Climatic Change and Agricultural Production in Europe

J. Goudriaan, J. Wolf and S. Nonhebel

ABSTRACT

In Europe the agricultural production per unit land area has risen over the past decades by a factor 2-3. In the North-Western European countries the agricultural yields are presently approaching the potential level. Potential yields are approximately proportional to the duration of the growth period. In non-determinate, non-maturing crops (silage crops, sugar beet) this duration is constrained by *climatic* conditions, in determinate crops (wheat, sunflower) it is constrained by plant *phenology*.

Climatic warming will extend the duration of the "*climatological*" growing season in most parts of Europe. The "*phenological*" growing season on the other hand will be shortened. The northern limit of cultivation of many crops will shift northward by about 300 km per °C temperature increase. For the southern part of Europe most GCM-studies suggest a decreasing precipitation in the summer. Therefore, in those regions interruption of the growing season by a period with water shortage in the middle of the summer will become more outspoken.

Increased CO_2 stimulates plant growth directly and will have a positive effect on yields, both in the potential growth situation and in conditions of water shortage. The annual rate of increase of atmospheric CO_2 (1.5 ppm per year) is responsible for a yield increase of up to 0.2% per year. However, the historic trend of improvement of agricultural technology has a much larger effect and has caused annual yield increases of about 2% per year.

This shows that the dynamics of possible changes in climate will probably be slower than the actual dynamics of technological change in farming. In some southern regions of Europe increasing drought may cause large problems, but in most regions farming is expected to adapt to changing conditions without large difficulties. Most adaptations are those that are needed anyway, such as improved nutrition, improved irrigation, improved plant protection, and breeding for better varieties.

INTRODUCTION

Atmospheric CO_2 has been rising over the last century and will most likely continue to do so. Its greenhouse effect, together with that of other trace gases such as nitrous oxide, methane and tropospheric ozone, might warm up the earth's surface and cool down the stratospheret. On a global scale a climatic signal of this greenhouse-effect has not been unequivocally detected against the background of ever-present natural fluctuations in weather.

Warmer air can contain more water vapour, which is a greenhouse gas itself, and in this way atmospheric warming may be amplified. The magnitude of this positive feedback loop is is not well known, and many factors such as the relation between water vapour content and cloud formation add to the uncertainty. Clouds have a cooling effect by intercepting solar radiation, but at the same time they have a warming effect by intercepting terrestrial long-wave radiation. This kind of uncertainty is one of the reasons why estimates on temperature change made by the IPCC(Houghton et al.,1990) have a relatively wide range, from 1.5 to 4.5 degree Celsius increase for a doubling of CO_2 . The very existence of feed-back mechanisms that might mitigate temperature effects, could mean unexpected side-effects to other climatic characteristics such as global radiation received at the earth surface, and air humidity. These other factors are of great importance to agriculture and to ecosystem functioning in general.

CLIMATE CHANGE IN EUROPE, RECORDED AND EXPECTED

On the basis of mostly circumstantial evidence Lamb (1984) established a curve for mean annual air temperature in England over the past one thousand years (Fig 1). Between the years 1100 and 1300 AC a warm period occurred, to be followed by a much colder period that is now known as the Little Ice Age. The transition from the warmer to the colder period was accompanied by many disasters, the pest, famine and inundations. In the middle of the cold period (17th century), the growing season was about one month shorter than it had been in the Middle Ages. From about the year 1850 onwards a gradual rise in temperature until present is observed. This is also indicated by the withdrawal of most glaciers in the Alps in Europe, which are much smaller now than they were one hundred years ago (Berger, 1992).

In The Netherlands an uninterrupted time series exists of the mean annual temperature, observed in De Bilt since the year 1706 (Schuurmans,1981). Until the end of the last decade the 30-years mean annual temperature in The Netherlands was 9.1 °C. Coops (1993) who investigated this temperature series, as well as those of a dozen other European stations, could not detect any recent significant change in temperature. He may have finished his analysis just too early, as this year, 1993, the Royal Dutch Meteorological Institute KNMI issued a report on the state of the climate in The Netherlands, showing a significant increase of the decadal time course of mean annual temperature from 9.1 °C to 10.5 °C (Fig 2; KNMI,1993). The report does warn against interpreting this sudden increase as a proof of real occurrence of the greenhouse-effect. First, it is just a local observation and not a global mean. Second, significant changes in temperature did occur in the past as well, although there was no concomitant change in atmospheric CO_2. Moreover, no significant changes were found in other climatic characteristics, such as precipitation, wind speed or radiation.

Future scenarios of climate change for Europe were constructed by Barrow (1993), and were applied for calculating the agricultural and horticultural potential in Europe (Kenny et al.,1993). These scenarios were based on the output of several general circulation models (GCM's). Such models are considered to give the best representation of the complex interactions of processes in the climate system. The best-estimate scenarios give 0.5 - 1.0 °C warming for most of Europe in all seasons for the year 2010, rising to about 2.0 °C by the year 2050, with some seasonal and geographical differences. For northern Europe the expected changes in precipitation are small, both for the year 2010 (0 to +4%) and the year 2050(0 to + 12%). For southern Europe the expected changes in precipitation range from -4 to + 4% for the year 2010 and from -18 to + 12% for the year 2050, with greatest decreases in precipitation in summer. However, individual model results appeared to vary strongly for identical regions, with both increases and decreases of GCM monthly precipitation in the order of 50%.

Such large discrepancies are a sign of immaturity of model results, but they do give a clear warning of the range of the physically possible, especially because precipitation is one of the most important climatic variables for agriculture.

HISTORICAL TREND OF AGRICULTURAL YIELD

The agricultural production per unit land area depends on climate, crop properties and farming methods. The time trend of wheat yields in North-Western Europe since the Middle Ages shows a dramatically accelerated increase around the year 1900 (Slicher van Bath,1963). Over the last decades agricultural production per land area has risen by a factor 2-3 by improvement of agricultural methods (Fig 3). Increased fertilization extended the duration of crop growth and plant breeding resulted in an increase of the fraction harvestable product (harvest index). The world-wide average grain production rose from 1210 kg/ha in 1938 to 2480 kg/ha in 1988 (Loomis and Connor,1992), in Europe from 1480 to 4340, and in The Netherlands even to 7255 kg/ha. At closer inspection the yield increase curve shows a strong acceleration at a yield level between 1500 and 2000 kg/ha (De Wit et al,1979). This is the level at which the use of nitrogen and phosphorus fertilizers is introduced. In the North-Western European countries the agricultural yields are presently approaching the potential level, roughly estimated to be around 10 tons/ha of grain yield. This potential level will probably increase with increasing atmospheric concentrations of CO_2.

Such high yields are only possible by skillful farm management techniques, proper nutrient supply, use of better plant varieties, timely protection against weeds, pests and diseases, and efficient harvest techniques. Also for other crops (sugar beet, potato) yield increases have been considerable.

CLIMATE AND CROPS

Potential yield and growing season

Sibma (1968) and De Wit et al. (1979) showed that potential growth rates of crops are remarkably stable and independent of the type of crop (Fig 4). In a situation of potential growth, growth rate is limited by the process of photosynthesis itself, which has appeared to be hardly amenable to plant breeding. As a consequence, the realized total crop production is mainly determined by the duration of the period that the growth can be maintained. It is useful to distinguish between external and internal factors that may limit this duration. Limitation by external, *climatic* factors is mainly seen in non-determinate, non-maturing crops (silage crops, sugar beet, pasture grass) . In such a situation the term growing season means *climatic* growing season. On the other hand, in determinate crops (wheat, sunflower, rice) the growth duration is constrained by plant phenology (internal factors) and the term growing season means *phenological* growing season. A determinate crop can only grow successfully, if the length of the *climatic* growing season is so long that its phenological growing season (also sometimes termed its growing cycle) can be completed.

