} in region 57. In France and largest part of Italy yields over 40 ton ha^{-1} were simulated. In northern and southern parts of Europe yields of this hypothetical crop ranged between 30 and 40 ton ha^{-1}. In the northern parts incoming radiation is less than in the south which leads to lower yields while in large parts of Spain, Southern Italy and Greece not enough water is available to use all incoming radiation for photosynthesis, which also leads to lower yields. The crop parameters of the hypothetical crop are similar to those of Eucalyptus, only the harvest index is higher. Thus in southern regions comparable yields as for Eucalyptus were obtained; yields were about 14% higher (due to the higher harvest index).

In the regions that are not suitable for Eucalyptus a large yield increase was simulated in comparison with the biomass crops that can be grown these regions. In northern parts of Europe highest simulated biomass yields with present crops were 15 -20 ton ha^{-1}, while with the hypothetical crop yields of over 40 ton ha^{-1} were simulated. So major yield increases with this hypothetical crop can be expected in regions that are not suitable for Eucalyptus.

To be able to produce yields of over 40 ton ha^{-1} in northern parts of Europe the hypothetical crop has to be frost-resistant and photosynthesis should not be limited by low temperatures. Breeding for frost-resistance must be possible since several crops exist that keep leaves at low temperatures (for instance winter wheat). However, in nearly all crops photosynthesis is limited at low temperatures; this is caused by the fact that the activities of enzymes in the biochemical processes are temperature-dependent. The growth rate of crops that keep their leaves during cold periods is very low (winter wheat survives during the winter, but it is hardly growing). For the C3 crops photosynthesis drops rapidly to zero when air temperature drops below 5°C. For C4 crops photosynthesis is even limited at temperatures below 15°C. Since this effect of temperature on photosynthesis is found in all crops, it is not likely that this can be easily improved through breeding; there is no genetic variation available. Within the coming decades crops will not grow in the cold winter months and yields of 40 ton ha^{-1} in northern regions of the EU are not likely to be achieved.

Some improvement with respect to present simulated yields can, however, be expected, based on the presently observed and available genetic variation in phenology for willow and poplar (Section 3.2.1 and 3.2.2). To study the effect of breeding biomass crops, the following new willow variety was constructed: leaf emergence started one month earlier than the standard willow crop described in Section 4.2, canopy closure occurred one month after leaf emergence, leaf fall started one month later than the standard and all leaves have fallen one month after start of the leaf fall. The simulated yield improvement of this new willow variety in comparison with the standard variety is given in Figure 5.13. In most regions yield increases of 6-10 ton ha^{-1} were observed; only in central Spain, yield improvement remained below 2 ton ha^{-1}. In these regions production is determined by the availability of water instead of the intercepted radiation.

For Eucalyptus, Miscanthus and Sorghum no yield improvement through lengthening of the growing season can be expected. Eucalyptus already intercepts all radiation during the growing season. Sorghum is an annual C4 crop with high heat requirements for crop emergence; earlier sowing does not result in earlier crop emergence. Miscanthus is a C4 crop and present cultivars are sensitive to frost. Earlier crop emergence will result in larger risks of frost damage. Furthermore, photosynthesis of C4 crops is strongly reduced at air temperatures below 15°C. Earlier crop emergence implies that the crop is growing at temperatures below this 15°C and production is limited.

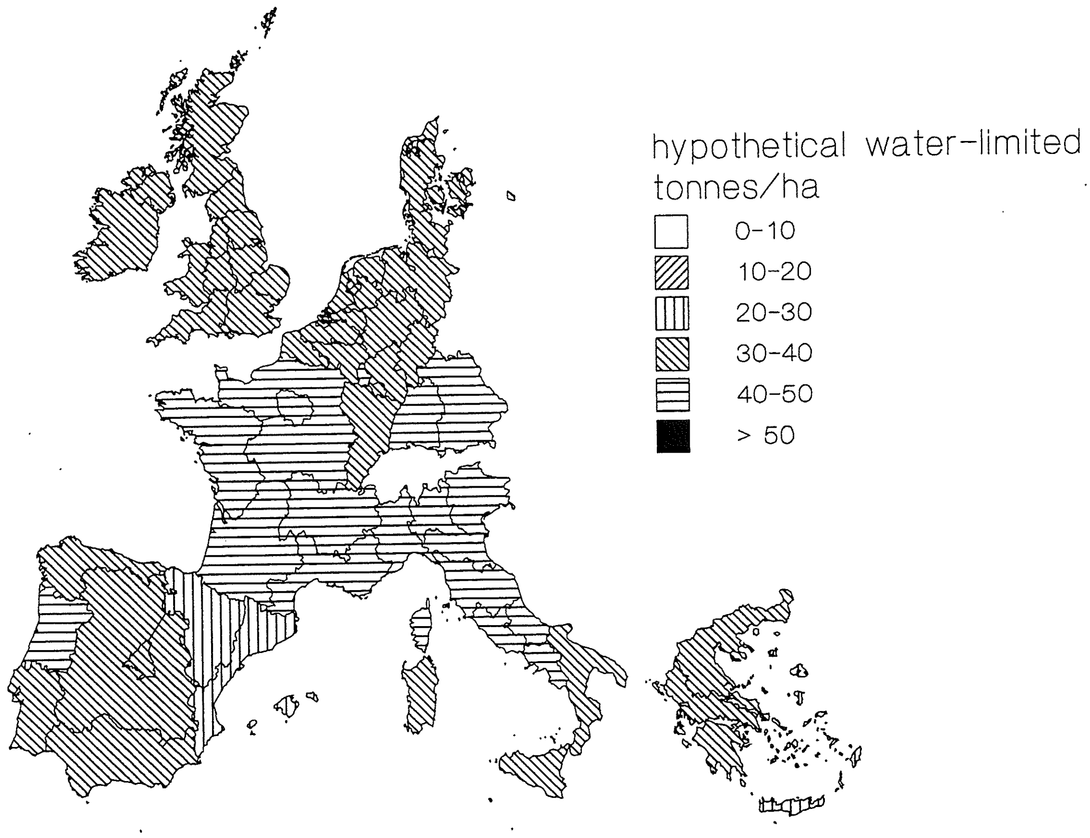

Figure 5.12 Water-limited production of a hypothetical biomass crop (intercepts all incoming radiation, harvest index = 0.8) in various regions of the EU

