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5 Effects of climate change on crop production and land use in the Rhine basin

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Summary

Changes in climate affect the hydrological cycle of river basins. This results in a changed annual course of river discharge which might cause problems in future. To attain a better understanding of the effects of climate change on the course of discharge of the river Rhine, a hydrological model for the Rhine basin is to be developed. As part of this project the effects of climate change on production and water use of crops in the Rhine basin and on the land use were analyzed. Information on land use was derived from the literature. Crop production levels and water use were calculated with a crop growth simulation model WOFOST. These calculations were done for winter wheat, permanent grassland and silage maize and both for current and future climate conditions. Also the sensitivity of production and water use to separately changed weather variables were determined. According to these analyses, the expected climate change in the Rhine basin will result in a higher level of production for most crops, will reduce the risk for water shortage and will allow the cultivation of crops with higher temperature sum requirements.

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5.1 Introduction

Considerable changes in the climate on this planet might occur within a limited period of time as a result of rising concentrations of so-called 'greenhouse' gases in the atmosphere. The climate changes that are to be expected for the Rhine basin, are mainly an increase in air temperature and a change in annual rainfall distribution. As higher temperatures may result in less snowfall and an earlier snow melting, it is to be expected that in winter and early spring river discharge will become

larger and that high water will occur more frequently and will attain higher levels and that in the summer the discharge will become smaller (CHR, 1989).
Changes in climate conditions may also result in changes in the level of crop production and in the use of agricultural land in the Rhine basin. This may affect for example the degree of soil coverage and hence the amounts of rainfall discharged by runoff, and the water use by evapo-transpiration and hence the amount of water leached to deeper soil layers. In this way climate change will cause changes in the course of discharge of the river Rhine too.
A change in the annual course of discharge might cause problems with respect to supply of drinking and irrigation water, shipping, etc. in future. A better understanding of the effects of climate change on the hydrological processes is needed to take purposeful actions for minimizing such negative effects. Hence, the international Comittee for the Hydrology of the Rhine basin (CHR) initiated in 1989 a project 'Effects of climate change on the discharge of the Rhine'. The main part of this project is the development of a hydrological model for the Rhine basin (CHR, 1989).
Rijkswaterstaat RIZA has taken responsibility for the development of the lowland part of this hydrological model and besides, of scenarios for changing land use in the Rhine basin as a result of climate change. In a preliminary phase of these projects the effects of climate change on crop production, water balance and land use in the Rhine basin have been analyzed. Information on changes in land use have been derived from agricultural statistics and information on changes in crop production and water balance have been calculated with a crop growth simulation model. These calculations have been carried out for a limited number of crops, meteorological stations and for artificially derived soil characteristics. This gives a first impression of the possible effects of climate change on land use and crop production in the Rhine basin.

5.2 Land use

The use of land for agriculture depends on environmental, socio-economic and other factors. Environmental factors that set limitations to land use, are mainly climate, soil, landscape and hydrology. For example, low temperatures may prevent maturing of the crop, for example of grain maize in the Netherlands, frost in late spring may damage orchards, and drought periods in summer may reduce yields, particularly on shallow or gravelly soils with small amounts of available water. Soils may set limitations to agriculture, being for example too heavy for cultivation of root crops or too gravelly. Landscapes with steep slopes cannot be used for arable cropping, as without permanent coverage erosion takes place at a too high rate. High groundwater levels and insufficient natural or artificial drainage generally prevent use of land for arable cropping.
Other factors that determine land use, are the size of the consumer market, market regulations of the European Community and hence, the prices for the various agricultural products, the historical development of agriculture per region, the distance to consumer markets and processing industries, the infra- and marketing structure, transport facilities and transport costs, the fodder demand of the animal husbandry sector, and the introduction of new crop species that produce raw material for non-food use (energy, paper, oil, plastic, medicines, etc.). In addition, a further increase

Table 5.1 Change in use of agricultural and arable land (cultivated area in 10^4 ha)in the Netherlands (CBS, 1986).

	1930	1950	1970	1987
Agricultural land	225	234	213	201
Permanent grassland	132	132	133	113
Horticulture	8	9	11	12
Arable land	85	93	69	77
Cereals	43	48	36	18
Root crops	26	30	27	30
Silage maize	0	0	0	20
Other crops[1]	16	16	6	9

[1] Pulses, rape seed, lucerne, etc.

in production per unit of land area in combination with a policy to curb the production of surplusses in the EC may lead to a concentration of farm production on a much smaller area of land than that currently under cultivation (Latensteijn & Rabbinge, 1992; WRR, 1992). Such a contraction of the agricultural area has occurred periodically in the past (periods 1350-1475 and 1650-1750) and may lead to abandonment of marginal farmlands and possibly to extensive reforestation in the next future (van der Woude, 1990).
The examples mentioned above indicate that a possible change in climate can only be just one of the many factors that together determine the changes in land use. Climate change may have only a minor impact compared to the effects of other future changes in agriculture (Rabbinge *et al.*, 1993). Also at present weather conditions, land use can already change quite rapidly as shown in Table 5.1. The areas of permanent grassland and cereals in the Netherlands appeared to decrease quite rapidly. Simultaneously, the area of arable land cultivated with silage maize increased strongly over the last 20 years.

5.2.1 Actual land use in the Rhine basin

For the regions that drain to the river Rhine, data on land use were derived from statistics (Eurostat, 1987, 1988). For each region it was also estimated which fraction of the area drains to the Rhine. Multiplication of the areas in use for specified types of agriculture per region by the draining fraction of the region resulted in data on the land use in regions that drain to the Rhine.

In 1985 the relative use of agricultural land in the regions draining to the Rhine was as follows in:

	Arable crops	Permanent crops	Permanent grassland
Netherlands	35 %;	3 %;	62 %
Germany	61 %;	3 %;	36 %
France	52 %;	5 %;	43 %
Luxemburg	43 %;	1 %;	56 %

The overall use of agricultural land in the Rhine basin, largely corresponding to the land use in the German regions and to less extent to that in the French regions, was: arable cropping 58 % ; permanent crops 4 % ; and permanent grassland 38 % .

