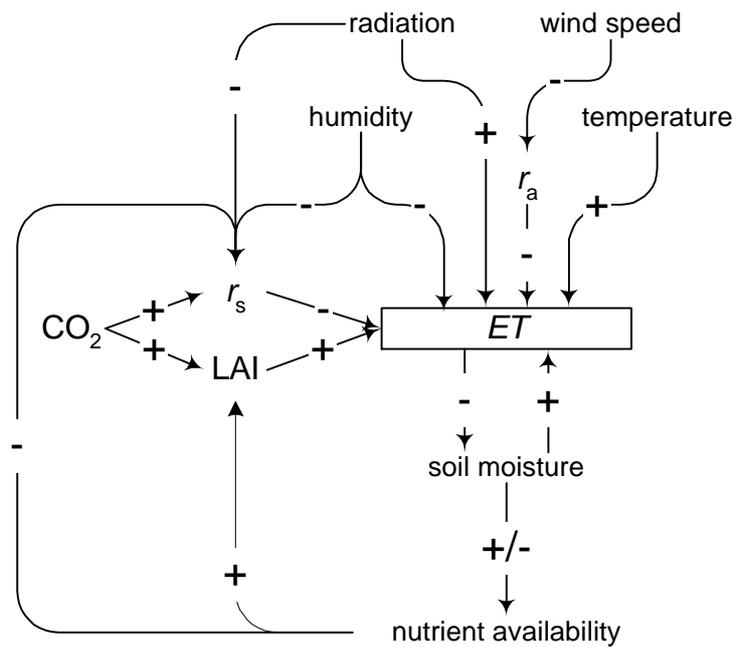




KWR 06.004

Januari 2006

## The effects of rising CO<sub>2</sub> levels on evapotranspiration



**KWR 06.003**

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# **The effects of rising CO<sub>2</sub> levels on evapotranspiration**

## **Clients**

**Rijkswaterstaat Riza**

**Kiwa Water Research**

## **Project number**

**30.6662.400**

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**Title**

The effects of rising CO<sub>2</sub> levels on evapotranspiration

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30.6662.400

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# Foreword

Through fossil fuel combustion, the concentrations of carbon dioxide in the atmosphere are increasing, causing a rise in temperatures on the earth. The effect of this temperature rise on potential evapotranspiration has been calculated for The Netherlands by the Dutch meteorological institute KNMI (Beersma et al., 2004): depending on the climate scenario, rising temperatures will cause an increase in annual potential evapotranspiration of between 1.9% and 18%.

However, another consequence of increased levels of CO<sub>2</sub> is that plants do not have to open their stomata as widely, or to create as many stomata, in order to absorb enough CO<sub>2</sub>. And the effect of this is that evapotranspiration decreases.

In a very short study, Doomen & Witte (2004) showed that the decrease in evapotranspiration through rising levels of CO<sub>2</sub> could be considerable, with serious consequences for hydrology in The Netherlands. Their study was too brief, however, to adequately substantiate the connection between an increase in CO<sub>2</sub> and a decrease in evapotranspiration. Furthermore, their study raised a number of questions concerning the usability of the experiments described in the literature and the interaction between a decrease in evapotranspiration and environmental factors such as drought stress, temperature and nutrient availability.

For this reason, the Institute of Integrated Water Management and Waste water Treatment, Riza, has asked Kiwa Water Research to do further research into the effects of CO<sub>2</sub> increases on decreasing evapotranspiration. This report is an account of this research, which was jointly financed by Riza's 'Drought Study' ([www.droogtestudie.nl](http://www.droogtestudie.nl)) and Kiwa. Comments on both the set-up of the research and the draft report were provided by Peter Droogers (Future Water), Reinder Feddes (Wageningen University, Soil Physics, Ecohydrology and Groundwater Management group) and Han Stricker (Wageningen University, Hydrology and Quantitative Water Management group). In a later stage, Adri Buishand and Jules Beersma from KNMI as well as Timo Kroon from Riza commented on the report.

It was Reinder Feddes who advised me to ask Alterra to calculate the reduction in evapotranspiration using the Penman-Monteith evapotranspiration equation and empirical observations of the relation between CO<sub>2</sub> and stomatal resistance. Thanks to Bart Kruijt of Alterra, this calculation could be performed in a satisfying manner.

Those who are only interested in the results of this study can go straight to the last chapter (page 45), which is readable without the preceding chapters.

Jan-Philip (Flip) Witte  
Nieuwegein, January 2006



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# 1 Introduction

## 1.1 Reasons for this study

In the context of Phase 2 of the Netherlands Drought Study, Kiwa Water Research conducted an exploratory literature study on the effects of CO<sub>2</sub> increases in evapotranspiration, biomass production and competition between plant species (Doomen & Witte, 20 04). One of the most important results of the study is that an increase in CO<sub>2</sub> levels can lead to a significant reduction in potential evapotranspiration. If this result is correct, it has important consequences for hydrology in The Netherlands in a period of climate change: instead of becoming drier, as is generally assumed, The Netherlands would become wetter.

However, this exploratory literature study was too brief to fully substantiate a relation between an increase in CO<sub>2</sub> levels and a decrease in evapotranspiration. Furthermore, their study raised a number of questions concerning the usability of the experiments described in the literature and the interaction between a decrease in evapotranspiration and environmental factors such as drought stress, temperature and nutrient availability. In view of the very significant consequences for hydrology, it is very important that the relationship between increased CO<sub>2</sub> and reduced evapotranspiration be substantiated.

## 1.2 Aims and Starting Points

Rijkswaterstaat uses the NAGROM and MOZART models to simulate water flow in saturated and unsaturated zones, respectively. These models are linked together by means of the MONA model (Bos et al., 1997). To be able to make its calculations, the MOZART model has to be fed with data about rainfall and the reference crop evapotranspiration, according to Makkink,  $ET_{ref}$ .

Since 1987, the Makkink evapotranspiration has been established for several weather stations in The Netherlands. This reference crop evapotranspiration is equivalent to the evapotranspiration of a healthy short grass lawn which is provided with enough nutrients and water; it is, therefore, by definition the potential evapotranspiration of such a hypothetical lawn. The potential evapotranspiration of other vegetations (i.e. crops) is obtained by multiplying the reference crop evapotranspiration by a crop factor:

$$ET_p = f \times ET_{ref} \quad [1.1]$$

In which (with the usual units between brackets):

$ET_p$  potential evapotranspiration of the vegetation (mm d<sup>-1</sup>)

$f$  crop factor (-)

$ET_{ref}$  reference crop evapotranspiration according to Makkink (mm d<sup>-1</sup>)

The term evapotranspiration covers evaporation from two sources: evaporation from soil and wet surfaces such as raindrops on leaves, and transpiration from the stomata and cuticula of plants.

Crop factors for a range of vegetations have been described in detail in the literature (e.g. Feddes, 1987). The actual evapotranspiration ( $ET_a$ ) is equal to or lower than the potential evapotranspiration, because if conditions are too dry, too wet or too salty, vegetation reduces the transpiration.  $ET_a$  can be calculated with MOZART using a transpiration reduction derived from Feddes et al. (1978), which is a function of the pressure head of the soil moisture in the root zone.

The Rijkswaterstaat models are used to calculate the hydrological consequences of climate change. The KNMI has drawn up climate scenarios, simulating changes in precipitation and potential evapotranspiration per decade (Beersma et al., 2004). According to the KNMI, there will be an increase in weather extremes. Potential evapotranspiration will also increase, due to rising temperatures. Table 1-1 gives the projections for four climate scenarios for the year 2050.

Table 1-1. Climate scenario's for 2050 (Beersma et al., 2004). Multiplying factors are given for precipitation and evapotranspiration (so, 1.015 means an increase of 1.5%).

	Market optimist	Controller	Environmentalist	Drought
<i>Temperature increase (°C)</i>				
Year	0.5	1	2	2.3
Summer	0.5	1	2	3.1
Winter	0.5	1	2	2.0
<i>Increase in precipitation (-)</i>				
Year	1.015	1.030	1.060	0.960
Summer	1.007	1.014	1.028	0.800
Winter	1.030	1.060	1.012	0.870
<i>Increase in potential evapotranspiration (-)<sup>1</sup> (c<sub>1</sub>)</i>				
Year	1.019	1.039	1.078	1.180
Summer	1.017	1.033	1.066	1.240
Winter	1.028	1.056	1.112	1.080

<sup>1</sup> Market optimist, Controller and Environmentalist are based on the formula of Penman-Monteith. The temperature effect comes out lower with the Makkink formula, used for MOZART (see Beersma et al., 2004, p. 46).

The increase in evapotranspiration caused by rising temperatures is called the temperature effect of climate change.