Along a gradient from south to north (on the northern hemisphere) spring starts later and autumn begins earlier, and hence the duration of the *climatic* growing season decreases. Following the same gradient, summer temperatures become lower, and consequently the rate of crop development slows down and the duration of the *phenological* growing season extends. The northern limit of cultivation is reached where both durations approach each other.

In temperate regions where the response of development rate to temperature is almost linear, the accumulation of daily temperatures above a crop specific base temperature(i.e. the temperature sum) is a convenient indication for the fulfillment of heat requirement during the growing season. In Table 1 a list is given of *available* and *required* temperature sums for a few locations and crops in Europe. In cool climates the potato crop appears to be particularly suitable because it can be harvested even before it has completed its growing cycle.It is only necessary that its tuber formation has started, and to do so it does not need a large temperature sum. Even on Iceland tuber formation can briefly proceed before the climatic growing season ends.

In The Netherlands, potatoes, faba bean, spring wheat and sugar beet (not shown) can be grown without any difficulty, because the available temperature sum amply exceeds the required one. Sunflower (*Helianthus annuus* L.) on the other hand is a marginal crop in The Netherlands. In average years it could theoretically obtain just sufficient summer heat to reach maturity. However, in practice the risk of crop failure in cool summers is too high and as a result, sunflower is not a common crop in The Netherlands. A few hundred kilometers to the south, in France, this risk of failure is much smaller and here we can find sunflower as a regular crop.

Agro-ecological zoning

For each crop an agro-ecological suitability map can be constructed, once we know the crop-specific temperature sum and the map of available temperature sums (Fig 5, from Kenny and Harrison, 1993).

Climatic warming will extend the duration of the "climatological" growing season in most parts of Europe, whereas the "phenological" growing season will be shortened (Kenny et al., 1993). At the northern margin of possible cultivation the phenological growing season will then better fit into the climatological season. As a result the northern limit of cultivation of many crops will shift northward by about 300 km per °C temperature increase in the western, maritime parts of Europe (Fig 6). In the central, more continental, parts of Europe the northward shift will be less, due to the much larger seasonal amplitude in temperature. The moment of the onset of spring will be less sensitive to warming than in the mild maritime climatic zone and hence, the northward shift in central Europe is only about 150 km per degree of warming. The northern limit of grain maize cultivation could reach the middle of Sweden upon a temperature increase of 3 degrees Celsius.

The magnitude of the expected shift differs for each type of crop. Cultivation of grapes for instance will be extended to a lesser extent (Fig 5b), presumably because of radiation requirements and frost sensitivity.

The southern limit of cultivation is less clearly defined. In southern Europe crops as sugar beet and wheat may still be grown, but on farmers decision they are partly replaced by more suitable crops (grain maize, sunflower, soybean, grapes, olives). The availability of water becomes an important factor in the southern regions. De Koning and Van Diepen (1992), in a study for the Netherlands Scientific Council for Government Policy, used a Geographical Information System (GIS) for this purpose. In the GIS, a map of soil characteristics (crop suitability, water availability etc), an agro-climatic map and an EC-administrative map were stored, and the information was combined by an overlay procedure and used for crop growth simulations. This procedure enabled them to make a geographically detailed estimation of the production potential for various crops in the countries of the European Community (De Koning and Van Diepen, Fig 7) . In this way they not only considered temperature sum, but also the amount of water available for transpiration.

For the southern part of Europe most GCM-scenarios indicate a decreasing precipitation in summer. Therefore, in those regions interruption of the growing season by a period with water shortage will become more outspoken and may result in the following changes in cropping pattern and management: more crops grown in spring and less in the middle of summer; crops grown that are less sensitive to drought; more irrigation water applied.

In view of the relative stability of growth rate as long as the crop still grows, potential yield is primarily determined by the duration of the growing season. The duration of the phenological growing season increases in northward direction, and so will the potential yield. The highest yields are therefore obtained close to the northern boundary of possible cultivation, and not in the centre of the suitable cultivation zone.

Climatic versus weather data

Crop growth simulation models are often used to assess possible effects of climatic change. As a first approximation, mean climatic data (i.e. weather data averaged over a large number of years) give a good impression of the crop growth potential in a certain region. Potential effects of a climatic change are then studied by imposing a certain shift of the climatic means. However, a recent study (Nonhebel,1993) has shown that the use of mean climatic data as weather input for crop simulation models can lead to a serious overestimation of the potential yield. The correct procedure is to run the model for a large number of years using actual weather data, and to assess the statistical means and standard deviation of simulated yields afterwards. The daily variability of actual weather reduces yield formation, even to the extent that the use of 10-day means may result in an overestimation of yield by 10% or more.

This finding has also implications for the way in which gaps in actual weather records should be filled, in case weather data are missing for a single day. Nonhebel (1993) showed that it is better to use an observed value of a station in the neighbourhood (up to 100 km away if it is in the same climatic region) than a 10-day mean value. For global radiation an alternative is to use sunshine duration.

DIRECT EFFECTS OF CO_2

Increased CO_2 stimulates plant growth directly and will have a positive effect on yields, both in the potential growth situation and in conditions of water shortage. The basic cause of the direct effect of CO_2 on vegetation is that air is the only source of carbon for plants and that atmospheric CO_2 is a trace gas at a concentration of only 0,035% (350 μmol mol^{-1}). Plant dry matter has a fairly stable carbon content of about 45% to 50%. This range is in fact much smaller than those for nutrients such as nitrogen, phosphorus and potassium, which may vary by a factor five. CO_2-enrichment is widely employed in glasshouses to improve horticultural yield, both in quantity and in quality (Wittwer and Robb,1964; Enoch and Kimball,1986; Nederhoff and Van Uffelen,1988). On a physiological level, not only CO_2-assimilation is stimulated, but also plant respiration rate may be reduced(Amthor, 1991; Mousseau,1993).

Other limiting factors

There is no doubt about the existence of the positive CO_2 effect on final dry matter formation under favourable conditions for plant growth, such as found in intensive agriculture, but this positive effect is not always maintained under natural conditions when plant growth is limited by other factors (Rozema et al., 1992). In common agricultural practice we see a strong response of plant growth to water and nutrients, suggesting that these factors are much more important than atmospheric CO_2. Without denying that the role of CO_2 is often limited, the possibility of co-limitation of CO_2 with other factors should be considered. This phenomenon is most clearly illustrated by the interaction of water and CO_2.

Water

Photosynthesizing plant cells of terrestrial plants can only absorb atmospheric CO_2 by dissolving it in their cell solution for further processing by the photosynthetic machinery. By exposing the wet cell surfaces to ambient air the plant will inevitably loose water by transpiration. Land plants have protected themselves from drying out by the formation of a dry skin, the epidermis, which contains pores, the stomatal apertures, to permit entrance of CO_2. Although the fraction of surface area of the stomatal apertures within a normal leaf is usually less than 1%, CO_2 uptake is not more reduced than to about 70 - 80% of what it could have been without stomatal constraint. Transpiration on the other hand, is much more reduced, down to even 10%, dependent on the circumstances. Clearly this morphological adaptation to life on land has improved the water use efficiency to a large extent.

Active control of stomatal aperture enables a fine-tuning of CO_2 and water vapour exchange, dependent on the relative losses of water and potential gain in CO_2 uptake. During the night for instance, when photosynthesis is impossible anyway, the stomatal apertures are usually closed. Another characteristic feature of stomatal fine-tuning is the induction of partial stomatal closure by rising CO_2 (Raschke, 1975; Morison, 1987). In addition, stomatal conductance appears to be well correlated with photosynthesis when light varies (Goudriaan and Van Laar, 1978). This also applies when unfavorable conditions occur such as air pollution, shortages of water or nutrients (Wong,1979, Goudriaan and Van Keulen, 1979), or senescence (Goudriaan and Van Laar,1978).