In 1985 the relative use of arable land in the regions draining to the Rhine was as follows in:

	Cereals	Root crops	Oil seeds	Other crops
Netherlands	22 %;	26 %;	4 %;	48 %
Germany	70 %;	7 %;	3 %;	20 %
France	67 %;	1 %;	8 %;	24 %
Luxemburg	62 %;	2 %;	1 %;	35 %

The overall use of arable land in the Rhine basin, largely corresponding to the land use in German regions, was: cereals 69 % ; root crops 6 % ; oilseed crops 4 % ; other crops 21 % . From statistics (Eurostat, 1987, 1988) it can be derived that cereals cultivated in the Rhine basin were mainly wheat, barley, oats and rye and that the main oil seed crops cultivated were rapeseed and turnip rapeseed.

5.2.2 Actual land use in southern France and nothern Italy

Increasing atmospheric CO_2 might result in changes in climate conditions. For example, according to the Bultot scenario (Section 5.5.1) temperatures rise with 3 °C, precipitation increases but not much more than the evapo-transpiration, and the other weather variables remain identical. Such climate conditions can be found at present in southern France and in northern Italy. For example, the average temperatures in Bordeaux, France and in Milan and Turin, Italy are 12.3, 13.1 and 13.0 °C and the annual amounts of rainfall are 900, 963 and 845 mm, respectively. The average temperatures in de Bilt, Netherlands and Freiburg, Germany are 9.3 and 10.3 °C and the annual amounts of rainfall 765 and 903 mm, respectively (Müller, 1987).

In 1985 the relative use of agricultural land was as follows in:

	Arable crops	Permanent crops	Permanent grassland
southern France	53 %;	9 %;	38 %
northern Italy	62 %;	8 %;	30 %

Compared to the overall land use in the Rhine basin, the relative area used for permanent crops in these regions is larger (8 % compared to 4 % in the Rhine basin) and the relative area in use for permanent grassland is smaller, particularly in northern Italy (compared to 38 % in the Rhine basin). Besides, the fraction of the area in use for permanent crops that is used as vineyards, increases from about half the area in the Rhine basin to three fourth of the area in southern France and northern Italy (Eurostat, 1987).

In 1985 the relative use of arable land was as follows in:

	Cereals	Root crops	Oil seeds	Other crops
southern France	50 %;	1 %;	11 %;	38%
northern Italy	59 %;	3 %;	0 %;	38%

Comparing these land use data with those for the Rhine basin, the relative areas used for cereals are smaller (compared to 69 % in the Rhine basin), for root crops are smaller too (compared to 6 % in the Rhine basin) and for other crops are larger (compared to 21 % in the Rhine basin). From statistics (Eurostat, 1987, 1988) it can be derived that the areas cultivated in southern France and northern Italy with other crops, are mainly used for green fodder production (about 30 % of the arable land area), that cereals cultivated in southern France and northern Italy are mainly wheat, barley and grain maize and that the main oil seed crop cultivated in southern France is sunflower and in Italy soyabean.

5.2.3 Effects of climate change on land use

Future climate conditions for the Rhine basin can be found at present in southern France and northern Italy. In all these European regions agriculture functions within the same system of market regulations of the European Community. Hence, socioeconomic conditions do not differ too much and comparison of the land use in southern France and northern Italy with that in the Rhine basin may give good indications of the possible changes in land use that are to be expected from climate change.

The following changes in land use in the Rhine basin may be expected:
- decrease in area of permanent grassland;
- increase in area of permanent crops;
- increasing part of the area with permanent crops used as vineyards;
- smaller areas cultivated with oats and rye and larger areas with grain maize;
- smaller areas cultivated with root crops;
- smaller areas cultivated with rapeseed and turnip rapeseed and larger areas cultivated with sunflower and soyabean.

5.3 Methodology

5.3.1 Model description

A dynamic crop growth simulation model, WOFOST, developed for calculating agricultural production potential on the basis of physiological, physical and agronomic information, was used. This model can be easily applied to a large number of combinations of different weather data, soil characteristics and crop species. The principles underlying this model have been discussed in detail by van Keulen & Wolf (1986), and the implementation and structure have been described by van Diepen *et al.* (1988, 1989). Its application for quantitative land evaluation and for regional analysis of the physical potential of crop production has been described by van Keulen *et al.* (1987) and van Diepen *et al.* (1990) and its use for analysis of the effects of climate on crop production has been discussed by van Diepen *et al.* (1987) and Wolf (1993).

In the model, the growth of a crop is simulated from emergence to maturity on the basis of physiological processes as determined by the crop response to environmental conditions. The simulation is carried out in time steps of one day. The major processes considered are CO_2 assimilation, respiration, partitioning of assimilates to various plant organs, transpiration and phenological development.

Two levels of crop production are calculated. Firstly, the potential production which is determined by crop characteristics, solar radiation and temperature, and can be realised in situations where the supply of water and plant nutrients, and crop management are optimal. Secondly, the water-limited production which is determined by crop characteristics, temperature, solar radiation and water availability (dictated by rainfall pattern and soil physical properties), and can be realised in situations where the supply of plant nutrients and crop management are optimal.

Available soil moisture in the root zone follows from quantification of the water balance including rainfall, surface runoff, soil surface evaporation, crop transpiration, and leaching from the root zone. If the moisture content in the root zone is too low or too high, water uptake by the plant roots is reduced, stomata close and the water-limited growth is reduced: in a dry soil due to water shortage, in a wet soil due to oxygen shortage.

5.3.2 Data

Effects of climate change on crop production have been calculated for three crops, winter wheat, silage maize and permanent grassland, growing on different soil types and in different climates of the Rhine basin. In order to apply the model, data that specify crop growth and phenological development are required, including information on initial crop weight, properties that determine assimilation and respiration processes and response to moisture stress, partitioning of assimilates to plant organs, life span of leaves, and death rates of plant organs. For the most part a standard crop data set was used (van Heemst, 1988). Data from the literature and field experiments (for winter wheat: Alblas et al, 1987; Darwinkel, 1985; Darwinkel, 1988; van Keulen *et al.*, 1988; PAGV, 1987; for silage maize: Alblas *et al.*, 1987; PAGV, 1985; de Jong, 1985; Sibma, 1987; for permanent grassland: PR, 1988; Wieling & de Wit, 1987; Lantinga, 1985; Noy, 1989; van Dijk, 1989) were used to assess the rate of phenological development, the partitioning of assimilates to the plant organs, the effective growth duration that determines the level of production, and the regrowth retardation after mowing of permanent grassland. For locations in Germany the same crop data as derived for wheat, maize and grass varieties in the Netherlands, were used in the calculations.