However, the method for calculating the actual evapotranspiration with MOZART does not take into account the fact that the way vegetation deals with water changes with higher CO<sub>2</sub> concentrations. *On the one hand, if CO<sub>2</sub> levels go up, plants produce more biomass*, leading to an increase in leaf surface (Leaf Area Index or LAI) and therefore in evapotranspiration. This we shall call the lai-effect. *On the other hand, when CO<sub>2</sub> levels are high, plants can fulfil their C-requirements more easily*, meaning that they don't have to open their stomata as wide, or to make as many of them, and they reduce their transpiration: the water use efficiency effect, or wue-effect. Experimental research seems to indicate that the wue-effect is greater than the lai-effect, and the plants therefore use less water for evapotranspiration. The combined lai- and wue-effects are called the CO<sub>2</sub>-effect on evapotranspiration of climate change, shortened to CO<sub>2</sub>-effect:

$$\text{CO}_2\text{-effect} = \text{lai-effect} + \text{wue-effect} \quad [1.2]$$

When calculating the potential evapotranspiration for a climate scenario, both the temperature effect and the CO<sub>2</sub>-effect should be taken into account. This can be done as follows<sup>2</sup>:

$$ET_p^* = c_1 \times c_2 \times f \times ET_{\text{ref}} \quad [1.3]$$

In which:

- $ET_p^*$  potential evapotranspiration of the vegetation, *corrected for both the temperature effect and the CO<sub>2</sub>-effect* (mm d<sup>-1</sup>)
- $c_1$  factor for the temperature effect (Table 1-1) (-)
- $c_2$  factor for the CO<sub>2</sub>-effect (-)

***The aim of this study is to quantify the relationship between the reduction factor  $c_2$  and the atmospheric CO<sub>2</sub>-concentration.***

If this study is successful, Rijkswaterstaat will be able to base its calculations on properly corrected figures for potential evapotranspiration (Klopstra et al., 2005).

We adopt the following three important starting points for this study:

1. Consequences of possible genetic adaptation to the new climate by plant species are not dealt with.
2. The impacts of the vegetation on the regional and global climate are not dealt with.

---

<sup>2</sup> With our correction method we implicitly link the potential evapotranspiration to the current CO<sub>2</sub> level. An alternative would be to involve the CO<sub>2</sub>-effect in the computation of the reference evapotranspiration. For this, the empirical constant in the Makkink equation ( $a$  in Eq. [4.4]) will have to depend on the CO<sub>2</sub>-level.

3. Changes in the moisture and nutrient balance of the soil resulting from changes in evapotranspiration are only incidentally discussed.

In this study we assume a CO<sub>2</sub> concentration of 520 ppm for the year 2050 (KNMI report according to Timo Kroon, Riza). Moreover, we include the year 2100 in our study. With the help of computer simulations, the IPCC has predicted a CO<sub>2</sub> level of 540- 970 ppm for the year 2100 (Gitay et al., 2002). Compared to the CO<sub>2</sub> level in 2000 (368 ppm, according to Gitay et al., 2002), this represents an average rise of approximately:

- 150 ppm in 2050
- 385 ppm in 2100

Especially the latter figure is surrounded by large uncertainties. If desired, effects of other CO<sub>2</sub> rises can be calculated with the aid of this report.

### 1.3 Research method

The research into the relationship between CO<sub>2</sub> concentration and evapotranspiration will be conducted as follows:

- 1a. Firstly, the evapotranspiration process will be briefly analyzed, based on a literature study. *This study will focus on the relationship between CO<sub>2</sub> and evapotranspiration*, and the factors which may influence it. The results of this first stage are described in Chapter 2.
- 1b. Armed with the insights gained from the first stage, source research will now be conducted, studying as many publications about CO<sub>2</sub> and evapotranspiration as possible, and recording the results in a database (Chapter 3).
2. In view of the various reservations about field research (a point to which we will return later), a second line of inquiry will be followed as well: calculating CO<sub>2</sub> effects with the Penman-Monteith evapotranspiration equation, from the plot level to the landscape level. (Chapter 4)
3. Finally, the results of both lines of inquiry will be discussed (Chapter 5).

## 2 The relationship between CO<sub>2</sub> and evapotranspiration: theory

### 2.1 Introduction

Carbon dioxide is the only source of carbon for plants. CO<sub>2</sub> is absorbed primarily through diffusion via the stomata. Plants have to open their stomata in order to absorb CO<sub>2</sub>, thereby causing a loss of moisture by transpiration (Figure 2-1). So plants have to lose moisture in order to absorb CO<sub>2</sub>. Since photosynthesis stops at night, plants close their stomata, so that moisture loss is limited.

The exact physiological process at cell level that underlies the opening of the stomata is only partially understood. This is not the focus of our study. However, observations consistently indicate that evapotranspiration from leaves and the amount they open their stomata diminish as the CO<sub>2</sub> concentration in the air increases. Intuition suggests, then, that the stomata regulate moisture loss from plants, which is usually advantageous to limit, except in cases where evapotranspiration can help to moderate the leaf temperature.

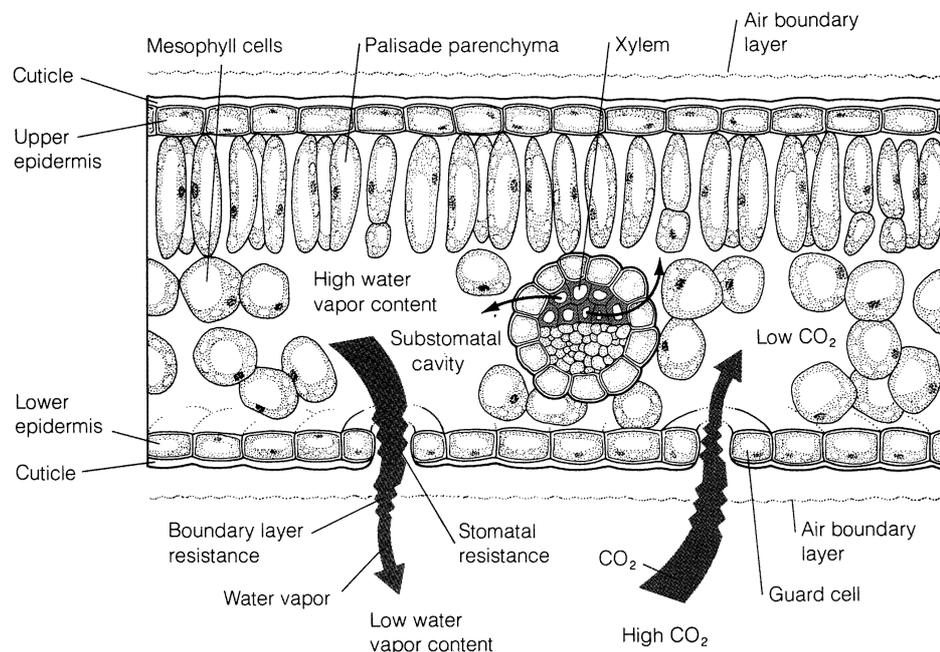


Figure 2-1. Absorption of CO<sub>2</sub> and release of water by a leaf (Taiz & Zeiger, 1991). Water moves from the xylem to the cell walls; from here it evaporates into the air-filled spaces in the leaves. Subsequently, water molecules move by diffusion through these sub-stomatal spaces, the stomata and the inert layer of air on the leaf surface. CO<sub>2</sub> transport in the opposite direction also takes place by diffusion.

The proportion of the number of CO<sub>2</sub> molecules fixed by the plant to the number of H<sub>2</sub>O molecules lost by transpiration is called the transpiration ratio,  $R_T$ :

$$R_T = \frac{\text{mol H}_2\text{O transpired}}{\text{mol CO}_2 \text{ fixated}} \quad [2.1]$$

In most plants in The Netherlands, the first product of photosynthesis is a compound consisting of three carbon atoms. The typical  $R_T$  value of these C<sub>3</sub> plants is 500. C<sub>4</sub> plants (of which the first fixation product has four carbon atoms) are more economical with water, and their transpiration ratio averages 250 (Taiz & Zeiger, 1991). The commonest and best-known C<sub>4</sub> plant among agricultural crops in The Netherlands is maize (*Zea mais*).

Another unit used in the literature instead of the transpiration ratio is water use efficiency,  $wue$ . It is customary to define this unit as the reciprocal of  $R_T$  (although there are other definitions in use in the literature):

$$wue = 1/R_T \quad [2.2]$$

Increases in the concentration of CO<sub>2</sub> in the atmosphere have two important and opposite consequences for evapotranspiration:

1. Plants do not have to open their stomata as wide, or they have to make fewer stomata in order to maintain their supply of carbon dioxide. The consequence is that the  $wue$  goes up and the transpiration loss goes down (wue-effect).
2. Plants can grow faster, producing more biomass. The evapotranspiration (via transpiration and interception) increases with the increase in biomass (lai-effect).