In spite of these adaptations the ratio between water loss and carbon gain is still very high. The basic problem for the plants is the low concentration of atmospheric CO_2. The gradient of CO_2 along the stomatal pores is always at least by a factor of one hundred smaller than the opposite gradient of water vapour. This simple physical fact explains the very large water requirements of plants, hundreds of kilograms of water transpired per kilogram of dry matter formed. Under droughty conditions plant growth will not only be stimulated by better availability of water, but also by increasing CO_2(Gifford,1979; Morison,1992).

Radiation

In addition to water, also other limiting factors are often used more efficiently under increased CO_2. The supply of both radiation and CO_2 is generally suboptimal, and photosynthesis is stimulated by an increase of ambient CO_2. It appears that this stimulation does not only occur under high light, but also under low light conditions, at least in C_3 plants. In C_3-plants the wasteful process of photorespiration occurs simultaneously with true photosynthesis and shows up in a lowering of the light use efficiency, and in a rather high CO_2 compensation point (about 50 μmol mol^{-1}). Increased CO_2 suppresses photorespiration and therefore raises the light use efficiency (Goudriaan et al.,1985).

In C_4 plants (mostly tall tropical grasses such millet, maize, sorghum and sugar cane) a different substrate is used as a preliminary binder of CO_2 from the external, and this process of photorespiration is not observed. These species have a very low CO_2 compensation point (about 5 μmol mol^{-1}). There is palaeological evidence that the C_4 plants evolved in the late Tertiary, as an adaptation to CO_2 concentrations as low as 200 µmol mol-1 . Although mainly found in tall grasses, the C_4 character also evolved in other plant genera such as the Chenopodiaceae growing in saline conditions. The C_4 plants mainly grow in hot and dry environments (savanna's), and in salt marshes and salt plains. Because of the high affinity to CO_2, they could keep their stomatal resistance about twice as large as C_3 plants, while retaining the same rate of photosynthesis. Normally however these plants maintain a higher rate of photosynthesis and higher growth rate than C_3-plants at similar transpiration rate. This feature approximately doubles their water use efficiency.

Nutrients

Nutrient shortage, especially of phosphorus and of potassium, tends to impose a real limitation to crop growth without leaving much room for stimulation by CO_2. Yet, most nutrients show a limited decrease in concentration in plant tissue under elevated CO_2 (Overdieck, 1992). Nitrogen differs from other nutrients in that it permits a positive CO_2 effect, even under rather severe nitrogen shortage (Goudriaan and De Ruiter,1983). Starch accumulation (Ehret and Jolliffe,1985) then occurs, and at the same time the amount of carboxylation enzyme Rubisco in the leaves decreases. There is so much of this enzyme in leaves that the leaf nitrogen content may significantly decrease in plants grown under high CO_2 (Lemon, 1983; Larigauderie et al.,1988). Data of Peñuelas and Matamala (1990) show that the existence of this negative correlation between atmospheric CO_2 and leaf nitrogen content for a century time scale. They found a significantly higher nitrogen concentration in herbarium material from 200 years ago than in recent plants of the same species growing in similar natural circumstances, presumably because of the lower atmospheric CO_2-concentration at that time.

There is evidence of both negative and positive adaptations during prolonged cultivation under increased CO_2. Photosynthesis per unit leaf area has often been found to be smaller in plants adapted to high CO_2 (Wong,1979; Mortensen,1983) than that of non-adapted plants, when measured at the *same* CO_2 concentration and equal circumstances otherwise. A stimulation, however, has also been found occasionally. Valle et al. (1985) and Campbell et al. (1988) found positive adaptation in soybean and Arp and Drake (1991) in the salt marsh sedge Scirpus olneyi. When leaves are both grown and measured at a higher CO_2 concentration, they generally maintain a higher rate of photosynthesis. This is particularly true for nitrogen fixing plants, that have nodules in their rooting system. The growth response of these leguminous plants to CO_2 tends to be particularly strong.

COMBINED EFFECTS OF CO_2 AND CLIMATE

As shown in reviews by Kimball (1983), Strain and Cure (1985) and Dahlman (1993), responses at the single leaf level to CO_2 are carried over to crop yield, and can be summarized by a mean 40% increase of dry matter for C_3-crops upon doubling of CO_2, and by 15% for C_4-crops.

A similar overall response for a C_3 crop was calculated with a physiologically based model (Goudriaan et al.,1985). This model showed that the relative change in crop biomass W could be well described by a logarithmic relation with the relative change in ambient CO_2 C:

$$\left(\frac{W}{W_0}\right) = 1 + \beta \ \ln\left(\frac{C}{C_0}\right)$$

This relation is only indicative and has no physiological meaning, but it serves well to summarize both many observations and simulation results. The response factor β of modelled crop dry weight was found to be 0.5 to 0.7 dependent on whether the increased carbon gain was reinvested in productive plant material, or just stored in passive organs such as tubers.

The combined effects of increased CO_2 and climate on wheat production were analysed by Nonhebel (1993) and Wolf (1993), who used the related models SUCROS87 (Spitters et al., 1989) and WOFOST (Van Keulen and Wolf, 1986; Van Diepen et al., 1989) respectively. Wolf (1993) concluded that by the year 2050 the climate change alone will have slightly negative effects on water-limited grain yields in Europe, but that the inclusion of the increase of atmospheric CO_2 will turn the loss into a much larger gain (about 2 ton/ha) (Fig 8). Nonhebel (1993), using a different model, reached similar conclusions. Moreover, the effects of climate and CO_2 did not show a strong interaction and could be practically superimposed (Fig 9).

IMPLICATIONS AND OUTLOOK

Two examples from history underline the importance of flexibility of the society. During the Little Ice Age climatic conditions in Europe were much worse than during the Middle Ages, in terms of climatic variability and farming conditions. Yet, the West-European society was better able to cope with climate than 200 years before, presumably because technology and trade had been better developed in the meantime. Around the year 1700 a climatic improvement occurred with a 40 year period of mild winters, to be suddenly interrupted in the year 1739-1740. This unexpected cold winter caused severe problems in the supply of fuel (peat)(De Vries, 1980). Yet, 50 years earlier the winters had been at least as cold without causing the same difficulties. A 40 year period was sufficiently long to let society forget about the potential danger of cold winters.

Another, more recent, example illustrates the flexibility of farming in the cultivation of maize in The Netherlands. Climatically, Holland is not suitable for the cultivation of kernel maize, and until 30 years ago hardly any maize was grown. Then research showed that maturation of the cobs was not necessary to obtain a valuable fodder crop in the form of silage maize. Within a period of 30 years, maize has replaced grass, rye and wheat on about 30% of the arable land in The Netherlands. Here we see the transition of a crop grown as a determinate species to one grown as if it were an indeterminate vegetative crop. This example also shows that it is not a simple task to include such flexibility of farmer's practices into models used for analyzing the agricultural effects of climatic change.

The annual rate of increase in atmospheric CO_2 (1.5 ppm per year) is responsible for a yield increase of up to 0.2% per year. However, improvement of agricultural technology has had a much larger effect and has caused annual yield increases of about 2% per year. Therefore, the dynamics of possible changes in climate will probably be slower than the actual dynamics of technological change in farming. In some southern regions of Europe increasing drought may cause large problems, but in most regions farming is expected to adapt to changing conditions without large difficulties.

A changing climate induces a need for adaptation to altered conditions. However, most adaptations are those that are needed anyway, such as improved nutrition, improved irrigation, improved plant protection, and breeding for better varieties. Agriculture is best served by maintaining a high standard of the research basis and of land and crop management.

REFERENCES

Amthor, J.S., 1991. Respiration in a future, higher-CO_2 world. Plant, Cell and Environment 14 : 13 - 20

Arp, W.J., 1991. Vegetation of a North American salt marsh and elevated atmospheric carbon dioxide. Vrije Universiteit, Amsterdam 181 pp.