For the calculation of CO_2 assimilation rates, daily minimum and maximum air temperatures, CO_2 concentration and solar radiation are required (Goudriaan & van Laar, 1978). To calculate the components of the water balance data on daily rainfall, windspeed and vapour pressure are also required. For example, the calculations of potential rates of evaporation and transpiration that are made with the Penman formula, require data on radiation, average daily air temperature, vapour pressure and windspeed (Frère & Popov, 1979). Daily weather data over a period of 20 years (1969 - 1988) for three meteorological stations (i.e. de Bilt, the Netherlands; Frankfurt and Freiburg, Germany) that cover the variation in the Rhine basin, have been used.

In order to calculate the soil water balance, the soil's infiltration, retention and transport properties must be known. These soil physical characteristics are defined by soil moisture characteristics (notably soil porosity and volumetric moisture contents at field capacity and wilting point, respectively), effective soil depth, maximum infiltration rate or surface runoff fraction and the hydraulic conductivity of the subsoil. Four soil types were specified for the calculations. They cover the extent of variation in soil water-holding capacity that can be expected in the Rhine basin, but they are theoretical concepts representing a sandy soil, a sandy loam soil, a loamy soil and an optimum soil. For each soil it was assumed that no groundwater influence occurs, that excess water may drain rapidly to the subsoil so that growth reduction due to oxygen shortage does not occur, that the infiltration rate is so large that no surface runoff may occur, and that the effective rooting depth is 100 cm for the cultivation of winter wheat and silage maize and also for permanent grassland on optimum soils, and 50 cm for permanent grassland on the other soils. This results in maximum amounts of available soil water for cultivation of winter wheat and silage maize on sandy, sandy loam, loamy and optimum soils of 7, 14, 21 and 50 cm , respectively and for permanent grassland of 3.5, 7, 10.5 and 50 cm, respectively. The optimum soil is fictive but allows to calculate the potential level of production (i.e. no water shortage during crop growth).

5.3.3 Model adaption to increasing atmospheric CO_2

For plants as wheat and grass that belong to the C_3 plant type, the atmospheric CO_2 concentration at present is generally suboptimal. In the model, the CO_2 assimilation - light response curve was therefore changed at increasing atmospheric CO_2 in the following way. Up to a CO_2 concentration of about three times the present one, the maximum assimilation rate of light-saturated individual leaves increased about proportionally to the atmospheric CO_2 concentration. Secondly, the initial light use efficiency, i.e. the initial angle of the CO_2 assimilation - light response curve, increased with increasing atmospheric CO_2 (Goudriaan *et al.*, 1984; Goudriaan *et al.*, 1985; Goudriaan, 1990; Goudriaan & Unsworth, 1990). For C_4 plants such as maize and other tall tropicall grasses, such as millet, sorghum and sugarcane, the photosynthetic response to CO_2 is very steep until an atmospheric CO_2 concentration of one third of the present one. At the natural range of atmospheric CO_2 at present (about 350 µmol/mol) the CO_2 assimilation - light response curve practically does not change with increasing CO_2, even under high light intensities (Goudriaan & Unsworth, 1990) and hence, at increasing CO_2 this curve was not changed in the model for maize. These photosynthetic responses to CO_2 are in agreement with the results from literature reviews by Cure (1985) and Cure & Acock (1986).

The effect of increasing CO_2 on leaf area development is rather difficult to quantify, as indicated in comparable studies on the effects of climate change (van Diepen *et al.*, 1987; Jansen, 1990). It has been observed that increased assimilate availability at increasing atmospheric CO_2 results partly in thicker leaves, rather than in increased leaf area growth (Goudriaan & de Ruiter, 1983; Goudriaan & Bijlsma, 1987). In agreement with these observations the specific leaf areas of wheat and grass have been reduced at increasing atmospheric CO_2.

High atmospheric CO_2 may result in a high CO_2 assimilation rate. In such a situation formation of plant organs may become more limiting for crop growth than the rate of the CO_2 assimilation process. In this study, however, it is assumed that also at high CO_2 concentrations and light intensities, the rate of organ formation never is the limiting factor for crop growth. This includes the assumption that plant breeding will be able to produce new crop varieties that are very well adapted to a possibly changed climate and increased atmospheric CO_2 in future.

The simulation model calculates the potential rates of evaporation and transpiration by way of the Penman formula. In a situation of soil water shortage, the actual transpiration rate becomes lower than its potential value. This reduction in transpiration is caused by the partial closure of stomatal pores in the leaves, resulting in a decrease in stomatal conductance. The stomata permit at the same time uptake of CO_2 from the ambient air and escape of water vapour, leading to transpiration. When ambient CO_2 is raised, CO_2 assimilation may increase and/or transpiration losses may be reduced, depending on how the stomata react. In both ways the water use efficiency of plants may be stimulated considerably. Typically in C_3 plants transpiration is reduced to a limited extent and the CO_2 assimilation is stimulated considerably and in C_4 plants that have a much higher affinity for CO_2, the transpiration is reduced considerably and the CO_2 assimilation does not change (Goudriaan & Unsworth, 1990). These changes in the transpiration rate due to changing stomatal conductance and closure at increasing atmospheric CO_2 cannot be handled with the simple method used in the WOFOST model.

A stratified micrometeorological model (Goudriaan, 1977; Chen, 1984) that includes detailed profiles of radiation and aerial conditions in the canopy and uses the Penman - Monteith equation for calculating the energy balances of canopy and soil surface, has been applied for simulating the effects of doubled atmospheric CO_2 concentration on the transpiration rate (Goudriaan & Unsworth, 1990). For C_4 plant species the CO_2 assimilation rate was not affected but the stomatal resistence almost doubled, proportional to the increased CO_2 concentration. The transpiration rate, however, was not about halved because of a negative feedback in two ways. First,

Table 5.2 Changes in specific leaf area (SLA), in initial light-use efficiency of CO_2 assimilation of single leaves (EFF), in maximum leaf CO_2 assimilation rate (AMAX) and in the reduction factor for potential transpiration (RTRA) for adaptation of the model to doubled atmospheric CO_2 concentration.