As previously mentioned, experimental results suggest that the first effect is dominant, and that vegetation generally creates less evapotranspiration at higher concentrations of CO<sub>2</sub>.

## 2.2 Effects of CO<sub>2</sub> and temperature on photosynthesis and water consumption

Under conditions of unlimited light and soil nutrient availability, the influence of CO<sub>2</sub> on photosynthesis is often described by means of experimental curves showing the relationship between CO<sub>2</sub> concentration  $C$  and assimilation rate  $A$  (Ammerlaan & De Visser, 1993; Noormets et al., 2001; Sage & Kubien, 2003). It appears from these A-C curves (Figure 2-2) that variations in the CO<sub>2</sub> level particularly affect the assimilation rate at low levels; at high levels, variations hardly play a role. Since the demand for CO<sub>2</sub> levels out with higher availability, the stomata can close up even more and the CO<sub>2</sub> effect (evapotranspiration reduction through rising CO<sub>2</sub> levels) increases.

The saturation point for CO<sub>2</sub> is lower in C<sub>4</sub> plants than in C<sub>3</sub> plants (Taiz & Zeiger, 1991). This would explain why in some experiments, C<sub>4</sub> plants react more strongly than C<sub>3</sub> plants to CO<sub>2</sub>-enriched air.

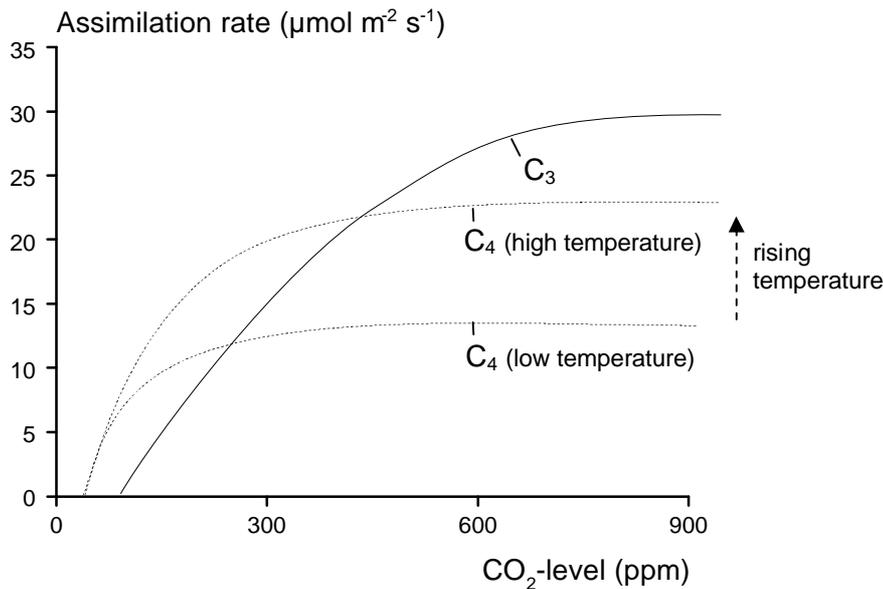


Figure 2-2. Example of the relationship between  $CO_2$  level and assimilation rate  $A$  for a hypothetical  $C_3$  and  $C_4$  plant.

According to De Wit (1958), photosynthesis is a process which is far more determined by radiation energy from the sun than by temperature. Respiration in plants is heavily dependent on temperature, but this is usually a minor factor, so that the effect of temperature on the net assimilation (photosynthesis minus respiration) remains small. De Wit (1958) showed that the crop yield (dry matter production) of the vegetation is in direct proportion to the transpiration.

According to Monteith (1981), the temperature is of particular influence on the developmental stages of the plant, such as the timing of germination and the opening of the leaves. In a temperate climate this development goes faster in rising temperatures, until an optimal temperature of c. 20 -25 °C is reached. Above this optimal temperature, the development rate slows down again until it comes to a complete standstill at 30 -35 °C. High temperatures damage the plant by attacking proteins.

However, this relatively temperature-sensitive character of photosynthesis does not apply in  $C_4$  plants at high  $CO_2$  concentrations: for this functional species group the assimilation rate (the 'ceiling' in Figure 2-2) actually increases with the temperature (Sage & Kubien, 2003), causing the saturation point on the A-C curve to move to the right (the sharp start to the curve hardly changes).  $C_4$  plants could therefore benefit from rising temperatures combined with an increase in  $CO_2$ . Sage & Kubien (2003) suggest this might explain the proliferation of the  $C_4$  plant *Spartina* in Western Europe.

On the basis of paleontological data, Farquhar (1997) speculated as to how water consumption may have changed in the course of geological history due to changes in  $CO_2$  levels. During the last glacial maximum (LGM) - about 20,000 years ago - the earth's climate must have been much drier than it is

now. This is thought to be related to the much lower atmospheric level of 180 ppm of CO<sub>2</sub> during the LGM. At such low concentrations, the wue of plants is in almost direct proportion to the CO<sub>2</sub> concentration. At a concentration level of 180 ppm (LGM), plants have to transpire twice as much to achieve the same amount of photosynthesis as under the current CO<sub>2</sub>-level. Furthermore, precipitation is much less at lower CO<sub>2</sub> concentrations. According to Farquhar (1997), the relationship between CO<sub>2</sub> and drought would also explain why 30% more carbon was deposited during the pre-industrial era (270 ppm) than during the LGM. Although plants are now less CO<sub>2</sub> limited than during the LGM, increased CO<sub>2</sub> would still lead to an increase in groundwater recharge. Farquhar (1997) suggests that this could be a positive side-effect of climate change, especially in agricultural areas which now suffer from drought<sup>3</sup>.

### 2.3 The role of transpiration in evapotranspiration

The term evapotranspiration combines two processes: evaporation (symbol: *E*) from wet soil and plant surfaces, and transpiration (symbol: *T*) via the stomata and cuticula of plants. The sum of these two processes is called evapotranspiration (*ET*):

$$ET = E + T \quad [2.3]$$

Evaporation takes place from the leaf surface after rain (interception) and from the soil (soil evaporation). In general, transpiration contributes the most to the total evapotranspiration *ET*. This is illustrated in Figure 2-3, in which the share of transpiration in the potential evapotranspiration is plotted against the leaf area index (*LAI*) of the vegetation. It is apparent from this figure that the share of transpiration increases with the *LAI* and with increased dryness of the soil. However, as soon as the vegetation covers the soil by more than 70-80% (*LAI*>2), the distinction between wet and dry soils becomes negligible.

In The Netherlands, vegetation usually covers the soil to a large extent, making transpiration the most important factor. For this reason, our research focuses mainly on transpiration.

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<sup>3</sup> There are certain reservations about this appealing account: Farquhar (1997) does not take into consideration the effects of changes in biomass production on evapotranspiration, for instance.