Arp, W.J. and B.G. Drake, 1991. Increased photosynthetic capacity of scirpus olneyi after 4 years of exposure to elevated CO_2. Plant, Cell and Environment 14(8):1003-1006

Berger, A., 1992. Le Climat de la Terre. 479 pp. De Boeck Université. Brussels, Belgium

Campbell, W.J., L.H. Allen and G. Bowes, 1988. Effects of CO_2 concentration on Rubisco activity, amount, and photosynthesis in soybean leaves. Plant Phys. 88: 1310-1316

Coops, A.J., 1993. Analyses of climatological series in relation to the detection of the CO_2 effect. Norsk Geologisk Tidsskrift, Vol 7: 179-182

Dahlman, R.C., 1993. CO_2 and plants: revisited. Vegetatio 104/105: 339- 355

Diepen, C.A.van, J. Wolf, H. van Keulen and C. Rappoldt., 1989. WOFOST: a simulation model of crop production. Soil Use and Management 5: 16 - 24

Ehret, D.L. and P.A. Jolliffe,1985. Photosynthetic carbon dioxide exchange of bean plants grown at elevated carbon dioxide concentration. Can. J. Bot. 63: 2026-2030

Enoch, H.Z. and B.A. Kimball, 1986. CO_2 enrichment of greenhouse crops. Volume I and II, CRC Press, Boca Raton, Florida, USA

KNMI, 1993. De toestand van het klimaat en van de ozonlaag in Nederland. KNMI, De Bilt, The Netherlands

Gifford, R.M., 1979. Growth and yield of carbon dioxide-enriched wheat under water-limited conditions. Australian J. of Plant Physiology 6 :367-378

Goudriaan, J. and H.H. van Laar, 1978. Relations between leaf resistance, CO_2 concentration and CO_2 assimilation in maize, beans, lalang grass and sunflower. Photosynthetica 12: 241-249

Goudriaan, J. and H. van Keulen, 1979. The direct and indirect effects of nitrogen shortage on photosynthesis and transpiration in maize and sunflower. Neth. J. agric. Sci. 27 : 227-234

Goudriaan, J. and H.E. de Ruiter, 1983. Plant growth in response to CO_2-enrichment, at two levels of nitrogen and phosphorus supply. Neth. J. of Agric. Sci. 31 : 157-169

Goudriaan, J., H.H. van Laar, H. van Keulen and W. Louwerse, 1985. Photosynthesis, CO_2 and Plant Production. In: Wheat growth and Modelling. W. Day and R.K. Atkin (Eds). NATO ASI Series, Series A: Life Sciences Vol 86. Plenum Press, New York, pp 107-122

Houghton, J.T., Jenkins, G.J. and Ephraums, J.J., 1990, Climate Change, The IPCC Scientific Assessment. Cambridge University Press, Cambridge. 365 pp

Kenny, G.J., P.A. Harrison and M.L. Parry (Eds), 1993. The Effect of Climate Change on Agricultural and Horticultural Potential in Europe. 224pp. Environmental Change Unit, Oxford, UK

Kenny, G.J. and P.A. Harrison, 1993. Analysis of effects of climate change on broadscale patterns of agroclimate in Europe. In: Kenny, G.J., P.A. Harrison and M.L. Parry(Eds), The Effect of Climate Change on Agricultural and Horticultural Potential in Europe. 224pp. Environmental Change Unit, Oxford, UK

Keulen, H. van and J. Wolf (Eds), 1986. Modelling of agricultural production: weather, soils and crops. Simulation Monographs, Pudoc, Wageningen. 479 pp.

Kimball, B.A., 1983. Carbon dioxide and agricultural yield: An assemblage and analysis of 430 prior observations. Agron. J. 75:779-788.

Koning G.H.J. de and C.A. van Diepen, 1992. Crop production potential of rural areas within the European Communities. IV: Potential, water-limited and actual crop production. W68. 83 pp. WRR, Netherlands Scientific Council for Government Policy, The Hague

Lamb, H.H., 1984. Climate in the last thousand years. pp 25 - 64. In H. Flohn and R. Fantechi (Eds), The Climate of Europe: Past, Present and Future. D. Reidel Publ. Comp. Dordrecht.

Larigauderie, A., Hilbert, D.W. and Oechel, W.C., 1988. Effect of CO_2 enrichment and nitrogen availability on resource acquisition and resource allocation in a grass, Bromus mollis. Oecologia 77 : 544 - 549

Lemon, E.R.(Ed), 1983. CO_2 and plants. AAAS Selected Symposium No 84. Westview Press, Boulder, Co

Loomis, R.S. and D.J. Connor, 1992. Crop Ecology. Cambridge University Press, 538 pp.

Morison, J.I.L., 1987. Intercellular CO_2 concentration and stomatal response to CO_2. In : Zeiger,E., G.D. Farquhar and I.R. Cowan (Eds). Stomatal function. Stanford University Press, Stanford, California.

Morison, J.I.L., 1992. Response of plants to CO_2 under water limited conditions. Vegetatio 104/105: 193-209

Mortensen, L.M., 1983. Growth responses of some greenhouse plants to environment. X Long-term effect of CO_2 enrichment on photosynthesis, photorespiration, carbohydrate content and growth of *Chrysanthemum morifolium* Ramat. Sci. Rep. of the Agric. Univ. of Norway.Vol 62. Report No 272.

Mousseau, M., 1993. Effects of elevated CO_2 on growth, photosynthesis and respiration of sweet chestnut (*Castanea sativa* Mill.). Vegetatio 104/105: 413 - 419

Nederhoff, E.M. and A.M. van Uffelen, 1988. Effects of continuous and intermittent carbon dioxide enrichment on fruit set and yield of sweet pepper(*Capsicum annuum* L.). Neth. J. of agric. Sci. 36 : 209-217

Nonhebel, S., 1993. The importance of weather data in crop growth simulation models and assessment of climatic change effects. PhD-Thesis Agricultural University Wageningen, ISBN 90-5485-114-7, 144 pp

Overdieck, D. ,1993. Elevated CO_2 and the mineral content of herbaceous and woody plants. Vegetatio 104/105: 403-411

Peñuelas, J. and Matamala, R., 1990. Changes in N and S leaf content, stomatal density and specific leaf area of 14 plant species during the last three centuries of CO_2 increase.

J. of Experimental Botany 41(230) : 1119 - 1124
Raschke, K., 1975. Stomatal action. Annual Review of Plant Physiology 26: 309-340
Rozema,J., H. Lambers, S.C. van de Geijn and M.L. Cambridge (Eds), 1992. CO_2 and the Biosphere. Advances in Vegetation Science 14. 484 pp. Kluwer Academic Publishers, Dordrecht
Schuurmans C.J.E., 1981. Central England and De Bilt series. In : A. Berger (Ed), "Climatic Variations and Variability: Facts and Theories", pp 254-258. Reidel Publ. Dordrecht, The Netherlands
Sibma, L., 1968. Growth of closed green crop surfaces in The Netherlands. Neth. J. of Agric. Sci. 16: 211 - 216
Slicher van Bath, B., 1963. The agrarian history of Western Europe AD 500 -1850., London
Spiertz, J.H.J., H.D.J. van Heemst and H. van Keulen, 1992. Field-crop systems in North-Western Europe. In C.J. Pierson(Ed), " Ecosystems of the World. Vol 18 , Field Crop Ecosystems". pp 357-371 Elsevier, Amsterdam, The Netherlands.
Spitters, C.J.T., D.W.G. van Kraalingen and H. van Keulen, 1989. A simple and universal crop growth simulator: SUCROS87. In: R.Rabbinge, S.A. Ward and H.H. van Laar (Eds). Simulation and systems management in crop protection. Simulation Monographs, Pudoc , Wageningen, pp 147 - 181
Strain, B.R. and J.D. Cure, 1985. Direct effects of increasing carbon dioxide on vegetation. U.S. Dept. of Energy. DOE/ER-0238. Washington DC,USA
Valle, R., J.W. Mishoe, W.J. Campbell, J.W. Jones and L.H. Allen, 1985. Photosynthetic responses of 'Bragg' soybean leaves adapted to different CO_2 environments. Crop Science 25: 333-339
Vries, J. de, 1980. Measuring the impact of climate on history.: the search for appropriate methodologies. J. of Interdisc. Hist X(4): 599 - 630
Wit, C.T. de, H.H. van Laar and H. van Keulen, 1979. Physiological potential of crop production. In J. Sneep and A.J.T. Hendriksen (Eds), Plant breeding perspectives. Pudoc, Wageningen (NL)
Wittwer, S.H. and W. Robb, 1964. Carbon dioxide enrichment of greenhouse atmospheres for food crop production. Economic Botany 18 : 34-56
Wolf, J., 1993. Effects of climate change on wheat production potential in the EC. European J. of Agronomy, in press.
Wong, S.C., 1979. Elevated atmospheric partial pressure of CO_2 and plant growth. I. Interactions of nitrogen nutrition and photosynthetic capacity in C_3 and C_4 plants. Oecologia 44:68-74