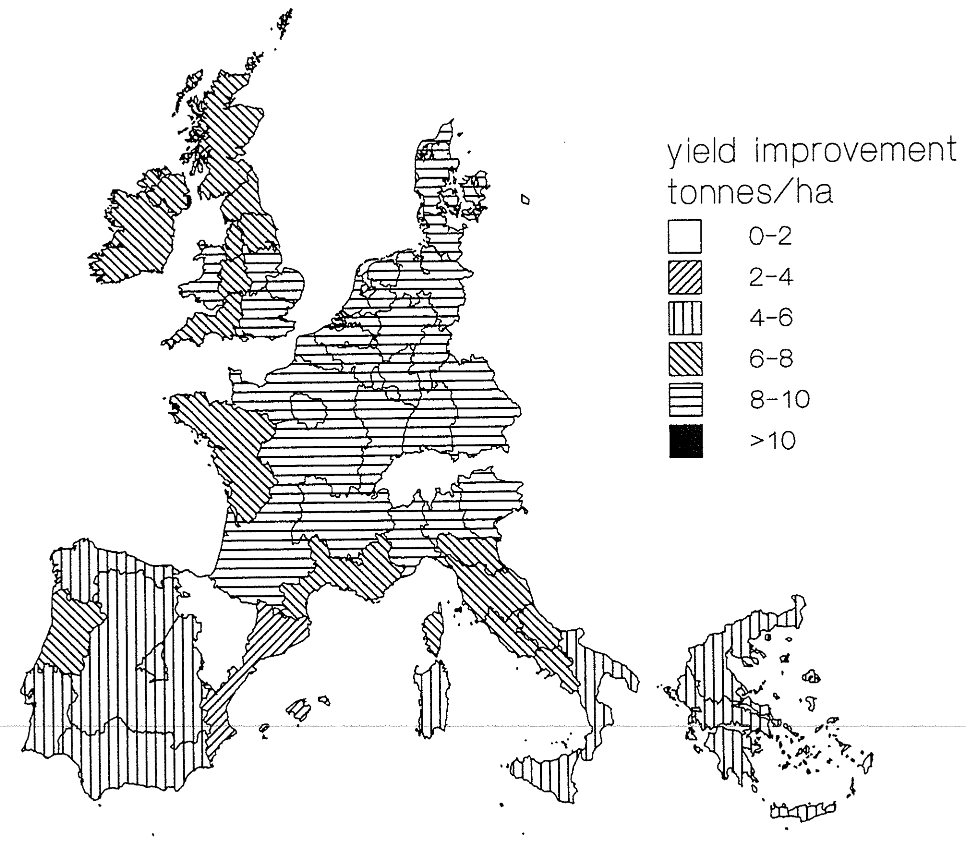

Figure 5.13 Simulated yield improvement in comparison with the standard willow crop that can be obtained with the 'new' willow variety

5.5.3 Improvement of the light use efficiency (LUE)

Changes in the value of the LUE will have large effects on yield potentials of all crops. The values found in field experiments for the biomass crops (Section 3.2) were still lower than the value of 1.4 used in this study. The values found in the literature concern crops in their first growing cycle. It is possible that the value of the LUE will increase after coppicing. For annual crops it is found that the LUE value is low at the start of the season and increases during the growing season. Averaged over the whole season values of 1.4 g MJ^{-1} are found. This fluctuation can be explained by the fact that early in the season a large part of the available assimilates is used for production of the root system. The LUE (based on above-ground biomass) is therefore lower; later in the season when the rooting system has been established, nearly all assimilates are directed to above-ground organs and the measured value of the LUE increases. Similar effects can be expected for perennials: after establishing the rooting system LUE value may increase. So it might be possible that LUE values are higher after coppicing, but since no experimental evidence exists on this subject it is not included in this study.

5.5.4 Biomass yields in the future

When the water-limited yield of the 'improved' willow crop is accepted as the attainable biomass yield, this would imply that yields of 20-30 ton ha^{-1} can be expected in the future. When such harvests can be obtained biomass can play an important role in energy supply (80 million ha of biomass crops can cover the total electricity demand of the EU). This yield of 20-30 ton ha^{-1} is of the same order of magnitude as the yield estimates given in scenario studies of Hall *et al.*, 1993, Shell (Kasler, 1994) and Okken *et al.*, 1994; they mention values of 18.5 (2010), 30 (future) and 19 ton ha^{-1} (2030). However, the values of 18.5 and 19 ton ha^{-1} are estimated for the beginning of the next century. Since in this report present yield levels of biomass crops were estimated at 5-10 ton ha^{-1}, the yields have to triple in the coming 30 years. Agricultural yields have doubled in the last 30 years (see also development of the RYF with time in Section 5.5.1), so large yield increases in this time span are possible. It should, however, be realized that a large research effort (breeding programs and research to improve growing techniques) forms the basis of this yield increase of agricultural crops during the last 30 years. The present research effort on yield improvements of biomass crops is totally disproportional to that on crops like potato or wheat. In the Netherlands there is no research on yield improvement of short rotation forestry and no breeding program exists. Furthermore, research on perennial crops requires more time than on annuals due to the fact that results only become available after a number of years instead of after one growing season. The above-mentioned facts indicate that it is not realistic to assume that biomass yields of 20 ton ha^{-1} are likely at the beginning of the next century. The rate of yield increase in the coming years depends on the research effort that can be spent on these crops.

5.6 Economic returns of biomass crops in comparison with agricultural crops

To be of interest for energy supply the price of energy obtained from biomass crops should not deviate too much from the price of energy obtained from fossil fuels, and to be of interest for farmers the economic returns of a biomass crop should not deviate too much from the returns of other agricultural crops. In several studies comparison is made between the economic returns of biomass crops (based on present energy prices) and the returns of agricultural crops (for instance winter wheat) grown under Dutch circumstances (Lijsen *et al.*, 1992; Darwinkel 1994).

Based on the present energy prices the returns of a hectare of biomass crops are much lower than for winter wheat. It has been concluded that under present circumstances growing of biomass crops is not a realistic option. However, large differences in returns exist between presently grown agricultural crops. To give an example the economic yield of potato is 10 kfl ha^{-1} while for strawberries it is 80 kfl ha^{-1} and for winter wheat it is 2 kfl ha^{-1}. Based on the yields given above, the best crop to grow for farmer is strawberries, since the yield per hectare is highest. However, growing one hectare of strawberries requires 3340 working hours and growing potatoes only 53. Based on the assumption that a farmer has 1700 hours per year available for working in the crops (in total 2100 hours per year, 400 hours required for administration (PAGV, 1995)), he would be able to manage only half a hectare of strawberries resulting in an income of 40 kfl $year^{-1}$ per person and 32 ha of potatoes resulting in gross income 320 kfl y^{-1} per person. The yield per hectare is therefore not a sufficient indicator for the suitability of growing biomass crops; the labor input has to be included as well.

In this paragraph the returns of growing biomass crops and the labor inputs required will be discussed and compared with the results of an agricultural crop. All data used concern the Dutch situation. As starting point production system 2 (Sections 2.4.1 and 4.7.2) is used. It is assumed that harvesting of the crop is done by a contractor, based on the fact that rather heavy machinery is required, and that it is not likely that farmers will invest in such machinery which is only used during a very limited number of hours per year. This implies that the hours for harvesting can be excluded, resulting in an average labor input of 2 hours per ha per year (see Tables 4. 2 and 5.2), and that costs for the contractor have to be subtracted from the yield. The costs for the contractor used here are the same as the costs for harvesting silage maize in The Netherlands (PAGV, 1995). In Table 5.2 input requirements of potato and Short Rotation Forestry (SRF) are compared on an annual basis. Growing potatoes requires 53 hours ha^{-1} and short rotation forestry 2 hours ha^{-1}, so that one farmer is able to manage 850 ha of short rotation forestry and only 32 ha of potato. Assuming that the gross income of the farmer should be kfl 60 $year^{-1}$ (1700 hours of work), the net return of SRF must be fl 71 ha^{-1} and that of potato fl 1875 ha^{-1}. When the costs for growing the crops are included, the gross return should at least be fl 991 ha^{-1} and fl 4580 ha^{-1}, respectively (Table 5.2). The costs involved in land and machinery are not included in these values; when these are added the required gross return increases. The costs of land is an uncertain factor in these calculations. Biomass crops are frequently mentioned as an option for surplus agricultural land, in that case it is not likely that the price of this land is the same as land on which potatoes are grown. Excluding the costs of land and assuming an energy price of fl 6 GJ^{-1} (= present price) the return of SRF would be fl 960 ha^{-1}. This value is very close (deviation of 30 fl ha^{-1}) to the return required for full income of the farmer. Thus only a very small subsidy (as CO_2 tax or set-aside regulation) or a small increase in energy price can fill this gap. When costs of land are also included the gap becomes over 1000 fl ha^{-1}, and energy prices have to double to fill this gap. It should, however, be realized that the present set-aside regulation amounts to fl 1500 ha^{-1}. So under present conditions (present energy price and set-aside regulations) an economic yield of fl 1991 can be obtained, which also covers costs of land. It is, however, not realistic to assume that this regulation will remain in the future and it should therefore not be included in the analysis.