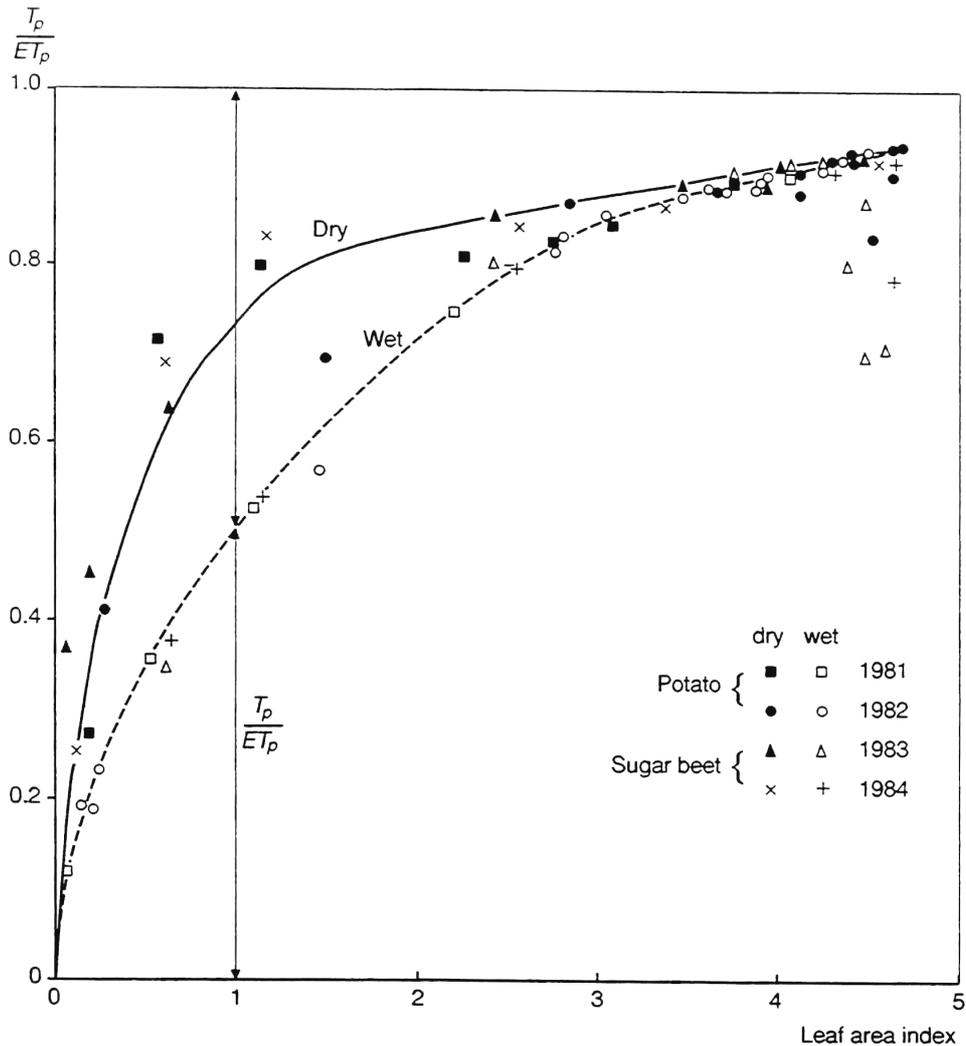


Figure 2-3. The share of potential transpiration  $T_p$  in the potential evapotranspiration  $ET_p$  as a function of the leaf area index LAI, for a soil that is moistened daily and for a dry soil.  $ET_p$  was measured as a remainder of the soil water balance (Sinderhoeve near Renkum);  $T_p$  was calculated with the unsaturated zone model SWATRE. From: Feddes et al. (1997).

## 2.4 Transpiration and resistance

Driving forces behind the transport of water through the system of soil, plant and atmosphere, are differences in osmotic energy and pressure energy (gravitational energy is negligible, except in very tall trees). Absorption of water through the plant roots is partially an active process, caused by the osmotic energy difference that roots build up by (selectively) taking ions from the soil. Transport of water through the stomata on the leaves is an entirely passive process, almost completely caused by the energy difference resulting from a difference in vapour pressure between substomatal spaces (Figure 2-1) and the atmosphere. There is a reduction in the 'water potential' (energy per unit of mass) from the soil to the atmosphere, in which the greatest potential loss occurs during the transition of the water from the substomatal space to the atmosphere (Figure 2-4).

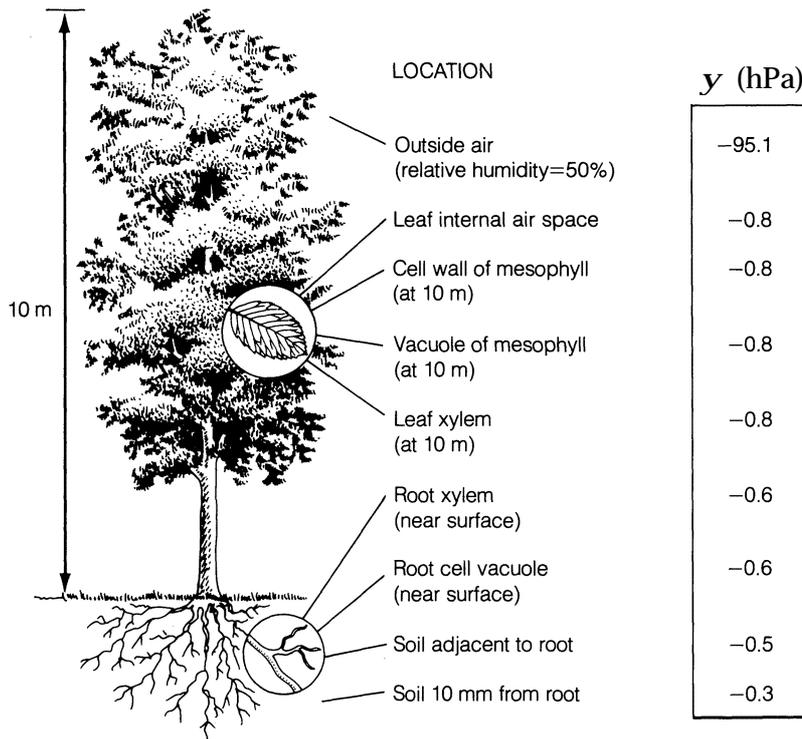


Figure 2-4. Typical course of the water potential  $y$  during water transport through the soil-plant-atmosphere system (Taiz & Zeiger, 1991).

The transport of water through the soil, the roots, the stem or trunk, branches, leaves and stomata is often described mathematically with a series circuit of resistances, in which the potential gradient of a resistance is in inverse proportion to the resistance. Evapotranspiration experts are particularly interested in the last resistance in the soil-plant-atmosphere continuum: the (diffusion) resistance which moisture meets between the substomatal space and the atmosphere. This is by far the largest resistance in the system (Figure 2-4) and is therefore decisive for the amount of transpiration. The relationship between the diffusion resistance and the transpiration is (see Feddes et al., 1997, among others):

$$T = \frac{M_w}{Rt} \frac{e_0^*(t) - e_z(t)}{r} \quad [2.4]$$

In which:

- $T$  transpiration ( $\text{kg m}^{-2}\text{s}^{-1} \sim \text{mm s}^{-1}$ )
- $M_w$  molecular mass of  $\text{H}_2\text{O}$  ( $0.0018 \text{ kg mol}^{-1}$ )
- $R$  universal gas constant ( $8.314 \text{ J mol}^{-1}\text{K}^{-1}$ )
- $t$  absolute temperature (K)
- $e_0^*$  saturated vapour pressure in the substomatal space (Pa)
- $e_z$  vapour pressure in the atmosphere at height  $z$ , in this case close to the plant (Pa)
- $r$  diffusion resistance ( $\text{s m}^{-1}$ )

Resistance  $r$  is made up of two components (Figure 2-5), namely an aerodynamic resistance and a crop resistance:

$$r = r_a + r_g \quad [2.5]$$

In which:

$r_a$  aerodynamic resistance ( $\text{s m}^{-1}$ )

$r_g$  crop resistance ( $\text{s m}^{-1}$ )

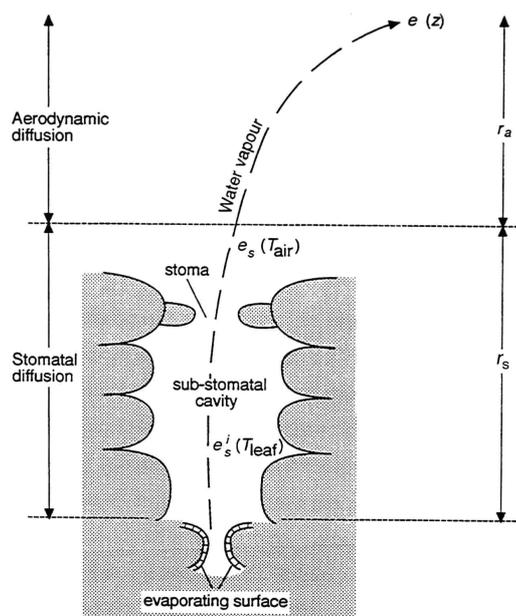


Figure 2-5. The diffusion resistance of water vapour from a leaf is the sum of the aerodynamic resistance and the stomatal resistance:  $r = r_a + r_s$  (Feddes et al., 1997).

According to Feddes et al (1997), the total resistance of the plant itself (excluding  $r_a$ ) is 99% determined by the resistance of the stomata ( $r_s$ ), so that:

$$r \approx r_a + r_s \quad [2.6]$$

Both  $r_a$  and  $r_s$  are important in the Penman-Monteith evapotranspiration equation, which is discussed in Chapter 4.

The aerodynamic resistance depends on both the wind speed and the aerodynamic roughness of the vegetation.

The higher the wind speed and the rougher the vegetation, the more intensive the air exchange and the lower  $r_a$  is. Figure 2-6 illustrates the big influence wind can have on the evapotranspiration process. For the sake of clarity, it should be mentioned here that  $r_a$  is a matter of how easily the air around a leaf is exchanged with the surroundings, so that vapour can be taken away. This goes more easily in a rough, well-ventilated forest than in a short, smooth grass lawn, so that such a forest has a lower aerodynamic resistance. Transpiration in such a forest is therefore relatively more determined by stomatal resistance. Because there is less mixing above a short grass lawn, water vapour is less quickly removed, so that the humidity gradient from leaf

to outside air, and thus the evapotranspiration, is less dependent on the wind. To sum up: the link between the vegetation and the atmosphere is lower when the vegetation structure is smooth ( $r_a > r_s$ ) than when it is rough ( $r_a < r_s$ ) (McNaughton & Jarvis, 1983; McNaughton & Jarvis, 1991; Bunce, 2004).