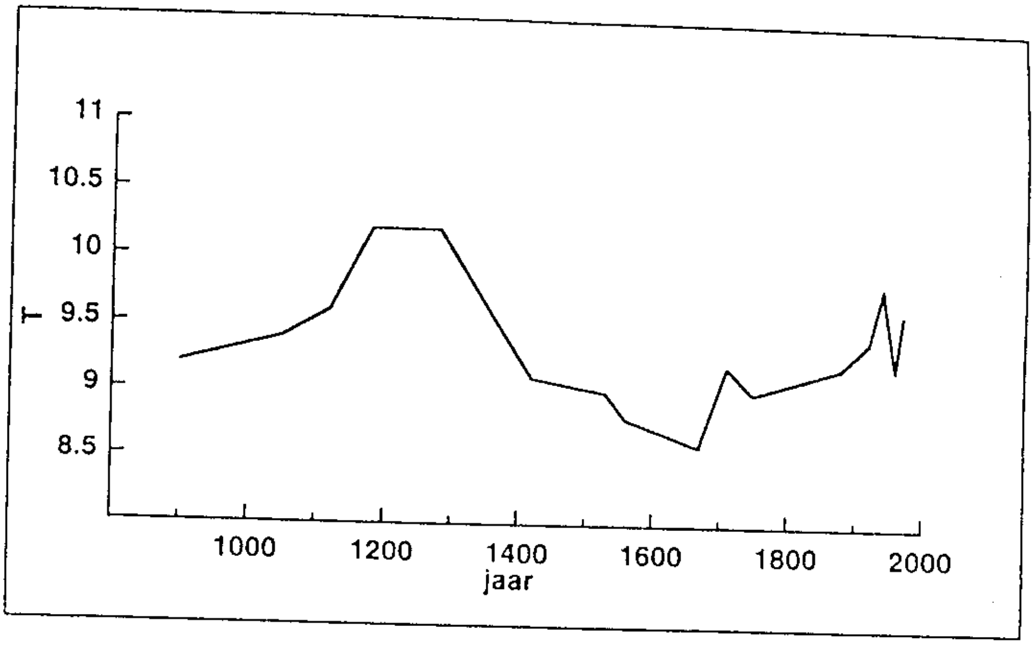

Figure 1 Mean annual temperature in England during the last 1000 years (After Lamb, 1984)