Thus the price per GJ obtained from biomass can be competitive with the price per GJ obtained from fossil fuels. But when farmers change from agricultural crops to biomass crops this will have an enormous effect on the social structure in the agricultural areas; a twenty-five-fold increase in farm size is required and an enormous number of jobs is lost. Energy crops may have a potential as an energy source, but they will not restore the present loss of jobs in the rural areas.

Table 5.2 Comparison between short rotation forestry (SRF) and potato production with respect to input requirements

Crop	SRF	Potatoes
Working hours crop ha^{-1}	2	53
Hectares for 1700 hours	850	32
Income farmer at 1700 hrs	60000	60000
Required income (fl ha^{-1})	71	1875
Costs contractor	720	0
Costs crop	200	2709
Total costs	920	2709
Required yield (fl ha^{-1})	991	4580
Costs land/machinery	1000	2000
Required yield incl, costs land (fl)	1991	6580
Yield kg ha^{-1}	9600	54000
Price (fl kg^{-1})	0.10	0.19
Obtained (fl ha^{-1})	960	10260

6. Conclusions

Biomass crops may yield 20-30 ton ha^{-1} without irrigation, and can thus play an important role in future energy supply if the 80 million hectares of potential surplus agricultural land in Europe are utilized for this purpose. However, in the coming decades yields will still be much lower and they will only be in the order of 5-10 ton ha^{-1}. This estimate is based on the present yield gap between potential and actual yields of agricultural crops. Increase in yield in the coming decades can only be obtained when research on cultivation techniques and breeding programs will be started for these crops.

Since irrigation of crops requires large energy and labor inputs, the energy and labor efficiencies of irrigated biomass crops are much lower than those of rain-fed crops. Cultivation of biomass crops under irrigation is therefore not a realistic option.

The labor requirements for growing biomass crops are much smaller than for growing agricultural crops. Therefore, the cultivation of energy crops will not generate a substantial increase of labor demand in the rural areas, and cannot compensate for the loss of labor requirement in regular agriculture.

7. Recommendations for further research

The information available with respect to timing and duration of the growing seasons of various biomass crops was very limited. For Miscanthus the relation between temperature sum and light interception had actually been measured in a field experiment, but for all other crops this relation had to be derived from other data. This relation is crucial for making reliable yield estimates and should be determined more accurately than could be done in this study. Indications exist that the value of the light use efficiency may vary during the growing cycle of perennial crops. Since this value plays an important role in the yield estimates, research on variation of the light use efficiency during the growing cycle will improve the yield estimates. Both subjects require the establishment of a well-designed field experiment in various regions of the European Union.

Since nitrogen fertilization and harvesting are the largest energy consumers in the cultivation of biomass crops, research on possibilities for reducing the energy requirements of these activities (use of nitrogen fixing crops and or less energy requiring harvesting equipment) can improve energy efficiency of biomass crops.

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Appendix I

Phenology and yield data

Phenology data (duration and timing growing season) and yield data (potential, water-limited and actual yields) of the biomass crops studied for all 58 European regions under interest.

Willow data

Region	growing season start	crop closure	start leaf fall	leafless	production (ton/ha) potential	water-lim.	actual
1	141	201	245	300	13.7	13.7	8.1
2	134	194	245	300	14.7	14.7	7.2
3	125	185	245	300	15.4	15.4	8.5
4	120	180	245	300	17.7	17.7	8.5
5	119	179	245	300	17.5	17.5	7.7
6	122	182	245	300	17.9	17.9	7.8
7	133	193	245	300	16.3	16.3	7.5
8	119	179	245	300	17.5	17.5	6.8
9	115	175	245	300	19.3	19.3	10.6
10	110	170	245	300	20.4	20.4	11.5
11	118	178	245	300	17.2	17.2	9.1
12	124	184	245	300	17.0	17.0	6.8
13	99	159	245	300	22.1	22.1	8.6
14	85	145	245	300	26.6	25.2	7.7
15	109	169	245	300	23.2	23.2	7.0
16	73	133	245	300	32.7	24.3	6.2
17	95	155	245	300	23.6	23.6	6.7
18	90	150	245	300	25.5	25.5	9.2
19	93	153	245	300	25.3	25.3	9.7
20	90	150	245	300	26.9	23.7	9.4
21	95	155	245	300	25.1	23.6	6.2
22	45	105	245	300	36.4	24.4	5.5
23	45	105	245	300	35.9	24.2	5.0
24	67	127	245	300	31.6	24.7	5.2
25	34	94	245	300	39.3	20.9	3.5
26	21	81	245	300	41.7	22.0	4.3
27	26	86	245	300	39.7	19.6	2.6
28	128	188	245	300	15.4	15.4	7.6
29	128	188	245	300	15.4	15.4	9.4
30	128	188	245	300	15.4	15.4	8.0
31	128	188	245	300	15.4	15.4	8.4
32	115	175	245	300	18.0	18.0	9.2
33	115	175	245	300	18.0	18.0	9.5
34	120	180	245	300	19.1	19.1	6.2
35	131	191	245	300	13.1	13.1	7.0
36	121	181	245	300	15.2	15.2	8.5
37	132	192	245	300	14.1	14.1	7.5
38	124	184	245	300	15.8	15.8	8.7
39	128	188	245	300	15.4	15.4	8.0
40	98	158	245	300	20.8	20.8	9.6
41	132	192	245	300	12.7	12.7	6.7
42	126	186	245	300	14.1	14.1	6.5
43	126	186	245	300	15.5	15.5	6.8
44	137	197	245	300	11.8	11.8	7.1
45	133	193	245	300	12.2	12.2	5.8
46	104	164	245	300	16.5	16.5	9.8
47	144	204	245	300	13.6	13.6	7.0
48	73	133	245	300	32.7	19.8	4.7
49	30	90	245	300	40.7	21.3	5.6
50	20	80	245	300	46.0	17.9	6.3
51	55	115	245	300	30.1	22.8	3.9
52	64	124	245	300	36.0	19.3	5.5
53	71	131	245	300	35.1	20.0	3.8
54	98	158	245	300	29.2	17.6	3.4
55	28	88	245	300	38.0	22.7	8.0
56	27	87	245	300	42.3	21.0	6.1
57	37	97	245	300	45.5	30.6	2.8
58	33	93	245	300	40.3	21.5	2.8