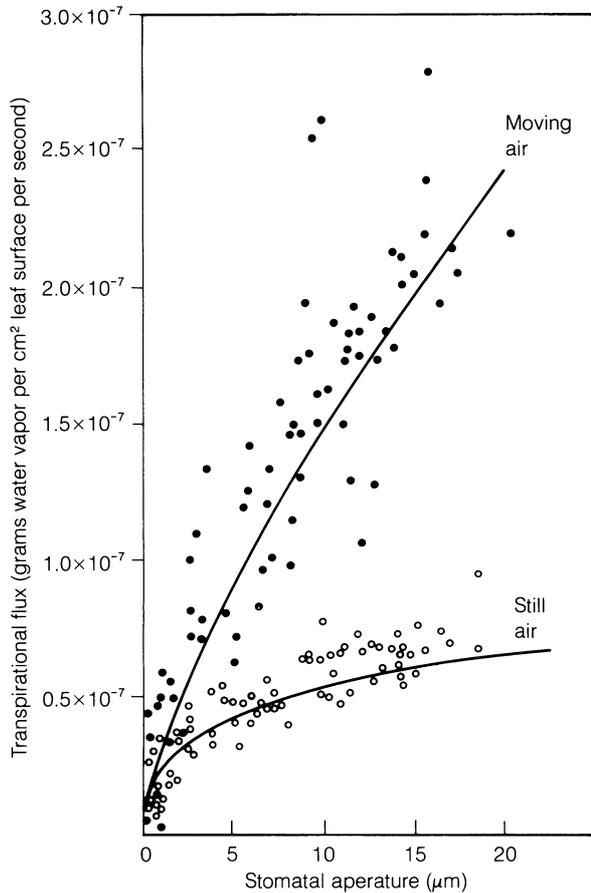


Figure 2-6. Relationship for the Zebra plant (*Zebrina pendula*) between transpiration flow and stomatal diameter, differentiated for wind still and windy conditions (Bange, 1953; fide Taiz & Zeiger, 1991). The windier it is, the more the boundary layer limits transpiration. Consequently, the stomatal resistance has least influence on the transpiration flow under wind still conditions.

The literature describes stomatal resistance  $r_s$  as dependent on:

1. the light intensity (stomata react to the visible light in the radiation spectrum, 0.4-0.7  $\mu\text{m}$ );
2. moisture conditions in the soil (under dry conditions the stomata open less wide so that  $r_s$  goes up; the same thing can happen under wet conditions if plants are not adapted to them);
3. the temperature;
4. the 'transpiration demand' from the atmosphere: with a lot of radiation and a strong, dry wind, the plant may be at risk of wilting. To prevent this, the stomata close up;

5. the CO<sub>2</sub> concentration in the atmosphere: the higher this is, the sooner the carbon needs are satisfied and the stomata can close up again.

Many publications about the effects of an anthropogenic CO<sub>2</sub> increase focus on this last factor, the relationship between CO<sub>2</sub> concentration and stomatal resistance.

In micrometeorology, the unit 'conductivity' is often used instead of 'resistance'. Conductivity  $g$  is the reciprocal of resistance and can therefore be expressed in the unit  $\text{m s}^{-1}$ . Another unit<sup>4</sup> encountered in the literature is  $\text{mol m}^{-2}\text{s}^{-1}$ . Two conductivities dominate the transpiration process: the stomatal conductivity  $g_s$  and the aerodynamic conductivity  $g_a$ .

## 2.5 Factors influencing the experimental relationship between CO<sub>2</sub> and *ET*

In this chapter we report on a literature study on the relationship between CO<sub>2</sub> and evapotranspiration in vegetation. Knowledge of the factors and processes affecting this relationship is necessary, to be able to evaluate the literature properly. In this section we briefly summarize the main points. Insights into processes gained from the literature will be covered in Chapter 3.

In the preceding sections it has been explained that the CO<sub>2</sub> effect is species-dependent, with important distinctions between C<sub>3</sub> and C<sub>4</sub> plants and between trees and smaller plants. The scale of an experiment plays a significant role, too. As will be clear in Chapter 3, there is a wide range of measurement methods, from placing a bag of CO<sub>2</sub> on an individual tree branch, to large-scale experiments studying effects on a whole ecosystem. Experimental results depend on the scale (Jarvis & McNaughton, 1986; Bunce, 2004); see Chapter 3.

The most significant relationships between site and evapotranspiration which can influence experimentally established CO<sub>2</sub>-effects are schematically displayed in Figure 2-7. A factor-enhancing relationship is indicated with a plus sign, a factor-diminishing one with a minus sign. E.g.: an increase in the CO<sub>2</sub> concentration (CO<sub>2</sub> in Figure 2-7) can lead to a rise (+) in the stomatal resistance  $r_s$ , which leads in turn to a drop (-) in *ET*.

Three areas can be distinguished in the figure:

1. *To the left of the evapotranspiration (ET) block are relationships with the plant.* These have already been discussed in detail and need no further explanation here.
2. *Above the ET block are relationships with the atmosphere.* Increases in global radiation, wind speed and air temperature, and decreases in humidity lead to an increase in *ET*. This does not always happen, however: if the evapotranspiration demand from the atmosphere

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<sup>4</sup> This unit had the same meaning: it is about the conductivity of the amount of *air* (moles or m<sup>3</sup> per m<sup>2</sup> leaf area). Hence, the metre in  $\text{de m s}^{-1}$  does not refer to metre of water but metre of air column in stead.

is higher than the vegetation can cope with, plants can wither and close their stomata. Vegetation does of course affect the atmosphere, but we assume that this is of much less influence at the level of an experiment.

3. *Below the ET block are relationships with the soil*

An increase in *ET* leads to a decrease in soil moisture content. If the soil dries out too much, there can be a reduction in *ET* whereas an increase in soil moisture will cause *ET* to increase. However, in agricultural crops, extremely wet conditions lead to a reduction in evapotranspiration (natural vegetation is by definition adapted to its environment; plants that grow in wet conditions have, for example, air roots, such as in reeds, or no roots, such as in Sphagnum mosses).

Like temperature, soil moisture has a considerable influence on the mineralization of organic matter and therefore on the availability of nutrients for the vegetation. Both excessively dry and excessively wet conditions result in a reduction in the mineralization rate. Nutrient availability influences biomass production and thus also evapotranspiration, via the Leaf Area Index.

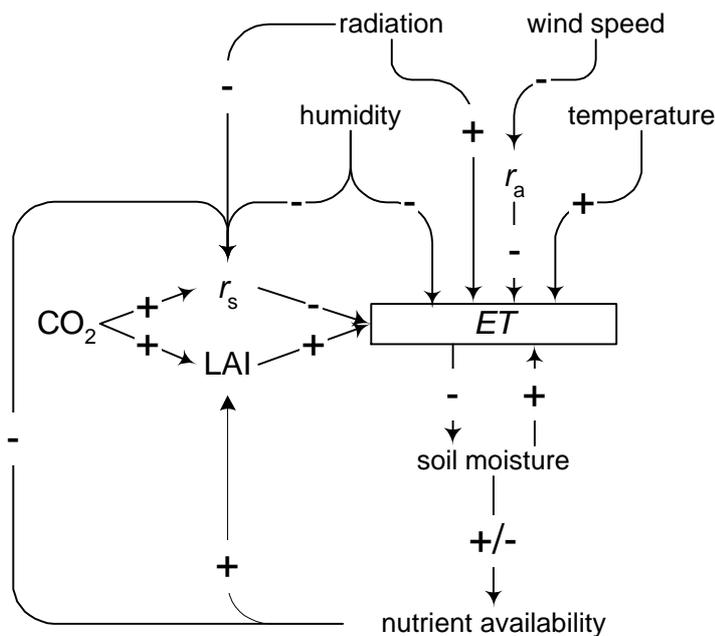


Figure 2-7. Factors influencing the effects of  $CO_2$  on evapotranspiration *ET* observed in experiments.

The above description is important for the interpretation of observed  $CO_2$  effects, and for selecting the most important factors for the literature study in the next chapter.

Particular attention should be paid to the role of the stomatal resistance  $r_s$  in the total resistance  $r$ . The greater the role of stomatal resistance, the greater the sensitivity of transpiration to increased  $CO_2$ . According to [2.4], transpiration is in inverse proportion to  $r$ . If we ignore the effects of  $CO_2$  enrichment on the aerodynamic resistance, and the effect of vegetation on the

atmosphere, while still assuming that temperature doesn't change, then it follows from [2.4] and [2.6] for the sensitivity that:

$$\frac{\Delta T}{T} = - \frac{\Delta r_s}{r_a + r_s} \quad [2.7]$$

Or, in terms of conductivity<sup>5</sup>:

$$\frac{\Delta T}{T} = \frac{\frac{\Delta g_s}{g_s}}{\frac{g_s}{g_a} + 1} \quad [2.8]$$

Equation [2.7] describes the relative change in the transpiration when there is a change in stomatal resistance, making the assumptions mentioned above. If  $r_a$  and  $r_s$  are of equal size, then, according to [2.7], a doubling of  $r_s$  will lead to a 50% reduction in transpiration. This reduction would be 33% if  $r_a$  were twice as big as  $r_s$ , and 67% if  $r_a$  were half as big. These examples illustrate the importance of the ratio between the resistances for the results of experimental research into the relationship between evapotranspiration and CO<sub>2</sub>.