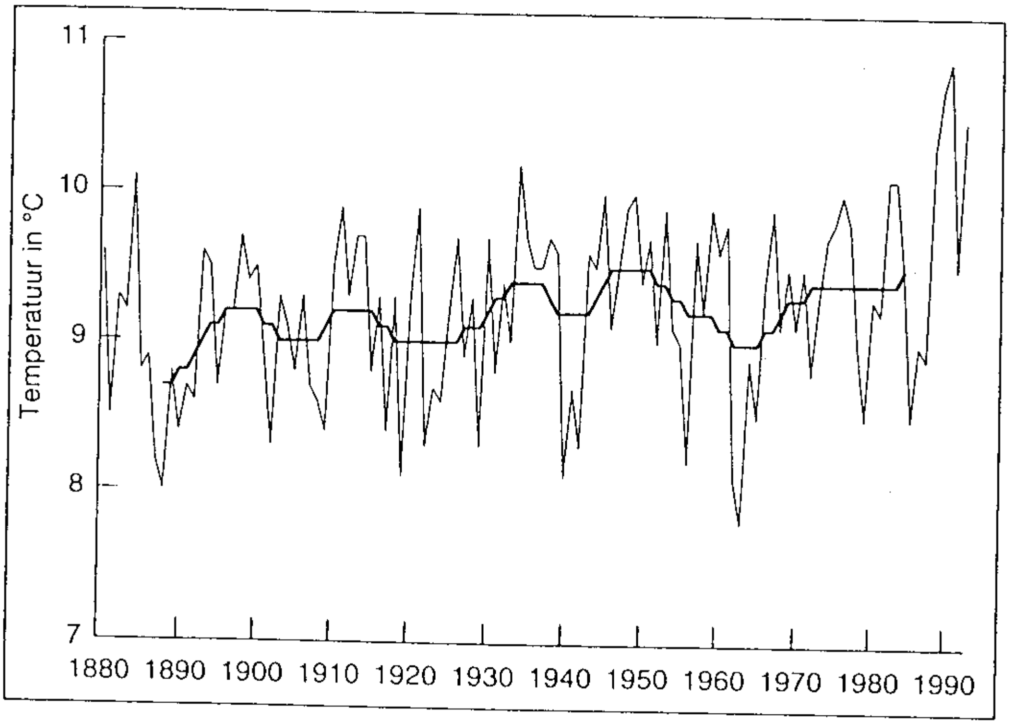

Figure 2 Mean annual air temperature, observed in The Netherlands, 1930 -1992

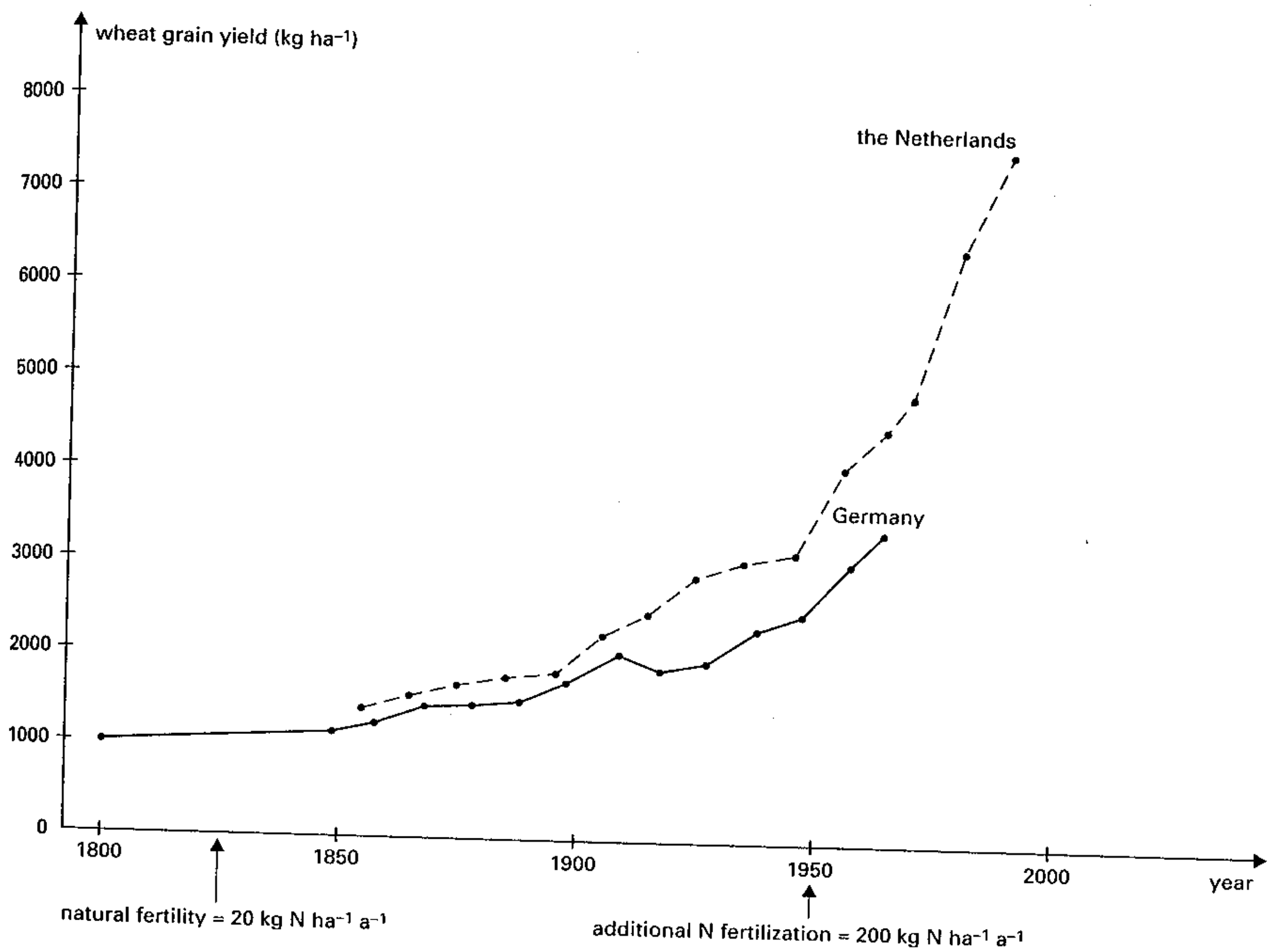

Figure 3 Wheat yields in Germany and The Netherlands since 1800 (from Spiertz et al., 1992)

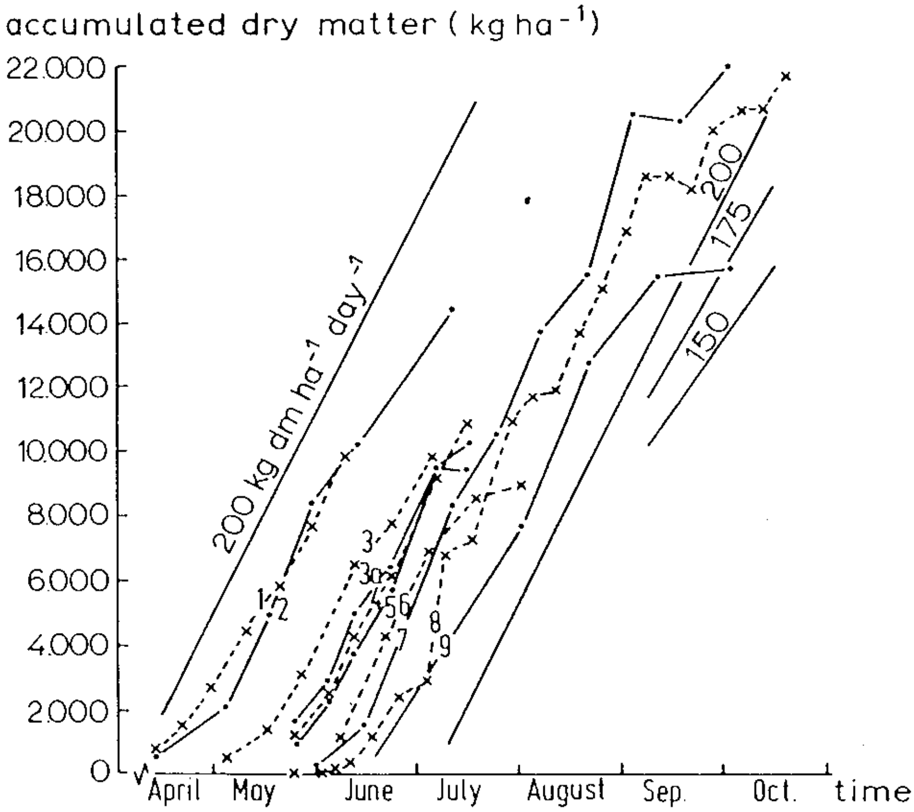

Figure 4 Growth rates of the main agricultural crops in The Netherlands under (near)-optimal conditions. 1. grass 2. wheat 3. oats + barley 3a. oats + peas 4. oats 5. peas 6. barley 7. potato 8. sugar beet 9. maize (Sibma,1968)

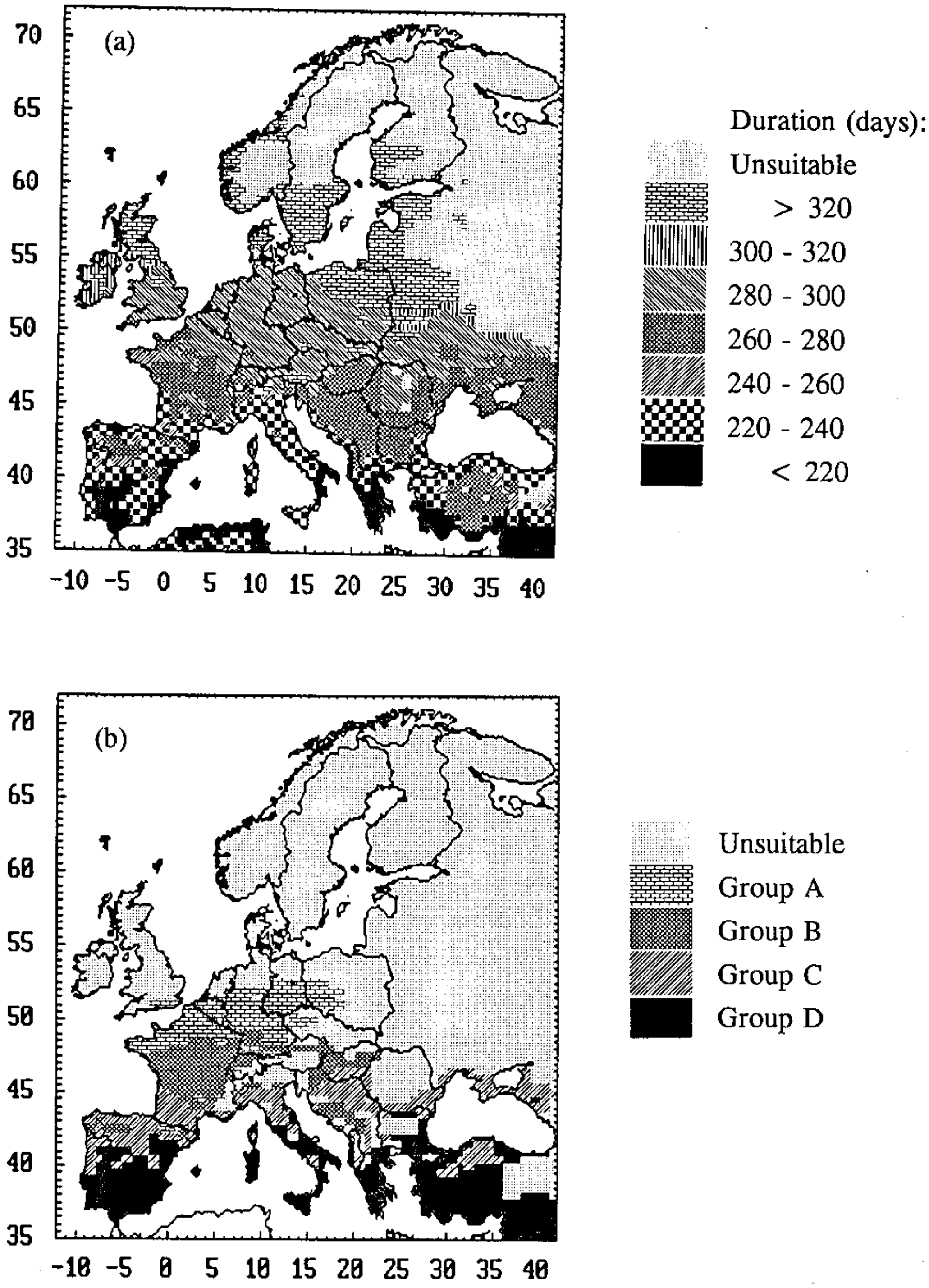

Figure 5 Agro-ecological suitability map of Europe (Kenny and Harrison, 1993)