	SLA (m^2 kg^{-1}	EFF (kg ha^{-1} h^{-1})/(J $m^{-2}s^{-1}$)	AMAX (kg ha^{-1} h^{-1})	RTRA (-)
Winter wheat				
1*CO_2	18.0	0.45	40	1.00
2*CO_2	14.4	0.55	80	0.90
Silage maize				
1*CO_2	26.0	0.45	70	1.00
2*CO_2	26.0	0.45	70	0.74
Grass				
1*CO_2	25.0	0.45	40	1.00
2*CO_2	20.0	0.55	80	0.90

the reduced transpiration rate caused an increase in leaf temperature. Secondly, the reduced transpiration rate affected air conditions inside the canopy. Both effects resulted in a transpiration rate of 74 % of that at the actual CO_2 concentration. For C_3 plant species the CO_2 assimilation rate is mainly affected by doubled atmospheric CO_2. In that case model simulations resulted in a transpiration rate of 90 % of that at current CO_2. These fractions of the transpiration rate calculated for a situation of doubled atmospheric CO_2, for which almost identical values were given in literature reviews by Cure (1985) and Cure & Acock (1986), have been used in the present study as overall reduction factors for calculating the transpiration rates at changing atmospheric CO_2. Changes in crop parameters of the model that reflect the changes in plant behaviour at increasing atmospheric CO_2 as discussed above, are summarized in Table 5.2 .

5.4 Sensitivity analyses

Weather variables that determine crop production directly are solar radiation and temperature. Those that affect the water balance and hence the duration and degree of drought stress are rainfall, windspeed, vapour pressure, and again solar radiation and temperature. The atmospheric CO_2 concentration also has direct and indirect effects on crop production. These variables were adjusted separately in a stepwise manner, in order to gauge the sensitivity of crop production and components of the water balance to changing values of each. These analyses have been done for the three crops of which each can be considered representative for a separate crop group. Winter wheat is a C_3 crop with a determinate growth cycle (shorter growth period at higher temperatures), silage maize is a C_4 crop with a determinate growth cycle, and grass is a C_3 crop with an indeterminate growth cycle (longer growth period at higher temperatures).

5.4.1 Crop production

The sensitivity analyses were carried out for the three crops on sandy loam and loamy soils in de Bilt, the Netherlands, using historical weather data for a period of 20 years (1969 - 1988). Table 5.3 summarizes the sensitivity of water-limited production to changing values of each weather variable. For winter wheat the grain production appears to increase with increasing atmospheric CO_2, rainfall, solar radiation and vapour pressure, and to decrease with rising temperature and increasing windspeed. Both increasing solar radiation and CO_2 positively affect the assimilation rate and thus production. Increasing rainfall and vapour pressure limit the degree of water shortage and hence result in a larger production too. Increasing windspeed results in a higher evapo-transpiration rate and longer periods with water shortage and hence, in a smaller production. At higher temperatures the growth period of wheat is reduced, which also results in a smaller production. For silage maize the total water-limited production appears to increase with increasing atmospheric CO_2, solar radiation, rainfall and vapour pressure, and to decrease with increasing temperature and windspeed. Increasing CO_2 results in a more efficient water use and hence a larger production for maize. Rising temperature results in a shorter growth period but also in a higher rate of CO_2 assimilation. This explains the much smaller, negative effect of rising temperatures compared to that for winter wheat. The sensitivity of silage maize to the other weather variables can be explained in the same way as done above for winter wheat. For permanent grassland the total water-limited production appears to increase with increasing atmospheric CO_2, temperature, rainfall, vapour pressure and solar radiation, and to decrease with increasing windspeed. Rising temperatures result in a longer growth period for grass and thus in a higher level of production. Increasing solar radiation causes a higher rate of CO_2

Table 5.3 Sensitivity of crop production[1] in de Bilt, the Netherlands, on sandy loam and loamy soils to increasing values for atmospheric CO_2 concentration (C), temperature (T), rainfall (R), solar radiation (S), windspeed (W) and vapour pressure (V) (expressed in relative change in production per unit change in temperature (°C) or per relative change in one of the other weather variables).

Crop	C	T	R	S	W	V
Winter wheat	+0.523	-0.034	+0.128	+0.600	-0.114	+0.312
Silage maize	+0.045	-0.004	+0.127	+0.691	-0.084	+0.239
Permanent grassland	+0.454	+0.027	+0.300	+0.240	-0.143	+0.480

[1] Production refers for winter wheat to grain production, for silage maize to total crop production and for grassland to grass production.

Table 5.4 Changes in crop production[1] (as a percentage of production at current climate) in de Bilt, the Netherlands on sandy loam and loamy soils if atmospheric CO_2 concentration (C) increases with 100 % , temperature (T) rises with 3 °C, rainfall (R) or windspeed (W) increases with 30 % , solar radiation (S) or vapour pressure (V) increases with 10 % .

Crop	C	T	R	S	W	V
Winter wheat	+52 %	-10 %	+4 %	+6 %	-3 %	+3 %
Silage maize	+5 %	-1 %	+4 %	+7 %	-3 %	+2 %
Permanent grassland	+45 %	+8 %	+9 %	+2 %	-4 %	+5 %

[1] Production refers for winter wheat to grain production, for silage maize to total crop production and for grassland to grass production.

assimilation but also a higher evapo-transpiration rate and thus longer periods with water shortage. This explains the smaller positive effect of increasing solar radiation compared to that for winter wheat. The sensitivity of grassland to the other weather variables can be explained in the same way as done above for winter wheat. As in reality the various weather variables do not change to the same extent, sensitivities of water-limited production are also given for specified changes in weather variables (Table 5.4). This gives an indication of the changes in production that might be expected for a changed climate.

5.4.2 Evapo-transpiration and leaching

The sensitivity analyses for crop production in de Bilt, the Netherlands have also been used to determine the sensitivity of cumulative water losses by evapo-transpiration to changing weather variables. The results of these analyses are summarized in Table 5.5. For the cultivation of winter wheat cumulative evapo-transpiration during the growth period appears to increase with increasing windspeed, solar radiation, and rainfall, and to decrease with increasing atmospheric CO_2, temperature and vapour pressure. With increasing solar radiation and windspeed the rate of evapo-transpiration increases and for increasing vapour pressure the opposite applies. Increasing atmospheric CO_2 results in a reduced crop transpiration rate. With increasing rainfall cumulative evapo-transpiration increases with the increasing amount of available soil water. Rising temperatures result in shorter growth periods and hence in reduced cumulative evapo-transpiration. For the cultivation of silage maize cumulative evapo-transpiration during the growth period appears to increase with increasing rainfall, solar radiation, and windspeed, to remain almost constant at rising temperature, and to decrease with increasing atmospheric CO_2 and vapour pressure. Increasing atmospheric CO_2 results in major reduction of the rate of crop transpiration. Rising temperatures cause a shorter growth period and thus a smaller cumulative evapo-transpiration, but this effect is about counterbalanced by the increase in evapo-transpiration rate as a result of a greater vapour pressure deficit at higher temperatures. For silage maize the sensitivity of cumulative evapo-transpiration to the other weather variables can be explained in the same way as done above for the cultivation of winter wheat. For permanent grassland cumulative evapo-transpiration during one year appears to increase at increasing temperature, rainfall, solar radiation and windspeed, and to decrease at increasing atmospheric CO_2 and vapour pressure. Rising temperatures result in a longer growth period and thus in an increase in cumulative evapo-transpiration. With increasing solar radiation cumulative evapo-transpiration increases but much less than that for winter wheat or silage maize. This can be explained from the fact that on grasslands water availability limits evapo-transpiration more strongly. The sensitivity of evapo-transpiration to the other weather variables can be explained in the same way as done above