As described in §2.4, the aerodynamic resistance is partly determined by wind speed. The possible influence of experiments on the wind profile deserves our attention, therefore. Furthermore,  $r_a$  is dependent on the roughness of the vegetation, with rougher vegetation types having a lower  $r_a$  than smooth ones. Plant species which naturally grow in dry conditions often have physiological adaptations which increase  $r_a$ : e.g. hairs on leaves, and stomata which are sunk into grooves on the leaves. Because moisture transport in these species is heavily dependent on  $r_a$ , one might expect that their transpiration would be less dependent on the CO<sub>2</sub> concentration.

In the field, the proportion  $r_a/r_s$  varies between approximately 0.03 (in dry forest) and 10 (in well irrigated short grass) (Jones, 1992).

## 2.6 What we don't take into account

In experimental research, temperature and humidity are often manipulated so that they are the same as those of the surrounding environment. It can be argued that this could lead to an overestimation of the CO<sub>2</sub>-effect (§3.4). Direct effects of the air temperature on evapotranspiration are described in the KNMI report, 'Droog, droger, droogst' ('Dry, drier, driest') (Beersma et al., 2004) but the leaf temperature also determines the relative humidity and the lack of vapour pressure close to the leaf, and therefore the evapotranspiration. In turn the evapotranspiration influences the leaf temperature through the energy balance on the surface: higher evapotranspiration makes it cool down. The temperature dependency of stomata and photosynthesis is a process that is seldom described and poorly

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<sup>5</sup> Substituting  $r_s = \frac{1}{g_s}$ ,  $r_a = \frac{1}{g_a}$  and  $\Delta r_s = \Delta \frac{1}{g_s} = -\frac{\Delta g_s}{g_s^2}$  into [2.7] leads to [2.8].

understood, yet assumptions made about it in many studies have major consequences for sensitivities (Jacobs & De Bruin, 1997).

Experimental research takes place on a small scale, e.g. the scale of a greenhouse or plot. Such experiments cannot take into account the interaction between this scale and the climate at regional or supra-regional level. This is also true for the theoretical approach to the CO<sub>2</sub>-effect at plot level that is presented in Chapter 4. A few remarks about effects on a larger scale are pertinent here.

The previously mentioned interaction via the viscous boundary layer of air around and immediately above the leaves also takes place at macro level. The humidity in the lowest 1-2 km of the atmosphere which is influenced daily by the land surface (the atmospheric boundary layer) depends on the evapotranspiration itself and on import of air from elsewhere (advection). Where there is little advection, the interaction with this boundary layer is significant and results in an extra suppression of the sensitivity of transpiration to CO<sub>2</sub>. In Chapter 4, we take the boundary layer into account, but not advection.

On the other hand, atmospheric humidity itself determines the opening of the stomata to a great extent: changes in atmospheric humidity can lead to changes in resistance, etc., until a new equilibrium is established.

Other interaction effects are part of the larger chain of the soil-vegetation-atmosphere system. Soil evaporation is not sensitive to the CO<sub>2</sub> concentration, but it does interact with the air humidity in a way which is influenced by transpiration. In the longer term, there is an interaction with soil moisture and with crop growth and the development of leaf surfaces with varying levels of evapotranspiration. Soil and vegetation feed back to the energy balance of the land surface and therefore influence the boundary layer and the formation of clouds. Clouds influence in turn the exposure to light rays and therefore also the stomata and the evapotranspiration.

# 3 Observed effects of CO<sub>2</sub> on a local scale

## 3.1 Methods

We have collected a lot of literature of experimental research into the relationship between CO<sub>2</sub> and evapotranspiration. Because we want to know how potential evapotranspiration is affected by CO<sub>2</sub>, the relevant experiments for our study are those in which drought stress and malnutrition do not occur. However, drought stress and malnutrition are sometimes part of an ecosystem and cannot be eliminated from an experiment without interfering with the system.

The results of the literature study are kept up to date in the database 'KWR 06.003 Literature study.xls', available on the website: [www.droogtestudie.nl](http://www.droogtestudie.nl)

Through literature study, we gain knowledge of the methods used by scientists to study the effects of increased CO<sub>2</sub>. In §3.2, a brief overview of these methods is given. Section 3.3 outlines the set-up of the database, which gained its final form during the course of the research, and the results are discussed in §3.4.

## 3.2 Experimental research methods

In research into the effects of increased CO<sub>2</sub>, two samples of vegetation cover are compared: one with an increased concentration and one with the current concentration. Two important differences between methods are (1) the treatment with which the samples are exposed to air and (2) the way evapotranspiration is measured.

### *Treatment methods*

There are various methods for exposing vegetation to CO<sub>2</sub>-enriched air (from Saxe et al., 1998, among others):

- **Branch-bag (BB)**  
This is applied to trees. A branch is wrapped in a transparent bag filled with CO<sub>2</sub>-enriched air. Disadvantages of this method are that (1) it is difficult to adjust the climate in the bag (in particular, temperatures can rise), (2) it is difficult to scale up measurements from branch to tree level, let alone to forest level, and (3) the system is not closed (exchange via the branch).
- **Open-top chamber (OTC)**  
Part of the vegetation is shielded with transparent material (glass, Plexiglas, Perspex, foil). To maintain as much uniformity as possible with the surrounding climate, the top is kept open. Climate-controlled and CO<sub>2</sub>-enriched air is blown over the vegetation.  
An advantage of OTC is that it is relatively easy to adjust the climate to

the external climate. Regulation of the wind, however, is far from optimal, as ventilation is usually much stronger than it is outside. Due to its limited scale, OTC cannot be used to research whole trees.

- **Closed-top chamber (CTC)**  
Several different names are used in the literature for the same sort of treatment: the total isolation of a section of an ecosystem from the outside world, treating it with CO<sub>2</sub>-enriched and climate-controlled air. The experiments vary in scale, which is reflected in the names: Growth Chamber (small), Glass cabinet (small), mini-ecosystem (small), Greenhouse (large). According to Saxe et al. (1998), climate control is better in these experiments than in OTCs, although the method is expected to have a considerable influence on the wind effect.
- **Free-air CO<sub>2</sub> enrichment (FACE)**  
Pure CO<sub>2</sub> is applied at several places and at varying heights in the natural environment, where it mixes with the atmosphere. The apparatus used may be for example a number of poles from which application takes place in a circle of 25 m in diameter. Of all the methods, this one has *the least effect on the natural climate*, particularly if the circle is large; the influence in this case is probably negligible (Saxe et al. 1998). One disadvantage is that the apparatus is expensive.
- **Mini-FACE**  
As in FACE, except that CO<sub>2</sub> is applied in a small circle, e.g. of one meter in diameter. The apparatus is cheaper than that of FACE, but the influence of the experiment on the measurements, due to the greater influence of air outside the circle, is likely to be greater.
- **Natural sources**  
Tognetti et al. (1998) made use of a natural source of CO<sub>2</sub> near Siena.

Because of their large scale, most experiments on trees are carried out on young trees.

With respect to the influence of aerodynamic resistance, information about the degree of air circulation in the experiment is desirable. Unfortunately, most of the publications do not supply this information (or only in qualitative terms, e.g. "heavy duty air blowers"). Yet it is clear from Stocker et al. (1999) and Dijkstra et al. (1993) – among others – that the influence of wind is considerable: they applied an average air circulation of 37 seconds in OTCs and 14 seconds in small greenhouses (CTCs), respectively<sup>6</sup>. Heijmans et al. (2004) showed in their experiments that the evapotranspiration measured increased with the number of ventilators used.

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<sup>6</sup> Stocker et al. (1999) report an air circulation of 2.5 m<sup>3</sup> per minute in OTCs of 1.27m<sup>2</sup> in surface, separate with foil of 120cm high; Dijkstra et al. (1993) report air circulation of 800 m<sup>3</sup> per hour in a small greenhouse of 125x125x200cm.