Poplar data

Region	growing season start	crop closure	start leaf fall	leafless	production (ton/ha) potential	water-lim.	actual
1	148	208	245	270	11.7	11.7	6.9
2	140	200	245	270	12.9	12.9	6.3
3	132	192	245	270	13.5	13.5	7.5
4	127	187	245	270	15.7	15.7	7.6
5	126	186	245	270	15.5	15.5	6.8
6	130	190	245	270	15.6	15.6	6.8
7	140	200	245	270	14.0	14.0	6.5
8	126	186	245	270	15.5	15.5	6.0
9	123	183	245	270	17.1	17.1	9.3
10	118	178	245	270	18.2	18.2	10.2
11	126	186	245	270	15.1	15.1	8.0
12	132	192	245	270	14.8	14.8	5.9
13	109	169	245	270	19.7	19.7	7.6
14	96	156	245	270	23.8	23.0	7.0
15	117	177	245	270	20.7	20.7	6.2
16	83	143	245	270	30.0	21.9	5.6
17	102	162	245	270	21.5	21.5	6.2
18	97	157	245	270	23.5	23.5	8.5
19	100	160	245	270	23.2	23.2	8.9
20	97	157	245	270	24.8	22.1	8.8
21	103	163	245	270	22.8	22.0	5.8
22	57	117	245	270	33.8	22.0	5.0
23	57	117	245	270	33.3	21.6	4.5
24	79	139	245	270	28.8	22.6	4.8
25	45	105	245	270	37.0	19.6	3.3
26	28	88	245	270	39.8	20.2	3.9
27	35	95	245	270	37.7	18.2	2.4
28	135	195	245	270	13.4	13.4	6.7
29	135	195	245	270	13.4	13.4	8.2
30	135	195	245	270	13.4	13.4	6.9
31	135	195	245	270	13.4	13.4	7.4
32	123	183	245	270	15.9	15.9	8.1
33	123	183	245	270	15.9	15.9	8.4
34	128	188	245	270	16.7	16.7	5.4
35	141	201	245	270	11.0	11.0	5.9
36	130	190	245	270	13.2	13.2	7.3
37	140	200	245	270	12.1	12.1	6.4
38	133	193	245	270	13.6	13.6	7.5
39	136	196	245	270	13.3	13.3	6.9
40	111	171	245	270	18.0	18.0	8.3
41	140	200	245	270	10.8	10.8	5.7
42	135	195	245	270	12.1	12.1	5.6
43	135	195	245	270	13.2	13.2	5.8
44	146	206	245	270	9.9	9.9	5.9
45	142	202	245	270	10.3	10.3	4.9
46	116	176	245	270	14.2	14.2	8.4
47	151	211	245	270	11.6	11.6	5.9
48	82	142	245	270	30.2	18.2	4.4
49	40	100	245	270	38.3	19.4	5.1
50	27	87	245	270	44.0	17.3	6.1
51	66	126	245	270	27.9	20.9	3.6
52	73	133	245	270	33.3	19.5	5.5
53	82	142	245	270	32.0	17.9	3.4
54	107	167	245	270	26.3	15.9	3.1
55	36	96	245	270	36.1	20.9	7.3
56	36	96	245	270	40.0	19.8	5.8
57	48	108	245	270	42.8	27.8	2.5
58	43	103	245	270	38.0	20.8	2.7

Miscanthus data

Region	growing season start	crop closure	start leaf fall	leafless	production (ton/ha) potential	water-lim.	actual
1	153	196	300	300	15.4	15.4	9.1
2	144	187	300	300	16.9	16.9	8.2
3	138	181	300	300	17.2	17.2	9.5
4	130	172	300	300	20.3	20.3	9.8
5	133	175	300	300	19.4	19.4	8.5
6	135	177	300	300	20.3	20.3	8.8
7	144	186	300	300	18.9	18.9	8.7
8	133	175	300	300	19.4	19.4	7.5
9	135	177	300	300	20.6	20.6	11.2
10	132	174	300	300	21.4	21.4	12.0
11	141	184	300	300	17.5	17.5	9.3
12	139	181	300	300	18.8	18.8	7.6
13	133	176	300	300	20.9	20.9	8.1
14	126	168	300	300	25.2	25.2	7.7
15	127	168	300	300	25.3	25.3	7.6
16	110	151	300	300	32.6	24.2	6.2
17	103	143	300	300	27.5	27.5	7.9
18	99	139	300	300	29.4	29.4	10.6
19	101	142	300	300	29.4	29.4	11.3
20	99	139	300	300	31.2	26.8	10.6
21	114	155	300	300	27.6	26.0	6.8
22	92	134	300	300	35.7	24.2	5.4
23	100	142	300	300	34.0	23.4	4.9
24	108	149	300	300	31.0	24.4	5.2
25	89	131	300	300	38.1	19.4	3.2
26	70	114	300	300	42.1	20.3	4.0
27	81	124	300	300	38.7	18.0	2.3
28	143	186	300	300	16.8	16.8	8.4
29	143	186	300	300	16.8	16.8	10.2
30	143	186	300	300	16.8	16.8	8.7
31	143	186	300	300	16.8	16.8	9.2
32	134	176	300	300	19.0	19.0	9.7
33	134	176	300	300	19.0	19.0	10.0
34	135	178	300	300	21.0	21.0	6.8
35	168	213	300	300	10.7	10.7	5.8
36	151	194	300	300	14.2	14.2	7.9
37	157	201	300	300	13.7	13.7	7.3
38	154	197	300	300	14.7	14.7	8.1
39	153	196	300	300	15.1	15.1	7.8
40	153	197	300	300	15.8	15.8	7.3
41	157	201	300	300	12.5	12.5	6.5
42	153	197	300	300	13.5	13.5	6.3
43	155	199	300	300	14.5	14.5	6.4
44	166	212	300	300	10.6	10.6	6.4
45	164	210	300	300	10.8	10.8	5.1
46	154	198	300	300	12.6	12.6	7.5
47	157	200	300	300	14.9	14.9	7.6
48	95	135	300	300	35.4	20.5	4.9
49	90	132	300	300	38.8	18.1	4.8
50	1	104	300	300	51.3	20.0	7.0
51	106	148	300	300	28.6	21.3	3.7
52	96	138	300	300	37.0	19.6	5.6
53	112	153	300	300	34.4	18.8	3.6
54	128	168	300	300	30.5	17.4	3.4
55	72	117	300	300	38.1	23.2	8.1
56	57	100	300	300	44.7	21.1	6.1
57	95	140	300	300	42.0	26.1	2.4
58	96	138	300	300	37.2	18.6	2.4

Eucalyptus data

Region	growing season start	crop closure	start leaf fall	leafless	potential	production (ton/ha) water-lim.	actual
1	0	0	0	0	.0	.0	.0
2	0	0	0	0	.0	.0	.0
3	0	0	0	0	.0	.0	.0
4	0	0	0	0	.0	.0	.0
5	0	0	0	0	.0	.0	.0
6	0	0	0	0	.0	.0	.0
7	0	0	0	0	.0	.0	.0
8	0	0	0	0	.0	.0	.0
9	0	0	0	0	.0	.0	.0
10	0	0	0	0	.0	.0	.0
11	0	0	0	0	.0	.0	.0
12	0	0	0	0	.0	.0	.0
13	0	0	0	0	.0	.0	.0
14	0	0	0	0	.0	.0	.0
15	0	0	0	0	.0	.0	.0
16	0	0	0	0	.0	.0	.0
17	0	0	0	0	.0	.0	.0
18	0	0	0	0	.0	.0	.0
19	0	0	0	0	.0	.0	.0
20	0	0	0	0	.0	.0	.0
21	0	0	0	0	.0	.0	.0
22	1	1	365	365	49.6	36.8	8.3
23	1	1	365	365	49.2	36.6	7.6
24	0	0	0	0	.0	.0	.0
25	1	1	365	365	51.8	28.0	4.7
26	1	1	365	365	54.5	30.0	5.9
27	1	1	365	365	52.2	26.6	3.5
28	0	0	0	0	.0	.0	.0
29	0	0	0	0	.0	.0	.0
30	0	0	0	0	.0	.0	.0
31	0	0	0	0	.0	.0	.0
32	0	0	0	0	.0	.0	.0
33	0	0	0	0	.0	.0	.0
34	0	0	0	0	.0	.0	.0
35	0	0	0	0	.0	.0	.0
36	0	0	0	0	.0	.0	.0
37	0	0	0	0	.0	.0	.0
38	0	0	0	0	.0	.0	.0
39	0	0	0	0	.0	.0	.0
40	0	0	0	0	.0	.0	.0
41	0	0	0	0	.0	.0	.0
42	0	0	0	0	.0	.0	.0
43	0	0	0	0	.0	.0	.0
44	0	0	0	0	.0	.0	.0
45	0	0	0	0	.0	.0	.0
46	0	0	0	0	.0	.0	.0
47	0	0	0	0	.0	.0	.0
48	0	0	0	0	.0	.0	.0
49	1	1	365	365	54.1	32.0	8.4
50	1	1	365	365	59.3	25.5	9.0
51	0	0	0	0	.0	.0	.0
52	0	0	0	0	.0	.0	.0
53	0	0	0	0	.0	.0	.0
54	0	0	0	0	.0	.0	.0
55	1	1	365	365	50.9	25.5	8.9
56	1	1	365	365	56.1	31.1	9.1
57	1	1	365	365	59.8	43.0	3.9
58	1	1	365	365	54.2	32.9	4.2