a. Grain maize, including water availability

b. Grapes

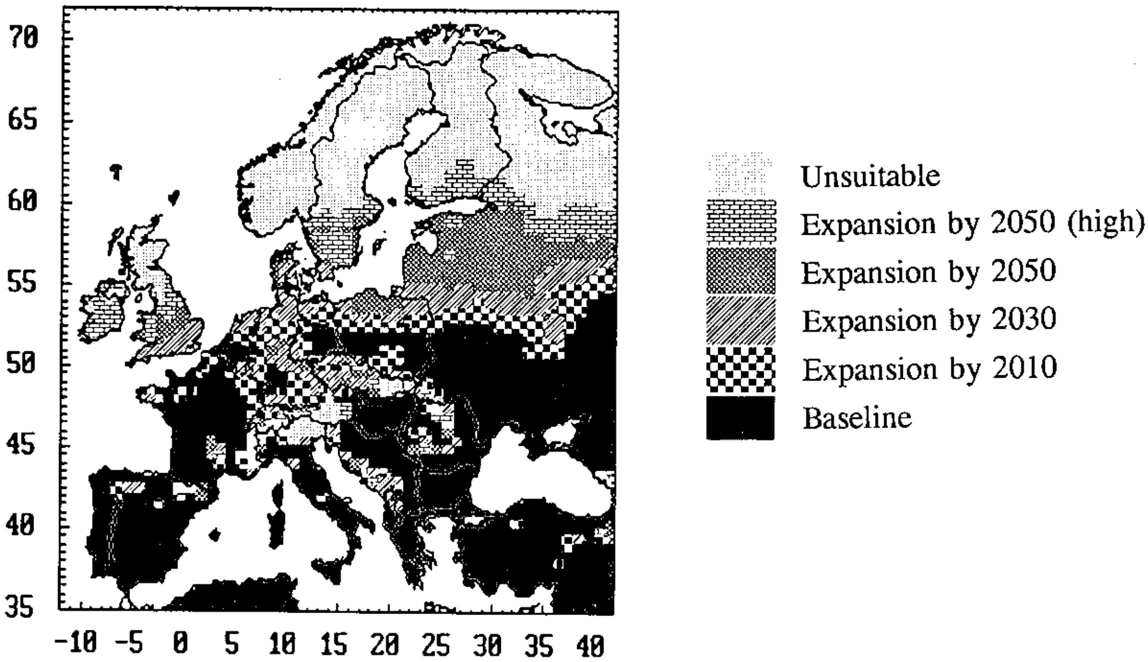

Figure 6 Detailed map of land suitability for wheat production in the countries of the European Community (De Koning and Van Diepen, 1992)

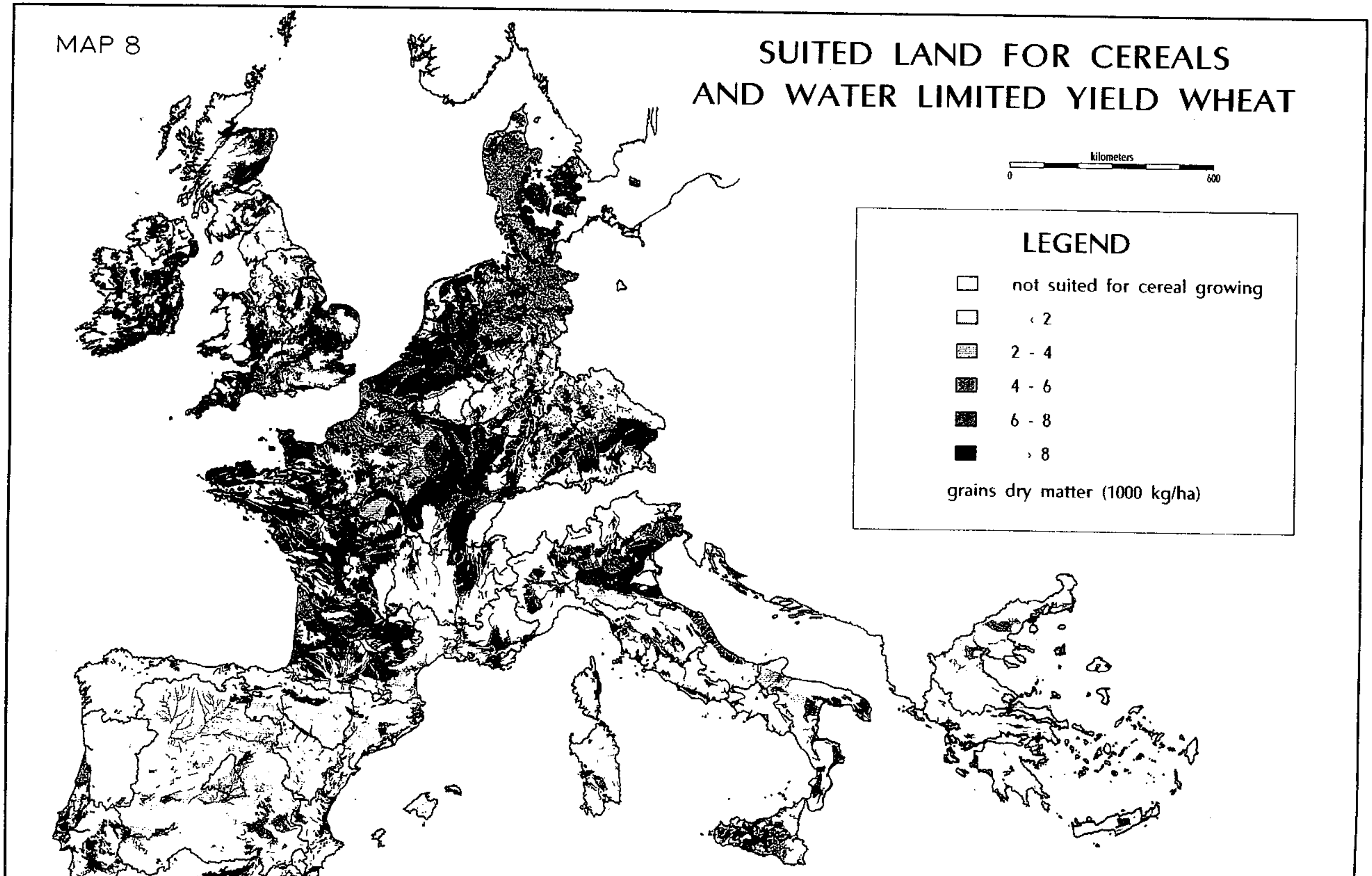

Figure 7 Expected potential cropping zones of grain maize in Europe for the baseline (1990), and for the years 2010, 2030 and 2050 respectively (Kenny and Harrison, 1993)