Table 5.5 Sensitivity of cumulative evapo-transpiration[1] in de Bilt, the Netherlands on sandy loam and loamy soils to increasing values for atmospheric CO_2 concentration (C), temperature (T), rainfall (R), solar radiation (S), windspeed (W) and vapour pressure (V) (expressed in relative change in evapo-transpiration per unit change in temperature (°C) or per relative change in one of the other weather variables).

Crop	C	T	R	S	W	V
Winter wheat	-0.036	-0.046	+0.122	+0.489	+0.201	-1.007
Silage maize	-0.174	+0.001	+0.136	+0.496	+0.152	-0.805
Permanent grassland	-0.057	+0.026	+0.235	+0.105	+0.213	-1.360

[1] For winter wheat and silage maize cumulative values for evapo-transpiration during the growth period (dependent on temperature) are compared and for permanent grassland cumulative values during one year.

Table 5.6 Changes in cumulative evapo-transpiration[1] (as a percentage of evapo-transpiration at current climate) in de Bilt, the Netherlands on sandy loam and loamy soils if atmospheric CO_2 concentration (C) increases with 100 % , temperature (T) rises with 3 °C, rainfall (R) or windspeed (W) increases with 30 % , solar radiation (S) or vapour pressure (V) increases with 10 % .

Crop	C	T	R	S	W	V
Winter wheat	-4%	-14%	+4%	+5%	+6%	-10%
Silage maize	-17%	+2%	+4%	+5%	+5%	-8%
Permanent grassland	-6%	+8%	+7%	+1%	+6%	-14%

[1] For winter wheat and silage maize cumulative values for evapo-transpiration during the growth period (dependent on temperature) are compared and for permanent grassland cumulative values during one year.

for winter wheat. As in reality the various weather variables do not change to the same extent, sensitivities of cumulative evapo-transpiration are also given for specified changes in weather variables (Table 5.6). This indicates the degree of changes in evapo-transpiration that might be expected for a changed climate.

The water balance for permanent grassland was calculated for a period of one year. The change in available soil water over this period is about zero. As a consequence, an increase in evapo-transpiration as a result of for example an increase in solar radiation results in a decrease in the amount of water leached from the root zone, if the amount of rainfall is not changed. In this way, leaching from permanent grassland is calculated to increase at increasing atmospheric CO_2, rainfall, and vapour pressure, and to decrease at increasing temperature, solar radiation and windspeed.

5.5 Results for climate changed according to Bultot scenario

Average potential and water-limited production levels and the coefficient of variation (CV) of the productions

were calculated for the sets of historical weather data and for the same data sets changed on the basis of a climate scenario. Results are given for the three crops, for the different soil types and for three locations, i.e. de Bilt, Frankfurt and Freiburg. They cover the degree of variation in climate in the Rhine basin. De Bilt has a relatively low average temperature, a small temperature variation over the year and an average rainfall, Franfurt has also a rather low average temperature but a a larger temperature variation over the year and less rainfall, and Freiburg has the highest average temperature and a larger temperature variation and more rainfall than de Bilt. Results calculated for the optimum soil represent the potential level of crop production. Average results for the sandy loam and loamy soils that are about representative for the waterholding capacity of soils in the Rhine basin, represent the water-limited level of production (without irrigation).

5.5.1 Bultot scenario

Best information on the response of the atmosphere to increasing concentrations of so-called greenhouse gasses is provided by general circulation models. These models are detailed, three-dimensional numerical simulation models that describe atmospheric motions, heat exchanges and land - ocean - ice interactions. However, the spatial resolution of the output of general circulation models is too coarse to be of interest for hydrologic studies of river basins. In addition, results from various general circulation models appear to differ considerably, both in magnitude and in geographical distribution, as shown for the U.S.A. (Croley, 1990) and for Europe (Barrow, 1993). So the output of general circulation models should be received with caution.

Scenarios on climate change have been developed for use in hydrological studies. In such scenarios weather variables are changed to various extents to test their effects on future water resources. But the internal consistency in the changed weather variables is often a weak point (Gleick, 1989). For river basins in Belgium a scenario of the climate change induced by doubling the actual atmospheric CO_2 concentration, has been reported (Bultot *et al.*, 1988). This scenario applies to an area close to the Rhine basin, was compiled in a consistent way and hence, is used for calculating 'future' climate conditions in the Rhine basin. It can be considered representative for the situation in the year 2080, if the 'Business-as-usual' emission scenario of the IPCC (Houghton *et al.*, 1990) comes true. It should be realized that in this situation there is not yet an equilibrium between the temperature rise and the increased radiative forcing on the earth-atmosphere system.

'Future' climate conditions are calculated from historical weather data (period 1969 - 1988) by changing the weather data for each location according to the Bultot scenario. The following changes are applied:

- change in air temperature + 3 °C;
- change in precipitation in November, December and January + 10 % ;
- " " " " February, March and April + 16 % ;
- " " " " May, June, July and August - 3 % ;
- " " " " September + 0 % ;
- " " " " October + 7 % ;
- no change in relative air humidity and hence, vapour pressure corrected for increased temperature;
- no change in windspeed (no information in Bultot scenario);
- no change in solar radiation because relative humidity does not change;
- doubling of current atmospheric CO_2 concentration.

5.5.2 Winter maize

Crop growth and the components of the water balance were simulated from January 1 till the date of maturing. Actually sowing occurs in October or November. After about two weeks crop emergence finds place, so that at January 1 a limited amount of crop material is already formed. An estimate for this amount is used as start weight in the crop growth simulation. The initial amount of available soil water at January 1 was set at the maximum per soil type.