Sorghum data

Region	growing season start	crop closure	start leaf fall	leafless	production (ton/ha) potential	water-lim.	actual
1	0	0	0	0	0.0	0.0	0.0
2	0	0	0	0	0.0	0.0	0.0
3	0	0	0	0	0.0	0.0	0.0
4	0	0	0	0	0.0	0.0	0.0
5	0	0	0	0	0.0	0.0	0.0
6	0	0	0	0	0.0	0.0	0.0
7	0	0	0	0	0.0	0.0	0.0
8	0	0	0	0	0.0	0.0	0.0
9	0	0	0	0	0.0	0.0	0.0
10	0	0	0	0	0.0	0.0	0.0
11	0	0	0	0	0.0	0.0	0.0
12	0	0	0	0	0.0	0.0	0.0
13	0	0	0	0	0.0	0.0	0.0
14	0	0	0	0	0.0	0.0	0.0
15	0	0	0	0	0.0	0.0	0.0
16	156	186	270	270	26.7	22.1	5.6
17	146	176	250	250	20.6	20.6	5.9
18	142	172	244	244	21.5	21.5	7.8
19	145	175	250	250	22.1	22.1	8.5
20	142	172	238	238	21.4	21.4	8.5
21	159	189	276	276	23.6	23.6	6.2
22	141	171	237	237	23.4	19.5	4.4
23	147	177	252	252	25.2	19.6	4.1
24	156	186	264	264	23.9	21.8	4.6
25	139	169	231	231	23.7	17.0	2.8
26	128	158	229	229	26.5	15.8	3.1
27	137	167	233	233	24.1	14.9	1.9
28	0	0	0	0	0.0	0.0	0.0
29	0	0	0	0	0.0	0.0	0.0
30	0	0	0	0	0.0	0.0	0.0
31	0	0	0	0	0.0	0.0	0.0
32	0	0	0	0	0.0	0.0	0.0
33	0	0	0	0	0.0	0.0	0.0
34	0	0	0	0	0.0	0.0	0.0
35	0	0	0	0	0.0	0.0	0.0
36	0	0	0	0	0.0	0.0	0.0
37	0	0	0	0	0.0	0.0	0.0
38	0	0	0	0	0.0	0.0	0.0
39	0	0	0	0	0.0	0.0	0.0
40	0	0	0	0	0.0	0.0	0.0
41	0	0	0	0	0.0	0.0	0.0
42	0	0	0	0	0.0	0.0	0.0
43	0	0	0	0	0.0	0.0	0.0
44	0	0	0	0	0.0	0.0	0.0
45	0	0	0	0	0.0	0.0	0.0
46	0	0	0	0	0.0	0.0	0.0
47	0	0	0	0	0.0	0.0	0.0
48	138	168	225	225	21.6	17.7	4.2
49	140	170	241	241	26.6	15.7	4.2
50	120	150	216	216	27.7	15.6	5.5
51	154	184	275	275	23.9	20.1	3.5
52	146	176	250	250	26.6	18.6	5.3
53	158	188	262	262	26.3	16.6	3.2
54	0	0	0	0	0.0	0.0	0.0
55	135	165	239	239	25.0	18.4	6.5
56	109	139	207	207	25.2	17.8	5.2
57	0	0	0	0	0.0	0.0	0.0
58	146	176	252	252	27.6	16.7	2.1

Wheat data

Region	growing season start	crop closure	start leaf fall	leafless	production (ton/ha) potential	water-lim.	actual	
1	76	136	198	213	10.1	10.1	6.0	0.59
2	76	136	198	213	9.9	9.9	4.8	0.49
3	76	136	198	213	9.3	9.3	5.2	0.55
4	76	136	198	213	10.4	10.1	4.9	0.48
5	76	136	198	213	10.2	10.2	4.5	0.44
6	76	136	198	213	10.2	10.2	4.4	0.43
7	76	136	198	213	10.3	10.3	4.7	0.46
8	76	136	198	213	10.2	10.2	4.0	0.39
9	50	110	181	196	10.4	10.4	5.7	0.55
10	66	126	194	209	11.1	9.4	5.3	0.56
11	76	136	217	232	11.6	10.8	5.7	0.53
12	76	136	217	232	11.8	11.1	4.5	0.40
13	54	114	202	217	12.9	10.7	4.2	0.39
14	54	114	202	217	13.7	12.1	3.7	0.31
15	54	114	202	217	14.0	12.9	3.9	0.30
16	54	114	202	217	15.6	10.4	2.6	0.25
17	45	105	181	196	11.2	11.2	3.2	0.29
18	45	105	181	196	11.5	11.3	4.1	0.36
19	45	105	181	196	11.5	11.1	4.2	0.38
20	45	105	181	196	12.0	10.8	4.3	0.40
21	45	105	176	191	10.4	10.1	2.6	0.26
22	45	105	176	191	12.4	9.7	2.2	0.23
23	35	95	166	181	11.5	9.5	2.0	0.21
24	45	105	176	191	11.8	9.7	2.1	0.21
25	35	95	166	181	12.3	7.8	1.3	0.17
26	35	95	166	181	12.4	7.8	1.5	0.20
27	35	95	166	181	12.2	7.4	1.0	0.13
28	71	131	205	220	10.9	10.9	5.4	0.50
29	71	131	198	213	10.3	10.3	6.3	0.61
30	71	131	222	237	12.5	12.5	6.4	0.52
31	71	131	205	220	10.9	10.9	6.0	0.55
32	71	131	205	220	11.0	9.9	5.1	0.51
33	71	131	205	220	11.0	9.9	5.2	0.53
34	86	146	207	222	11.1	10.3	3.3	0.32
35	70	130	212	227	10.4	10.4	5.6	0.54
36	70	130	212	227	10.6	10.5	5.8	0.55
37	70	130	212	227	10.9	10.6	5.6	0.53
38	70	130	212	227	11.3	10.4	5.8	0.55
39	70	130	212	227	11.4	10.8	5.6	0.52
40	70	130	212	227	11.9	11.4	5.3	0.46
41	70	130	212	227	9.8	9.8	5.2	0.52
42	70	130	212	227	10.4	10.4	4.8	0.46
43	70	130	212	227	11.5	11.5	5.1	0.44
44	70	130	212	227	10.0	10.0	6.0	0.60
45	70	130	212	227	10.1	10.1	4.8	0.48
46	86	146	223	238	9.8	9.8	5.8	0.59
47	70	130	212	227	12.7	10.8	5.5	0.51
48	45	105	181	196	13.1	8.6	2.1	0.24
49	45	105	181	196	13.7	7.8	2.1	0.26
50	45	105	181	196	15.4	5.8	2.1	0.35
51	40	100	181	196	11.6	9.8	1.7	0.17
52	40	100	181	196	14.6	9.2	2.6	0.28
53	50	110	192	207	15.3	9.3	1.8	0.19
54	45	105	197	212	15.2	9.4	1.8	0.20
55	45	105	197	212	15.4	8.1	2.9	0.35
56	30	90	161	176	13.4	8.9	2.6	0.29
57	50	110	192	207	18.0	12.3	1.1	0.09
58	50	110	192	207	15.2	8.7	1.1	0.13