### *Methods of measuring evapotranspiration*

The literature provides little information about the methods of measuring the evapotranspiration or the transpiration. The main methods are:

- **Balance studies**  
Evapotranspiration can be determined as a remainder of the soil moisture balance, using lysimeters for example. Changes in the storage of soil moisture can be determined by weighing or by measuring the soil moisture content.
- **Analysis of incoming and outgoing air**  
The moisture content of incoming and outgoing air is continuously measured automatically. Differences are put down to evapotranspiration.
- **Measuring with a measuring cuvette**  
A measuring cuvette is placed over part of the plant. It measures gas exchange, including that of water vapour, via electronic sensors.  
Disadvantages: the measurement period is short (often just a few hours), probably influences the transpiration and is not representative for the whole plant or vegetation cover (so scaling up is required).
- **Chamber**  
This is like the measuring cuvette, but is larger, so that a more representative picture of the vegetation as a whole can be gained.
- **Stem flow measurement**  
This gives continuous measurement of the transpiration rate. See Dugas et al. (1996). Disadvantage: difficult to upscale to vegetation level.

### **3.3 Set-up of the database**

The database 'KWR 06.003 Literature study.xls' ([www.droogtestudie.nl](http://www.droogtestudie.nl)) contains the results of the literature study and consists of the following columns:

#### *Column A. Seen by*

Gives the initials of the person who studied the literature: Cees Maas (CM) or Flip Witte (FW)

#### *Column B. Source*

Cites the literature source as done throughout this report: author(s), date.

#### *Column C. Vegetation type*

Characterizes the vegetation type (crop, plant species) on which the experiment is carried out.

#### *Column D. CO<sub>2</sub>-effect*

Observed effects of CO<sub>2</sub>-enrichment on transpiration ( $\Delta T/T$ ) or evapotranspiration ( $\Delta ET/ET$ ).

#### *Column E. Treatment*

Categorizes the way the vegetation was treated with CO<sub>2</sub> (§3.2: OTC, FACE, etc).

*Column F. Details*

Information about the measurements of the treatment method, the measurement method (§3.2), etc.

*Column G. Duration of the experiment*

The duration is important because only longer-term experiments are applicable; i.e. *experiments in which the vegetation was able to adjust to the raised CO<sub>2</sub>-concentration.*

*Column H. CO<sub>2</sub>-concentration control*

*Column I. CO<sub>2</sub>-concentration experiment*

*Column J. Location*

Country and place where the experiment was carried out. It may be relevant to obtain an impression of the climate, if details of this are not given.

*Column K. Climate*

Characterizes the climate, thus determining how representative it is for The Netherlands.

*Column L. Moisture stress*

As explained in §2.5, moisture shortages in the soil lead to a reduction in evapotranspiration. It is to be expected that the CO<sub>2</sub>-effect on plants growing on dry soils is smaller since reduced transpiration leads to greater availability of soil moisture.

*Column M. Nutrient availability*

Nutrient availability influences evapotranspiration via biomass production (§2.5). In nutrient-poor conditions, the CO<sub>2</sub>-effect can be suppressed, as discussed in the next paragraph.

*Column N. Remarks*

Relevant remarks that did not fit in columns A –M.

*Column O. Decision*

Assessment of the usability of the data source for immediate quantitative assertions about the CO<sub>2</sub>-effect.

### 3.4 Discussion and analysis

*Analysis of observed CO<sub>2</sub>-effects*

On the basis of data from the literature, Figure 3-1 displays the increases in evapotranspiration and in CO<sub>2</sub> side by side (the underlying data are stored on a separate page in the database). In the first instance, the treatment methods are differentiated (CTC, OTC, FACE including mini-FACE, Natural source). Beyond this, information is added about possible drought stress, nutrient poverty, and whether the experiment was carried out on a tree or forest.

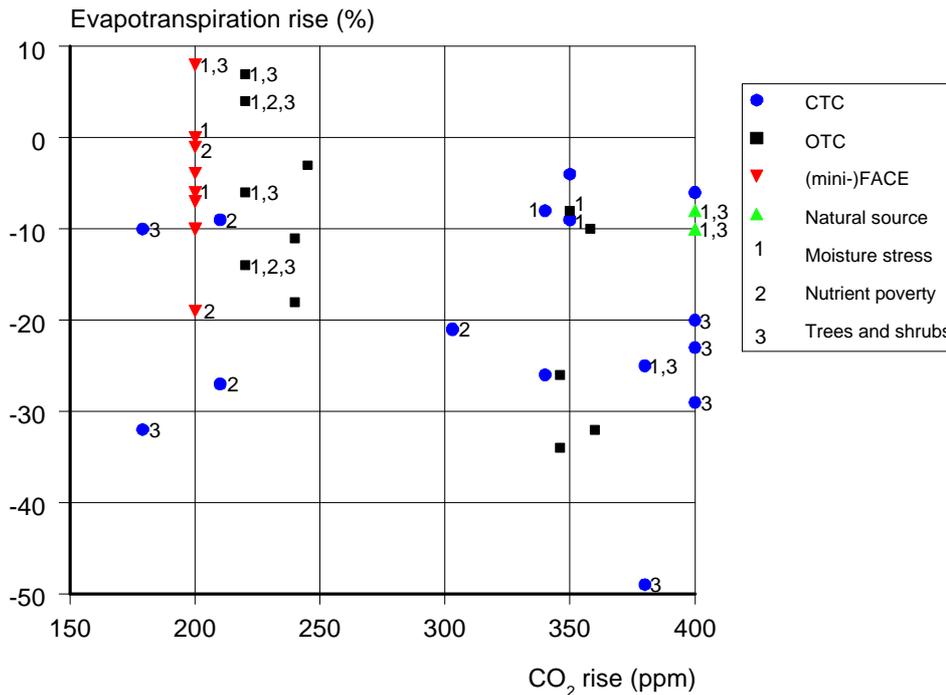


Figure 3-1. Observed changes in evapotranspiration ET with increased CO<sub>2</sub>-concentrations compared with the current concentrations in the air.

Before proceeding to a discussion of this figure, some explanation of how it came about is in order:

- The database includes observed effects on both transpiration ( $\Delta T/T$ ) and evapotranspiration ( $\Delta ET/ET$ ). We converted the first figures into evapotranspiration figures by multiplying by a factor of 0.8, on the assumption that transpiration constitutes about 80% of the evapotranspiration (see also Figure 2-3 and §4.5)<sup>7</sup>.
- A value that may vary in the literature is reduced to an average in Figure 3-1.
- Data from two publications about steppe vegetation (Szente et al., 1998; Tuba et al., 1996) have been excluded from the analysis because they completely contradict each other, even though they were published by the same scientists. A number of observations in temperatures like 40 °C, which would be extreme for The Netherlands, have also been left out of the account.
- Many publications have nothing to say about possible drought stress and nutrient poverty. Only when we could make reasonably safe assumptions on these points, is information about them included in Figure 3-1.

In the study which preceded this report, Witte & Doomen (2004) calculated a decrease in evaporation of 5.2% per 100 ppm CO<sub>2</sub> increase. This amounts to a

<sup>7</sup> From  $T = 0.8ET$  and  $\Delta ET = \Delta T$  follows:  $\Delta ET/ET = 0.8\Delta T/T$

decrease of 20% given an average rise of 385 ppm in the year 2100 (see §1.2). On the basis of linear regression through all the points in Figure 3-1, we arrive at a comparable decrease, namely 23% (regression line:  $y = 2.1 - 0.054x$ ;  $r^2 = 0.14$ ,  $n = 41$ ). However, in the current study the variation in the observations increased.

Figure 3-1 seems to suggest that *the CO<sub>2</sub>-effect is somewhat diminished by drought stress and is a bit higher in trees*. Predictions of the effect given an increase of 385 ppm confirm this: -13% for drought stress (regression model  $y = 12.8 - 0.066x$ ;  $r^2 = 0.39$ ,  $n = 14$ ) and -22% for trees ( $y = 8.6 - 0.078x$ ;  $r^2 = 0.23$ ,  $n = 14$ ). The nutrient poverty points in Figure 3-1 lie too close together to provide the basis for any conclusions.

We could describe the various effects of the different treatment methods statistically, and investigate the differences, but we expressly choose not to do this. Firstly, because this is beyond the scope of this limited study, but more importantly because it would not be worthwhile, as our literature study has led us to the conclusion that *the influence of wind on OTCs and CTCs is so great that it is impossible to draw conclusions about evaporation from plants in natural environments from experiments with these kinds of apparatus*. In these experiments, the introduction of air through “heavy duty air blowers” will have led to a lowering of aerodynamic resistance, causing transpiration to be more strongly influenced by CO<sub>2</sub> enrichment than it would be in a natural context.

*We have therefore excluded all evaporation measurements taken using OTCs and CTCs from our analysis of the CO<sub>2</sub> effect.*

Measurements taken using these methods are, however, useful for several other analyses, such as *the study of the relationship between CO<sub>2</sub> concentration and stomatal resistance*. We shall make use of them in Chapter 4.

For the analysis in this chapter, we are left with the results of FACE experiments and the natural CO<sub>2</sub> source near Siena. These are, respectively, the red and green triangles in Figure 3-1. The most relevant information from these literature sources is summarized in Table 3-1.