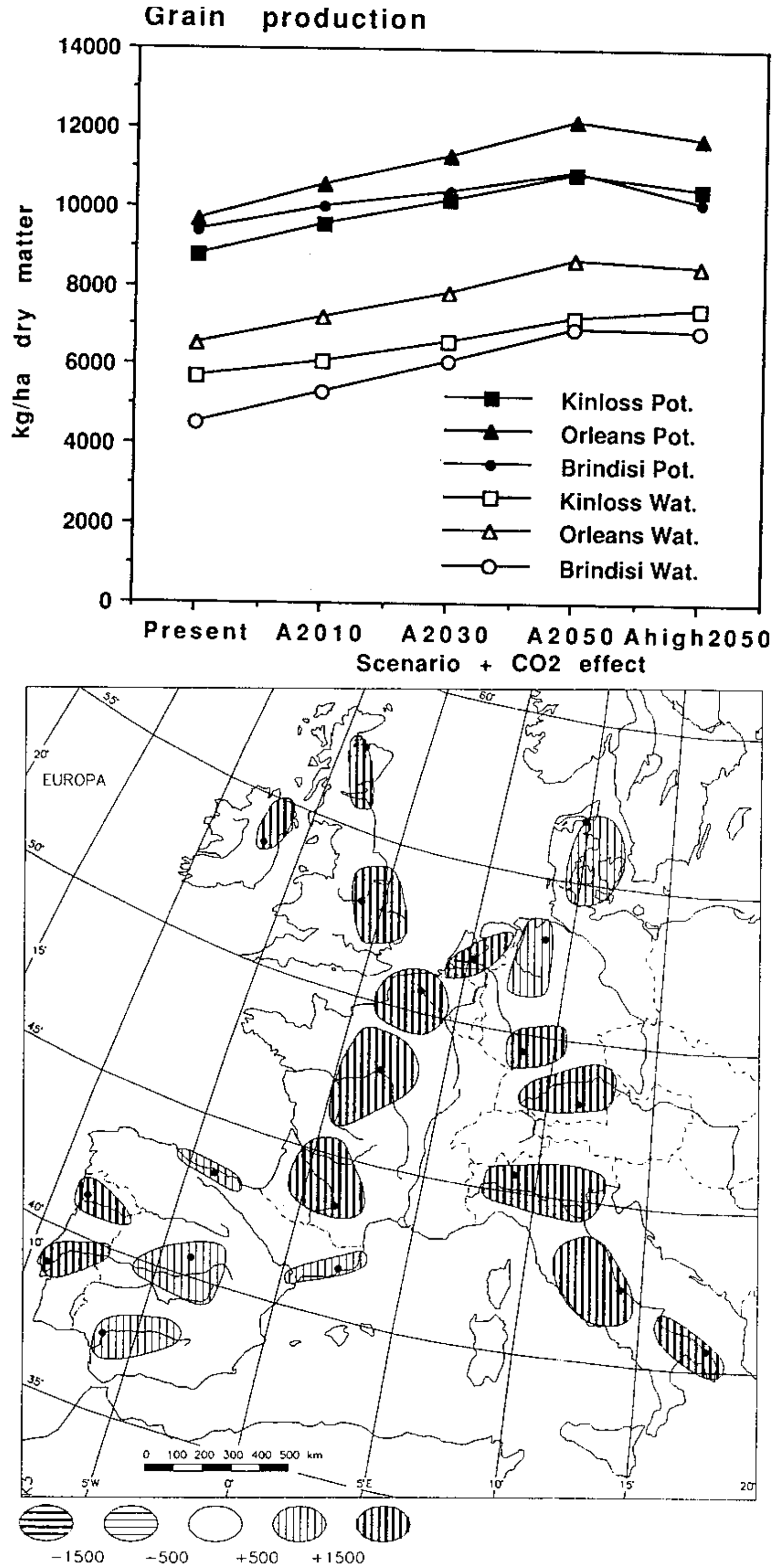

Figure 8 Simulated changes of wheat yields up to the year 2050. Both temperature and CO_2 are included (Wolf, 1993).

a. Time course for potential and water-limited yields at three regions in Europe: Kinloss(Scotland), Orleans (Central France) and Brindisi (Southern Italy)

b. Expected changes in water-limited grain production of winter wheat in kg/ ha (dry matter

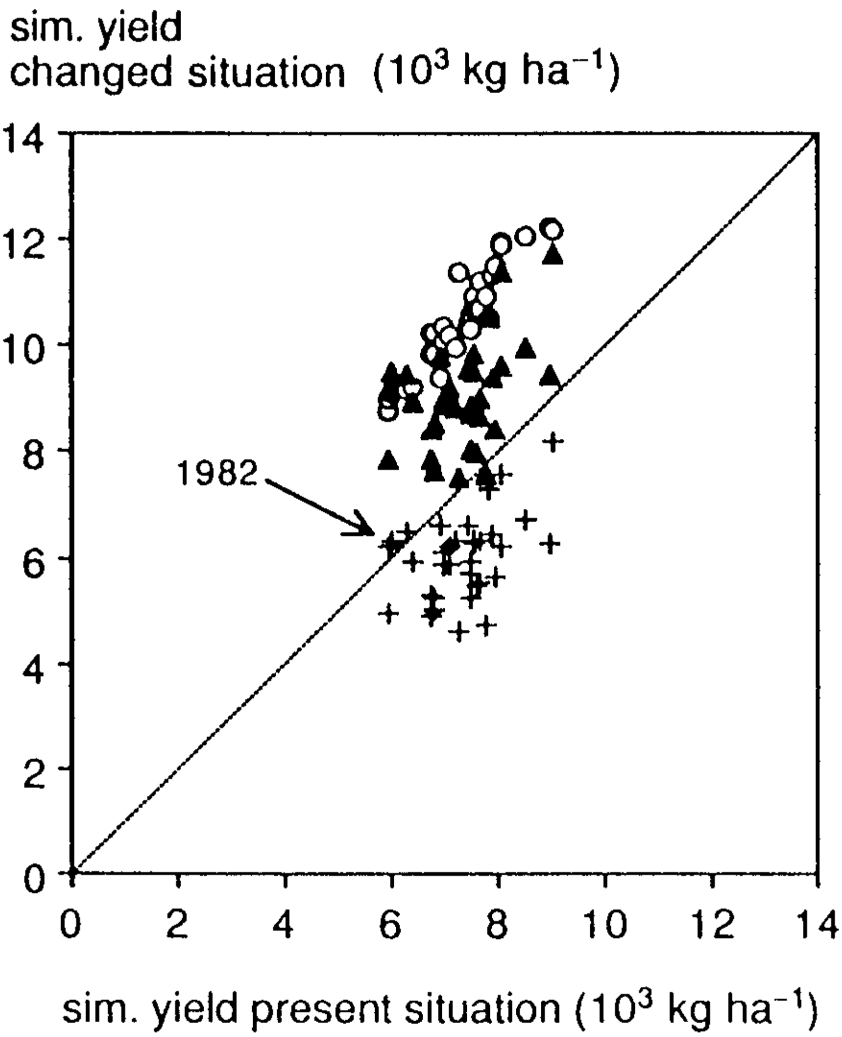

Figure 9 Scatter diagram of simulated spring wheat yields by the year 2080 versus present as affected by temperature increase and CO_2 doubling (Nonhebel, 1993)

Table 1

Required and available temperature sums, expressed in degree-days. Temperature sums are calculated by accumulating the number of degrees Centigrade above a base temperature for each day of the growing season. Base temperature and required temperature sum are crop specific.

	spring wheat	early potato	silage maize	sunflower
Base temperature	0	2	6	7.2
Required temperature sum	1700	1250	1460	1300
Available temperature sum per region				
Iceland	1590	1100	370	215
Netherlands (De Bilt)	3410	2690	1610	1340
France:				
Brest	3930	3200	1750	1390
Strassbourg	3550	2890	1850	1590
Dijon	3830	3120	2010	1730
Lyon	4140	3410	2230	1940