Data hypothetical crop

Region	start	growing season crop closure	start leaf fall	leafless	production (ton/ha) water-lim.
1	1	1	365	365	37.2
2	1	1	365	365	37.1
3	1	1	365	365	36.5
4	1	1	365	365	40.0
5	1	1	365	365	39.3
6	1	1	365	365	41.6
7	1	1	365	365	41.9
8	1	1	365	365	39.3
9	1	1	365	365	42.0
10	1	1	365	365	42.0
11	1	1	365	365	38.6
12	1	1	365	365	39.8
13	1	1	365	365	41.2
14	1	1	365	365	46.6
15	1	1	365	365	47.9
16	1	1	365	365	45.1
17	1	1	365	365	46.7
18	1	1	365	365	46.4
19	1	1	365	365	47.2
20	1	1	365	365	43.8
21	1	1	365	365	45.2
22	1	1	365	365	42.0
23	1	1	365	365	41.8
24	1	1	365	365	43.3
25	1	1	365	365	32.0
26	1	1	365	365	34.3
27	1	1	365	365	30.4
28	1	1	365	365	37.7
29	1	1	365	365	37.7
30	1	1	365	365	37.7
31	1	1	365	365	37.7
32	1	1	365	365	38.5
33	1	1	365	365	38.5
34	1	1	365	365	43.3
35	1	1	365	365	32.5
36	1	1	365	365	33.6
37	1	1	365	365	35.4
38	1	1	365	365	36.5
39	1	1	365	365	37.3
40	1	1	365	365	39.6
41	1	1	365	365	32.9
42	1	1	365	365	33.7
43	1	1	365	365	37.6
44	1	1	365	365	31.8
45	1	1	365	365	32.2
46	1	1	365	365	33.1
47	1	1	365	365	37.4
48	1	1	365	365	32.4
49	1	1	365	365	36.5
50	1	1	365	365	29.1
51	1	1	365	365	38.2
52	1	1	365	365	24.3
53	1	1	365	365	33.7
54	1	1	365	365	32.9
55	1	1	365	365	29.1
56	1	1	365	365	35.5
57	1	1	365	365	49.1
58	1	1	365	365	37.6

Data new willow variety

Region	growing season start	crop closure	start leaf fall	leafless	production (ton/ha) water-lim.	improvement
1	111	141	275	330	22.8	9.1
2	104	134	275	330	23.5	8.8
3	95	125	275	330	23.7	8.3
4	90	120	275	330	26.7	9
5	89	119	275	330	26.3	8.8
6	92	122	275	330	26.9	9
7	103	133	275	330	25.7	9.4
8	89	119	275	330	26.3	8.8
9	85	115	275	330	28.2	8.8
10	80	110	275	330	28.6	8.2
11	88	118	275	330	25.7	8.5
12	94	124	275	330	25.7	8.8
13	69	99	275	330	29.5	7.4
14	55	85	275	330	33.5	8.3
15	79	109	275	330	32.8	9.7
16	43	73	275	330	31.4	7.1
17	65	95	275	330	32.2	8.6
18	60	90	275	330	33.8	8.3
19	63	93	275	330	33.8	8.5
20	60	90	275	330	31.1	7.3
21	65	95	275	330	30.7	7.1
22	15	45	275	330	31.3	6.9
23	15	45	275	330	31.0	6.8
24	37	67	275	330	31.4	6.8
25	4	34	275	330	25.6	4.7
26	1	31	275	330	26.6	4.6
27	1	31	275	330	24.3	4.6
28	98	128	275	330	24.2	8.8
29	98	128	275	330	24.2	8.8
30	98	128	275	330	24.2	8.8
31	98	128	275	330	24.2	8.8
32	85	115	275	330	26.3	8.4
33	85	115	275	330	26.3	8.4
34	90	120	275	330	28.6	9.5
35	101	131	275	330	20.9	7.7
36	91	121	275	330	22.8	7.6
37	102	132	275	330	22.4	8.3
38	94	124	275	330	24.1	8.3
39	98	128	275	330	23.9	8.6
40	68	98	275	330	28.6	7.8
41	102	132	275	330	20.5	7.7
42	96	126	275	330	21.9	7.7
43	96	126	275	330	24.1	8.6
44	107	137	275	330	19.5	7.7
45	103	133	275	330	20.0	7.8
46	74	104	275	330	23.4	6.9
47	114	144	275	330	23.1	9.5
48	43	73	275	330	24.5	4.7
49	0	30	275	330	26.6	5.3
50	1	31	275	330	22.0	4.1
51	25	55	275	330	28.7	5.9
52	34	64	275	330	20.3	0.9
53	41	71	275	330	25.8	5.8
54	68	98	275	330	22.8	5.3
55	1	31	275	330	25.1	2.5
56	1	31	275	330	26.6	5.5
57	7	37	275	330	37.2	6.7
58	3	33	275	330	27.1	5.6

Appendix II
Annual input requirements

The annual input requirements (both energy and labour) of 5 poplar production systems during the complete rotation of 20 years

production system 1

yield level: stems: 12 ton/ha + leaves: 5 ton/ha

year	action		Freq./Quantity(kg)	GJ	Labour (hr)
1	tillage			3	4
	planting			3	13
	fertilization	nitrogen	306	20	
		application	1 x	0.25	0.5
	weeding		2 x	0.7	3
	crop protection	fungicides	3	0.6	
		spraying	3 x	0.6	1.5
2	fertilization	nitrogen	71	5	
		application	1 x	0.25	0.5
	crop protection	fungicides	3	0.6	
		spraying	3 x	0.6	1.5
3	fertilization	nitrogen	71	5	
		application	1 x	0.25	0.5
	crop protection	fungicides	3	0.6	
		spraying	3 x	0.6	1.5
4	fertilization	nitrogen	71	5	
		application	1 x	0.25	0.5
	crop protection	fungicides	3	0.6	
		spraying	3 x	0.6	1.5
	harvest			28.8	9.6
5	fertilization	nitrogen	71	5	
		application	1 x	0.25	0.5
	weeding		2 x	0.7	3
	crop protection	fungicides	3	0.6	
		spraying	3 x	0.6	1.5
6	fertilization	nitrogen	71	5	
		application	1 x	0.25	0.5
	crop protection	fungicides	3	0.6	
		spraying	3 x	0.6	1.5
7	fertilization	nitrogen	71	5	
		application	1 x	0.25	0.5
	crop protection	fungicides	3	0.6	
		spraying	3 x	0.6	1.5
8	fertilization	nitrogen	71	5	
		application	1 x	0.25	0.5
	crop protection	fungicides	3	0.6	
		spraying	3 x	0.6	1.5
	harvest			28.8	9.6
9	fertilization	nitrogen	71	5	
		application	1 x	0.25	0.5
	weeding		2 x	0.7	3
	crop protection	fungicides	3	0.6	
		spraying	3 x	0.6	1.5
10	fertilization	nitrogen	71	5	
		application	1 x	0.25	0.5
	crop protection	fungicides	3	0.6	
		spraying	3 x	0.6	1.5

production system 1 (continued)