Potential grain production calculated for current climate conditions is more than 9 t ha^{-1} in de Bilt and more than 8 t ha^{-1} in Frankfurt and Freiburg (Figure 5.1). For the climate change according to the Bultot scenario potential production increases to almost 13 t ha^{-1} in de Bilt, to 11 t ha^{-1} in Frankfurt and 10 t ha^{-1} in Freiburg. Increases in water-limited production by climate change are almost identical to those in potential production (Figure 5.1). They are mainly caused by the doubled atmospheric CO_2 concentration that results in a larger assimilate production of the leaves. The growth period of winter wheat decreases if the average temperature rises. At locations with relatively high temperatures (Freiburg) and thus rather short growth periods, production increases as a result of climate change appear to be much lower than those on locations with relatively lower temperatures (Figure 5.1: de Bilt).

The CV is a good indicator of production variability and the risk of a relatively low production. Climate change may cause changes in the CV. Calculated increases or decreases in the CV indicate that the agricultural risks in future may increase or decrease. For potential production the CV appears to remain almost identical with

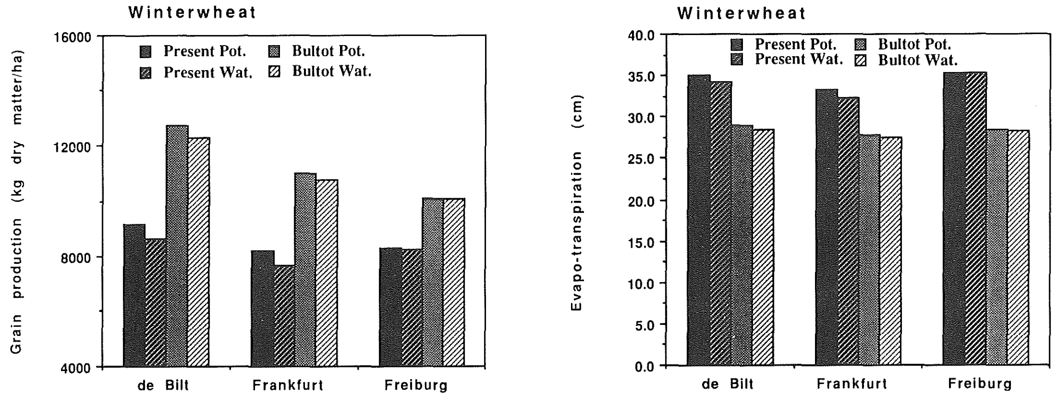

Figure 5.1 Average potential (Pot.) and water-limited (Wat.) grain production (kg dry matter/ha) and evapo-transpiration (cm) during the growth period of winter wheat in current and scenario climate conditions. Average values have been established for historical weather data over a period of twenty years (1969 - 1988) from de Bilt, the Netherlands, and Frankfurt and Freiburg, Germany without and with changes on the basis of the Bultot scenario, and for cultivation on optimum (Pot.) and on sandy loam and loamy soils (Wat.).

climate change for all locations and for water-limited productions the CV decreases (Table 5.7). This indicates that the risk for a low production in relatively dry years that at present is small to moderately large (e.g. Frankfurt) in the Rhine basin, decreases as a result of climate change.

Cumulative water losses by evapo-transpiration during the growth period decrease considerably by climate change (Figure 5.1). This can be explained from the rise in temperature that results in a shorter growth period (Table 5.7). The amount of rainfall during the growth period decreases with climate change too but slightly less than the decrease in evapo-transpiration, which results in less depletion of available soil water. However, such a comparison of water balances over different periods of time can only be of limited value. For water-limited production the water losses by evapo-transpiration are almost identical to those of potential production (Figure 5.1) which indicates that evapo-transpiration and thus production are almost not limited by water availability.

Table 5.7 Average values (AV) and coefficients of variation (CV) for potential (POT) and water-limited (WAT) grain productions[1] and the components of the water balance[2] during the growth period of winter wheat at current and scenario climate conditions in de Bilt, the Netherlands, and in Frankfurt and Freiburg, Germany; average values have been established for historical weather data over a period of 20 years (1969 - 1988) without and with changes on the basis of the Bultot scenario.

Location,	Climate	Duration growth period[2] (d)	Dry matter production (kg ha^{-1})				Rainfall (cm)	Transpiration (cm)	Evaporation (cm)	Leaching (cm)	Change Soil water[3] (cm)
			POT		WAT						
			AV	CV	AV	CV					
de Bilt,	Present	228	9170	0.09	8640	0.17	46.8	25.2	9.0	20.4	-7.8
de Bilt,	Bultot	195	12740	0.09	12310	0.13	42.9	21.3	7.1	20.9	-6.4
Frankfurt,	Present	218	8190	0.12	7680	0.22	38.6	24.0	8.3	15.3	-9.0
Frankfurt,	Bultot	191	10990	0.09	10740	0.12	36.0	20.5	6.9	15.5	-6.9
Freiburg,	Present	207	8290	0.11	8220	0.13	56.9	25.4	9.9	24.9	-3.3
Freiburg,	Bultot	181	10090	0.14	10080	0.14	51.7	19.4	9.0	25.3	-2.0

[1] Average water-limited production situation on sandy loam and loamy soils.

[2] Growth period was considered from January 1 till moment of crop maturing and components of the water balance (on sandy loam and loamy soils) were calculated for the indicated duration.

[3] Initial amount of available soil water at January 1 was set at the maximum amount.

Table 5.8 Average values (AV) and coefficients of variation (CV) for potential (POT) and water-limited (WAT) total productions[1] and the components of the water balance[2] during the growth period of silage maize at current and scenario climate conditions in de Bilt, the Netherlands, and in Frankfurt and Freiburg, Germany; average values have been established for historical weather data over a period of 20 years (1969 - 1988) without and with changes on the basis of the Bultot scenario.

Location,	Climate	Duration growth period[2] (d)	Dry matter production (kg ha^{-1})				Rainfall (cm)	Transpiration (cm)	Evaporation (cm)	Leaching (cm)	Change Soil water[3] (cm)
			POT		WAT						
			AV	CV	AV	CV					
de Bilt,	Present	138	19790	0.10	18900	0.11	29.9	22.9	6.5	3.4	-2.9
de Bilt,	Bultot	118	19080	0.08	18720	0.09	24.3	18.5	6.5	3.2	-3.9
Frankfurt,	Present	126	19730	0.10	17940	0.16	25.4	23.6	6.4	2.9	-7.5
Frankfurt,	Bultot	110	16310	0.13	16010	0.16	22.0	16.4	6.7	3.1	-4.2
Freiburg,	Present	114	20190	0.07	19920	0.08	38.8	27.2	6.6	7.8	-2.8
Freiburg,	Bultot	104	16500	0.13	16010	0.12	35.0	17.4	7.6	10.3	-0.3

[1] Average water-limited production situation on sandy loam and loamy soils.