yield level: stems: 12 ton/ha + leaves: 5 ton/ha

year	action		Freq./Quantity(kg)	GJ	Labour (hr)
11	fertilization	nitrogen	71	5	
		application	1 x	0.25	0.5
	crop protection	fungicides	3	0.6	
		spraying	3 x	0.6	1.5
12	fertilization	nitrogen	71	5	
		application	1 x	0.25	0.5
	crop protection	fungicides	3	0.6	
		spraying	3 x	0.6	1.5
	harvest			28.8	9.6
13	fertilization	nitrogen	71	5	
		application	1 x	0.25	0.5
	weeding		2 x	0.7	3
	crop protection	fungicides	3	0.6	
		spraying	3 x	0.6	1.5
14	fertilization	nitrogen	71	5	
		application	1 x	0.25	0.5
	crop protection	fungicides	3	0.6	
		spraying	3 x	0.6	1.5
15	fertilization	nitrogen	71	5	
		application	1 x	0.25	0.5
	crop protection	fungicides	3	0.6	
		spraying	3 x	0.6	1.5
16	fertilization	nitrogen	71	5	
		application	1 x	0.25	0.5
	crop protection	fungicides	3	0.6	
		spraying	3 x	0.6	1.5
	harvest			28.8	9.6
17	fertilization	nitrogen	71	5	
		application	1 x	0.25	0.5
	weeding		2 x	0.7	3
	crop protection	fungicides	3	0.6	
		spraying	3 x	0.6	1.5
18	fertilization	nitrogen	71	5	
		application	1 x	0.25	0.5
	crop protection	fungicides	3	0.6	
		spraying	3 x	0.6	1.5
19	fertilization	nitrogen	71	5	
		application	1 x	0.25	0.5
	crop protection	fungicides	3	0.6	
		spraying	3 x	0.6	1.5
20	fertilization	nitrogen	71	5	
		application	1 x	0.25	0.5
	crop protection	fungicides	3	0.6	
		spraying	3 x	0.6	1.5
	harvest			28.8	9.6

total input	289.6	120
average input per year	14.5	6
gross yield (GJ)= 20*12*18=	4320.0	
net yield (GJ)= gross- input=	4030.4	
average net yield/year	201.5	
efficiency	13.9	

production system 2

yield level: stems: 9.6 ton/ha + leaves: 4 ton/ha leaves

year	action		Freq./Quantity(kg)	GJ	Labour (hr)
1	tillage			3	4
	planting			3	13
	fertilization	nitrogen	245	16	
		application	1 x	0.25	0.5
	weeding		2 x	0.7	3
2	fertilization	nitrogen	56	4	
		application	1 x	0.25	0.5
3	fertilization	nitrogen	56	4	
		application	1 x	0.25	0.5
4	fertilization	nitrogen	56	4	
		application	1 x	0.25	0.5
	harvest			23.04	7.68
5	fertilization	nitrogen	56	4	
		application	1 x	0.25	0.5
	weeding		2 x	0.7	3
6	fertilization	nitrogen	56	4	
		application	1 x	0.25	0.5
7	fertilization	nitrogen	56	4	
		application	1 x	0.25	0.5
8	fertilization	nitrogen	56	4	
		application	1 x	0.25	0.5
	harvest			23.04	7.68
9	fertilization	nitrogen	56	4	
		application	1 x	0.25	0.5
	weeding		2 x	0.7	3
10	fertilization	nitrogen	56	4	
		application	1 x	0.25	0.5
11	fertilization	nitrogen	56	4	
		application	1 x	0.25	0.5
12	fertilization	nitrogen	56	4	
		application	1 x	0.25	0.5
	harvest			23.04	7.68
13	fertilization	nitrogen	56	4	
		application	1 x	0.25	0.5
	weeding		2 x	0.7	3
14	fertilization	nitrogen	56	4	
		application	1 x	0.25	0.5
15	fertilization	nitrogen	56	4	
		application	1 x	0.25	0.5
16	fertilization	nitrogen	56	4	
		application	1 x	0.25	0.5
	harvest			23.04	7.68
17	fertilization	nitrogen	56	4	
		application	1 x	0.25	0.5
	weeding		2 x	0.7	3
18	fertilization	nitrogen	56	4	
		application	1 x	0.25	0.5
19	fertilization	nitrogen	56	4	
		application	1 x	0.25	0.5
20	fertilization	nitrogen	56	4	
		application	1 x	0.25	0.5
	harvest			23.04	7.68

	GJ	Labour (hr)
total input	215.3	80.4
average input per year	10.8	4.0
gross yield (GJ)= 20*9.6*18=	3456.0	
net yield (GJ)= gross- input=	3240.7	
average net yield/year	162.0	
efficiency	15.0	

production system 3
yield level: stems: 43 ton/ha + leaves: 8 ton/ha

year	action		Freq./Quantity(kg)	GJ	Labour (hr)
1	tillage			3	4
	planting			3	13
	fertilization	nitrogen	1100	72	
		application	4 x	1	2
	weeding		2 x	0.7	3
	crop protection	fungicides	3	0.6	
		spraying	3 x	0.6	1.5
	irrigation		33 x 15 mm	35	17
2	fertilization	nitrogen	253	16	
		application	1 x	0.25	0.5
	crop protection	fungicides	3	0.6	
		spraying	3 x	0.6	1.5
	irrigation		33 x 15 mm	35	17
3	fertilization	nitrogen	253	16	
		application	1 x	0.25	0.5
	crop protection	fungicides	3	0.6	
		spraying	3 x	0.6	1.5
	irrigation		33 x 15 mm	35	17
4	fertilization	nitrogen	253	16	
		application	1 x	0.25	0.5
	crop protection	fungicides	3	0.6	
		spraying	3 x	0.6	1.5
	irrigation		33 x 15 mm	35	17
	harvest			103.2	34.4
5	fertilization	nitrogen	253	16	
		application	2 x	0.5	1
	weeding		2 x	0.7	3
	crop protection	fungicides	3	0.6	
		spraying	3 x	0.6	1.5
	irrigation		33 x 15 mm	35	17
6	fertilization	nitrogen	253	16	
		application	1 x	0.25	0.5
	crop protection	fungicides	3	0.6	
		spraying	3 x	0.6	1.5
	irrigation		33 x 15 mm	35	17
7	fertilization	nitrogen	253	16	
		application	1 x	0.25	0.5
	crop protection	fungicides	3	0.6	
		spraying	3 x	0.6	1.5
	irrigation		33 x 15 mm	35	17
8	fertilization	nitrogen	253	16	
		application	1 x	0.25	0.5
	crop protection	fungicides	3	0.6	
		spraying	3 x	0.6	1.5
	irrigation		33 x 15 mm	35	17
	harvest			103.2	34.4
9	fertilization	nitrogen	253	16	
		application	2 x	0.5	1
	weeding		2 x	0.7	3
	crop protection	fungicides	3	0.6	
		spraying	3 x	0.6	1.5
	irrigation		33 x 15 mm	35	17
10	fertilization	nitrogen	253	16	
		application	1 x	0.25	0.5
	crop protection	fungicides	3	0.6	
		spraying	3 x	0.6	1.5
	irrigation		33 x 15 mm	35	17
11	fertilization	nitrogen	253	16	
		application	1 x	0.25	0.5
	crop protection	fungicides	3	0.6	
		spraying	3 x	0.6	1.5
	irrigation		33 x 15 mm	35	17

production system 3 (continued)