[2] Growth period was considered from crop emergence (May 15 and April 25 for de Bilt and May 8 and April 18 for Frankfurt and Freiburg for current and scenario climate conditions respectively) till date of crop maturing or date of harvest (set at October 2 when crop is not yet mature at that date) and components of the water balance (on sandy loam and loamy soils) were calculated for the indicated duration.

[3] Initial amount of available soil water at crop emergence was set at the maximum amount minus 3 cm water.

Table 5.9 Average values (AV) and coefficients of variation (CV) for potential (POT) and water-limited (WAT) productions[1] and the components of the water balance[2] for mown permanent grassland at current and scenario climate conditions in de Bilt, the Netherlands, and in Frankfurt and Freiburg, Germany; average values have been established for historical weather data over a period of 20 years (1969 - 1988) without and with changes on the basis of the Bultot scenario.

Location,	Climate	Dry matter production (kg ha^{-1})				Rainfall (cm)	Transpiration (cm)	Evaporation (cm)	Leaching (cm)	Change Soil water[3] (cm)
		POT		WAT						
		AV	CV	AV	CV					
de Bilt,	Present	18190	0.04	15820	0.16	79.4	28.3	12.1	38.8	+0.2
de Bilt,	Bultot	27790	0.04	24860	0.11	84.1	28.1	13.5	42.2	+0.3
Frankfurt,	Present	17870	0.04	14400	0.24	63.3	28.3	12.0	23.0	0.0
Frankfurt,	Bultot	26900	0.03	22450	0.18	66.6	28.0	13.1	25.5	0.0
Freiburg,	Present	19660	0.05	19020	0.07	96.3	39.2	14.7	42.4	0.0
Freiburg,	Bultot	28590	0.04	27870	0.06	100.7	38.2	16.6	45.9	0.0

[1] Average water-limited production situation on sandy loam and loamy soils.

[2] Production and components of the water balance (on sandy loam and loamy soils) were calculated for a period of one year.

[3] Initial amount of available soil water at January 1 was set at the maximum amount.

5.5.3 Silage maize

Crop growth and the components of the water balance were simulated from the date of crop emergence, i.e. May 15 and April 25 for de Bilt and May 8 and April 18 for Frankfurt and Freiburg for current and 'future' climate conditions respectively, till the date of maturing or the date of harvest. If the maize crop is not yet mature at October 2, it is assumed to be harvested on that date anyway. With climate change the date of emergence is advanced by three weeks, which can be explained from the rise in average temperature by 3 °C. The initial amount of available soil water at crop emergence was set at the maximum amount per soil type minus 3 cm water.

Potential production calculated for current climate conditions, is about 20 t ha^{-1} in de Bilt, Frankfurt and Freiburg (Figure 5.2). With climate change potential production decreases to 19 t ha^{-1} in de Bilt and to about 16 t ha^{-1} in Frankfurt and Freiburg. Particularly on locations with a relatively high average temperature (e.g. Freiburg), the negative effect of temperature rise on the growth duration and hence on production, appears to be large. Decreases in water-limited production by climate change are generally smaller than those in potential production (Figure 5.2). Particularly in Frankfurt where the water supply may limit production at present, the increased water use efficiency of maize at doubled atmospheric CO_2 reduces the decrease in production by climate change.

For potential and water-limited production the CV remains about identical with climate change for all locations (Table 5.8). This indicates that the risk for low production in relatively dry years that at present is very small in the Rhine basin, does not change as a result of climate change.

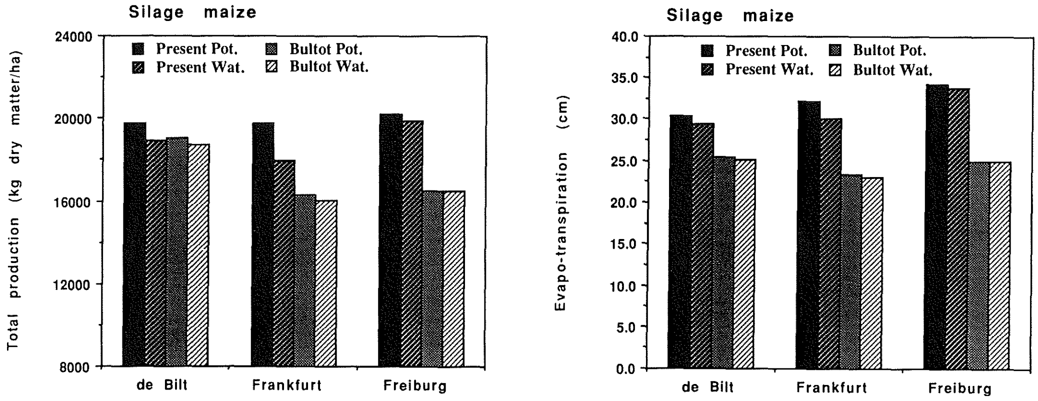

Figure 5.2 Average potential (Pot.) and water-limited (Wat.) total production (kg dry matter/ha) and evapo-transpiration (cm) during the growth period of silage maize in current and scenario climate conditions. Average values have been established for historical weather data over a period of twenty years (1969 - 1988) from de Bilt, the Netherlands, and Frankfurt and Freiburg, Germany without and with changes on the basis of the Bultot scenario, and for cultivation on optimum (Pot.) and on sandy loam and loamy soils (Wat.).

Cumulative water losses by evapo-transpiration during the growth period decrease considerably by climate change (Figure 5.2). This can be explained from the rise in temperature that results in a shorter growth period (Table 5.8) and from the decreased transpiration rate at doubled atmospheric CO_2. The cumulative amount of rainfall decreases as a result of climate change and the shorter growth period too. In Frankfurt and Freiburg the decrease in evapo-transpiration is larger than that in rainfall, which results in a decreased depletion of available soil water. However, such a comparison of water balances over different periods of time can only be of limited value. For water-limited production the water losses by evapo-transpiration are almost identical to those of potential production (Figure 5.2). This indicates that evapo-transpiration and thus production are almost not limited by water availability, with only Frankfurt at present as an exception.