yield level: stems: 43 ton/ha + leaves: 8 ton/ha

year	action		Freq./Quantity(kg)	GJ	Labour (hr)
12	fertilization	nitrogen	253	16	
		application	1 x	0.25	0.5
	crop protection	fungicides	3	0.6	
		spraying	3 x	0.6	1.5
	irrigation		33 x 15 mm	35	17
	harvest			103.2	34.4
13	fertilization	nitrogen	253	16	
		application	2 x	0.5	1
	weeding		2 x	0.7	3
	crop protection	fungicides	3	0.6	
		spraying	3 x	0.6	1.5
	irrigation		33 x 15 mm	35	17
14	fertilization	nitrogen	253	16	
		application	1 x	0.25	0.5
	crop protection	fungicides	3	0.6	
		spraying	3 x	0.6	1.5
	irrigation		33 x 15 mm	35	17
15	fertilization	nitrogen	253	16	
		application	1 x	0.25	0.5
	crop protection	fungicides	3	0.6	
		spraying	3 x	0.6	1.5
	irrigation		33 x 15 mm	35	17
16	fertilization	nitrogen	253	16	
		application	1 x	0.25	0.5
	crop protection	fungicides	3	0.6	
		spraying	3 x	0.6	1.5
	irrigation		33 x 15 mm	35	17
	harvest			103.2	34.4
17	fertilization	nitrogen	253	16	
		application	2 x	0.5	1
	weeding		2 x	0.7	3
	crop protection	fungicides	3	0.6	
		spraying	3 x	0.6	1.5
	irrigation		33 x 15 mm	35	17
18	fertilization	nitrogen	253	16	
		application	1 x	0.25	0.5
	crop protection	fungicides	3	0.6	
		spraying	3 x	0.6	1.5
	irrigation		33 x 15 mm	35	17
19	fertilization	nitrogen	253	16	
		application	1 x	0.25	0.5
	crop protection	fungicides	3	0.6	
		spraying	3 x	0.6	1.5
	irrigation		33 x 15 mm	35	17
20	fertilization	nitrogen	253	16	
		application	1 x	0.25	0.5
	crop protection	fungicides	3	0.6	
		spraying	3 x	0.6	1.5
	irrigation		33 x 15 mm	35	17
	harvest			103.2	34.4

total input	1640.1	587.5
average input per year	82.0	29.4
gross yield (GJ)= 20*43*18=	15480.0	
net yield (GJ)= gross- input=	13839.9	
average net yield/year	692.0	
efficiency	8.4	

production system 4

yield level: stems: 27.8 ton/ha + leaves :12 ton/ha

year	action		Freq./Quantity(kg)	GJ	Labour (hr)
1	tillage			3	4
	planting			3	13
	fertilizer	nitrogen	729	47	
		application	3 x	0.75	1.5
	weeding		2 x	0.7	3
	crop protection	fungicides	3	0.6	
		spraying	3 x	0.6	1.5
2	fertilizer	nitrogen	165	11	
		application	1 x	0.25	0.5
	crop protection	fungicides	3	0.6	
		spraying	3 x	0.6	1.5
3	fertilizer	nitrogen	165	11	
		application	1 x	0.25	0.5
	crop protection	fungicides	3	0.6	
		spraying	3 x	0.6	1.5
4	fertilizer	nitrogen	165	11	
		application	1 x	0.25	0.5
	crop protection	fungicides	3	0.6	
		spraying	3 x	0.6	1.5
	harvest			67.2	22.4
5	fertilizer	nitrogen	165	11	
		application	1 x	0.25	0.5
	weeding		2 x	0.7	3
	crop protection	fungicides	3	0.6	
		spraying	3 x	0.6	1.5
6	fertilizer	nitrogen	165	11	
		application	1 x	0.25	0.5
	crop protection	fungicides	3	0.6	
		spraying	3 x	0.6	1.5
7	fertilizer	nitrogen	165	11	
		application	1 x	0.25	0.5
	crop protection	fungicides	3	0.6	
		spraying	3 x	0.6	1.5
8	fertilizer	nitrogen	165	11	
		application	1 x	0.25	0.5
	crop protection	fungicides	3	0.6	
		spraying	3 x	0.6	1.5
	harvest			67.2	22.4
9	fertilizer	nitrogen	165	11	
		application	1 x	0.25	0.5
	weeding		2 x	0.7	3
	crop protection	fungicides	3	0.6	
		spraying	3 x	0.6	1.5
10	fertilizer	nitrogen	165	11	
		application	1 x	0.25	0.5
	crop protection	fungicides	3	0.6	
		spraying	3 x	0.6	1.5
11	fertilizer	nitrogen	165	11	
		application	1 x	0.25	0.5
	crop protection	fungicides	3	0.6	
		spraying	3 x	0.6	1.5
12	fertilizer	nitrogen	165	11	
		application	1 x	0.25	0.5
	crop protection	fungicides	3	0.6	
		spraying	3 x	0.6	1.5
	harvest			67.2	22.4

production system 4 (continued)
yield level: stems: 27.8 ton/ha + leaves :12 ton/ha

year	action		Freq./Quantity(kg)	GJ	Labour (hr)
13	fertilizer	nitrogen	165	11	
		application	1 x	0.25	0.5
	weeding		2 x	0.7	3
	crop protection	fungicides	3	0.6	
		spraying	3 x	0.6	1.5
14	fertilizer	nitrogen	165	11	
		application	1 x	0.25	0.5
	crop protection	fungicides	3	0.6	
		spraying	3 x	0.6	1.5
15	fertilizer	nitrogen	165	11	
		application	1 x	0.25	0.5
	crop protection	fungicides	3	0.6	
		spraying	3 x	0.6	1.5
16	fertilizer	nitrogen	165	11	
		application	1 x	0.25	0.5
	crop protection	fungicides	3	0.6	
		spraying	3 x	0.6	1.5
	harvest			67.2	22.4
17	fertilizer	nitrogen	165	11	
		application	1 x	0.25	0.5
	weeding		2 x	0.7	3
	crop protection	fungicides	3	0.6	
		spraying	3 x	0.6	1.5
18	fertilizer	nitrogen	165	11	
		application	1 x	0.25	0.5
	crop protection	fungicides	3	0.6	
		spraying	3 x	0.6	1.5
19	fertilizer	nitrogen	165	11	
		application	1 x	0.25	0.5
	crop protection	fungicides	3	0.6	
		spraying	3 x	0.6	1.5
20	fertilizer	nitrogen	165	11	
		application	1 x	0.25	0.5
	crop protection	fungicides	3	0.6	
		spraying	3 x	0.6	1.5
	harvest			67.2	22.4

	GJ	Labour (hr)
total input	625.8	185
average input per year	31.3	9.25
gross yield (GJ) = 20*27.8*18=	10008.0	
net yield (GJ)= gross- input=	9382.2	
average net yield/year	469.1	
efficiency	15.0	

production system 5

yield level: stems: 5 ton/ha + leaves 2 ton/ha

year	action		Freq./Quantity(kg)	GJ	Labour (hr)
1	tillage			3	4
	planting			3	13
	fertilizer	nitrogen	124	8	
		application	1 x	0.25	0.5
	weeding		2 x	0.7	3
2					
3					
4	harvest			12	4
5	weeding		2 x	0.7	3
6					
7					
8	harvest			12	4
9	weeding		2 x	0.7	3
10					
11					
12	harvest			12	4
13	weeding		2 x	0.7	3
14					
15					
16	harvest			12	4
17	weeding		2 x	0.7	3
18					
19					
20	harvest			12	4

	GJ	Labour (hr)
total input	77.8	52.5
average input per year	3.9	2.6
gross yield (GJ)= 20*5*18	1800.0	
net yield (GJ)= gross- input=	1722.2	
average net yield/year	86.1	
efficiency	22.1	