5.5.4 Permanent grassland

Growth of regularly mown grassland and the components of the water balance were simulated over one year.

The initial amount of available water at January 1 was set at the maximum amount per soil type.

Potential productions of mown permanent grassland calculated for current climate conditions are 18 t ha^{-1} in de Bilt and Frankfurt and 20 t ha^{-1} in Freiburg (Figure 5.3). Highest productions are found on locations where the temperature is relatively high and hence the period of grass growth is relatively long. For the changed climate potential productions increase to between 27 and 29 t ha^{-1}.

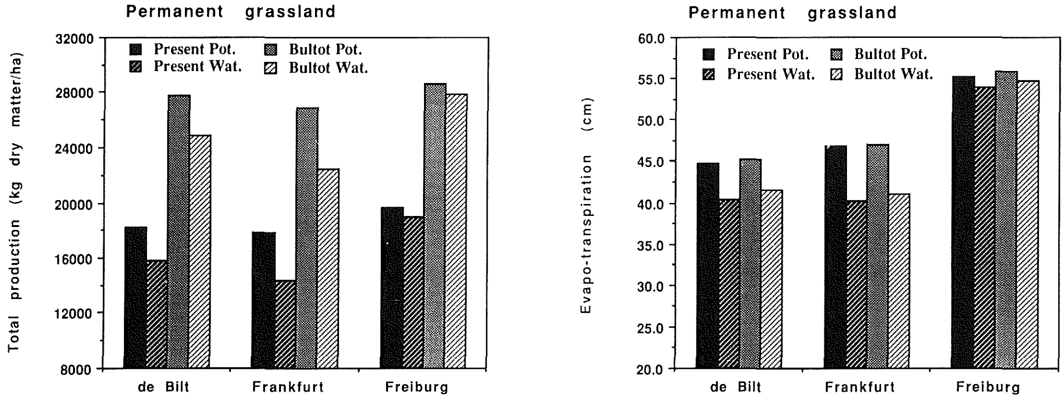

Figure 5.3 Average potential (Pot.) and water-limited (Wat.) total production (kg dry matter/ha) and evapo-transpiration (cm) per year of mown permanent grassland in current and scenario climate conditions. Average values have been established for historical weather data over a period of twenty years (1969 - 1988) from de Bilt, the Netherlands, and Frankfurt and Freiburg, Germany without and with changes on the basis of the Bultot scenario, and for grasslands on optimum (Pot.) and on sandy loam and loamy soils (Wat.).

Increases in water-limited production by climate change are about identical to those in potential production (Figure 5.3). They are mainly caused by the doubled atmospheric CO_2 concentration that results in a larger assimilate production of the leaves, and by the longer growth duration at higher temperatures.

For potential production the CV remains about identical with climate change for all locations (Table 5.9). For water-limited production the CV decreases considerably with climate change in Frankfurt, where at present the CV of water-limited production is much higher than that of potential production. In Freiburg no water shortage occurs at present and with climate change and consequently, the CV of water-limited production remains almost identical with climate change. In de Bilt the CV decreases slightly with climate change, as the degree of water shortage is in between those for Frankfurt and Freiburg. As indicated by these changes in CV, the risk for a low production in relatively dry years that at present is small to moderately large (e.g. Frankfurt) in the Rhine basin, decreases as a result of climate change.

Cumulative water losses by evapo-transpiration over one year increase slightly with climate change (Figure 5.3). This can be explained from the rise in temperature that results in increases in evaporation and in transpiration (via longer growth period and larger vapour pressure deficit) which are largely counterbalanced by a reduction in transpiration rate (via decreased stomatal conductance) at doubled atmospheric CO_2 (Table 5.9). For water-limited production the increase in evapo-transpiration by climate change is almost identical to that for potential production. The annual amount of rainfall increases with climate change too and to a larger extent than the increase in evapo-transpiration. As over a period of one year the change in available soil water is about nil, leaching from the root zone appears to increase by about 10 % as a result of climate change. For water-limited production the water losses by evapo-transpiration are smaller than those of potential production in de Bilt and particularly in Frankfurt (Figure 5.3) which indicates that evapo-transpiration and thus grass production are limited by water availability on these locations.

5.6 Conclusions

Future climate conditions in the Rhine basin according to the applied climate change scenario can be found at present in southern France and northern Italy. Socio-economic conditions in the Rhine basin and in southern France and northern Italy do not differ much and consequently, the effects of climate change on future land use in the Rhine basin may be derived from the comparison of actual land use in the Rhine basin and that in southern France and northern Italy, respectively. The derived changes in land use are mainly an increase in area for permanent crops and for arable crops with large temperature sum requirements (e.g. grain maize and sunflower) and a decrease in area for permanent grassland and for root crops.

For the three crops, winter wheat, silage maize and permanent grass, that can be considered representative for determinate C_3 crops, determinate C_4 crops and indeterminate C_3 crops, the sensitivity to separately changed weather variables has been calculated. Rising temperatures have a positive effect on the production of indeterminate crops but a negative one on the production of determinate crops. By growing crop varieties with higher temperature sum requirements this negative effect can be avoided. Increasing rainfall and vapour pressure have a positive effect

on the production of all crops by increasing water supply or decreasing water use. Increasing windspeed has a negative effect on the production of all crops by increasing water use. Increasing atmospheric CO_2 results in a higher assimilation rate of the leaves for C_3 crops and a higher water use efficiency for C_4 crops, which causes a larger crop production in both cases. Also increasing solar radiation has a positive effect on production of all crops.
For the three crops the effects of climate change on their production in the Rhine basin have been calculated. The main changes in climate included are an increase in temperature, a doubling of atmospheric CO_2 and a moderately increased amount of annual rainfall with a changed distribution over the year. This results for permanent grassland in a slightly increased annual evapo-transpiration. As the annual amount of rainfall increases more strongly by climate change, water losses by leaching from the root zone increase and the risk for water shortage decreases. Climate change also results in less water limitation for the production of winter wheat and silage maize in the Rhine basin. With climate change grain production of winter wheat was calculated to become roughly 35 % higher, production on permanent grassland 50 % higher and production of silage maize 10 % lower. The negative effects of higher temperatures on the production of determinate crops can be avoided by growing better adapted crop varieties. This means that in reality maize production will not decrease with climate change. Largest increases in production have been calculated for grassland which can be explained from the higher assimilation rate at doubled atmospheric CO_2 and the extended growth period at higher temperatures.

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