We would like to make the following comments on this table:

- The distribution of ‘vegetations’ is limited: *Sorghum bicolor*, bog, *Triticum aestivum* and three tree species, *Pinus taeda*, *Quercus ilex* and *Quercus pubescens*.
- The decrease in evapotranspiration from bog signalled by Heijmans et al. (2004) is remarkable, as bog is dominated by peat moss (*Sphagnum spec.*), which has no stomata and therefore cannot be sensitive to CO<sub>2</sub>. The authors ascribe the decrease in evapotranspiration to the wind-breaking effect of vascular plants which have grown faster due to higher concentrations of CO<sub>2</sub>.
- The experiments of Conley et al. (2001) confirm that drought stress diminishes CO<sub>2</sub> sensitivity.

- The increase in transpiration in a stand of trees dominated by 14 m high *Pinus taeda* observed by Schäfer et al. (2002) is ascribed by the authors to a reduction in soil evaporation. This reduction is assumed to be caused by an increase in leaf fall, and assumed to improve soil moisture content. Transpiration from trees was measured using stem flow measurements, which were scaled up to the level of the entire stand of trees. All things considered, calculating the CO<sub>2</sub> effect from transpiration figures is dubious, and we consider the results less reliable.
- If we exclude two outliers from our calculations, the one of Schäfer et al. (2002) and the one from nutrient-poor conditions of Kimball et al. (1999), the reduction in evapotranspiration reported in Table 3-1 is 6.5% on average (standard deviation 3.5%) with an increase of 200 ppm. The decrease in evapotranspiration is likely to be greater in conditions without drought stress.

Table 3-1. Data from usable CO<sub>2</sub>-experiments (mini-FACE, FACE and natural source). Figures marked with an asterisk are drawn from transpiration figures ( $\Delta ET/ET=0.8\Delta T/T$ ).

Source	Vegetation	CO <sub>2</sub> - increase (ppm)	$\Delta ET/ET$ (%)	Treatment	Limiting factors
Conley et al., 2001	<i>Sorghum bicolor</i> (C <sub>4</sub> )	200	-9 to -11	FACE	
Conley et al., 2001	<i>Sorghum bicolor</i> (C <sub>4</sub> )	200	0 to -6	FACE	Drought stress
Heijmans et al., 2001	Peat bog	200	-9 to -10	Mini-FACE	Natural = nutrient-poor
Hunsaker et al., 2000	<i>Triticum aestivum</i>	200	-3.7 to -4.0	FACE	
Hunsaker et al., 2000	<i>Triticum aestivum</i>	200	-0.7 to -1.2	FACE	Nutrient poor
Kimball et al., 1999	<i>Triticum aestivum</i>	200	-7	FACE	
Kimball et al., 1999	<i>Triticum aestivum</i>	200	-19	FACE	Nutrient poor
Schäfer et al., 2002	<i>Pinus taeda</i>	200	+7.6*	FACE	Drought stress
Tognetti et al., 1998	<i>Quercus ilex</i>	150-650	-8*	Natural source	Drought stress
Tognetti et al., 1998	<i>Quercus pubescens</i>	150-650	-10*	Natural source	Drought stress

### Relevant information from the literature

During our research we came across some information that seems worth mentioning, even though it is of no direct use in the quantification of the CO<sub>2</sub>-effect.

- *Nutrients.* The availability of nutrients may affect biomass production and, with it, evapotranspiration (§2.5). Grant et al. (2001) describe the FACE-measurements of Kimball et al. (1999) on Wheat (*Triticum aestivum*), given in Table 3-1, in which the nutrient-poor treatment (7 g N m<sup>-2</sup>) is more sensitive to CO<sub>2</sub> (*ET* drops 19%) than the nutrient-rich treatment (35 g N m<sup>-2</sup>) (7%). Their likely explanation is that in N-poor circumstances the biological yield is raised less and therefore the reduction of *ET* is higher (N-limitation).  
In contrast, with the same FACE apparatus Hunsaker et al. (2000) found the lowest CO<sub>2</sub>-effect on *Triticum aestivum* in nutrient-poor conditions (Table 3-1): a significant *ET*-decrease of 0.7-1.2% at a supply of 1.5-7.0 g N m<sup>-2</sup> against 3.7-4.0% at 35 g N m<sup>-2</sup>. Hunsaker et al. (2000) suggest the small effect at low N-supply might be due to a better utilization of nutrients and soil moisture at the end of growth period, when, in contrast, they measured a higher *ET* than in the control.  
There are more studies which describe that vegetations on nutrient-poor soils are less sensitive to CO<sub>2</sub> enrichment. One explanation for this is that plants try to maintain a certain C/N ratio in their leaves (Jarvis, 1983) so that they respond to CO<sub>2</sub> enrichment by extending their root system in search of N (Sonnleitner et al., 2001). It is likely that the CO<sub>2</sub>-effect is especially small on nutrient-poor and dry soil, since in especially that case extending roots leads to a better utilization of soil moisture.
- When there is extreme nutrient poverty in very wet conditions, species may dominate which have a physiognomy more usually associated with drought-resistance. For example, among the vascular plants in a living peat bog, the heather-type plants are dominant (*Erica tetralix*, *Calluna vulgaris*, *Andromeda polifolia*, *Vaccinium myrtillus*, *Oxycoccus palustris*, etc.): plants with thick leathery leaves. They have a 'peinomorphic' (hunger-shaped) form (Weeda et al., 1988), which does not suggest high transpiration rates. Bearing in mind that statements about the purpose of natural characteristics are always speculative, we think that the reason for this is that plants in extremely poor environments are limited in their growth by N and P, so that their CO<sub>2</sub> consumption and therefore their transpiration are also limited.
- *Ozone* in the atmosphere is harmful to plants because it attacks their photosynthesis organs (Pleijel et al., 2003). McKee et al. (1997) put forward the hypothesis that increased CO<sub>2</sub> limits this damage because with less transpiration, less O<sub>3</sub> gets into the plant via the stomata.
- *Fossils.* According to Saxe et al. (1998) and Sellers et al. (1996), analysis of stomata in fossil plant material reveals that stomatal resistance in plants increased in the course of geological history due to rises in CO<sub>2</sub> concentrations.

- *Literature.* During our research we came across a number of excellent publications on the subject, which we recommend to those who wish to explore the subject in greater depth: Ainsworth & Long (2005), Allen et al. (2003), Bunce (2004), Conley et al. (2001), De Wit (1958), Field et al. (1995), Hunsaker et al. (2000), Jacobs & De Bruin (1992), Medlyn et al. (2001), Poorter & Navas (2003), Riedo et al. (1999), Ruddiman (2003), Sage & Kubien (2003), Saxe et al. (1998) and Sellers et al. (1996).



# 4 Calculating CO<sub>2</sub> effects at plot level

## 4.1 Introduction

In this chapter we shall try to calculate the CO<sub>2</sub> effect. As discussed in the introduction (Chapter 1), we do not take into consideration either the influence of soil moisture and temperature on stomata, or more complex issues like cloud cover and advection. These effects are either too poorly understood or too complex to deal with in a relatively simple study like this. *We restrict our analysis to well-watered vegetation and thereby ignore effects of water stress.*

## 4.2 Observations of CO<sub>2</sub> effects on stomatal conductance

The decrease in stomatal conductance with increased CO<sub>2</sub> levels has been described in numerous experiments, most of which make use of OTCs or CTCs in which plants are exposed to higher CO<sub>2</sub> concentrations for a long time while temperature, humidity and radiation are kept in line with those of the surroundings. Such chambers must therefore be well ventilated, which means that there is no vertical humidity gradient such as occurs naturally above plots of land out of doors. Measurements of evapotranspiration in such chambers are made with either small cuvettes for gas exchange measurements, or with a water balance, or lysimeter. In both cases an evapotranspiration measurement is obtained in which the aerodynamic conductance is great, relative to the stomatal conductance; therefore the measured changes in evapotranspiration are approximately proportional to changes in stomatal conductance, and may be interpreted as such<sup>8</sup>. They are not, however, representative for a change in evapotranspiration in the field, although these experiments are usually of long enough duration to give an idea of the adaptation of plants to higher CO<sub>2</sub> concentrations in the medium term.

A number of measurements were taken in a FACE experiments, in which CO<sub>2</sub> concentrations were raised in the open field or even in the forest, by releasing large amounts of CO<sub>2</sub> into the area over a long period. Evapotranspiration readings from lysimeters under such conditions are scarce, but they do give a better direct measurement of the projected changes in evapotranspiration, even though there may be an overestimation of the CO<sub>2</sub>-effect, due to artificial ventilation and advection from outside the FACE area.

We investigated a number of studies in greater detail; published results for CO<sub>2</sub>-sensitivity in conductance are presented in Table 4-1 and in graph form in Figure 4-1, including the margin of error (standard error), where this was

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<sup>8</sup> If  $g_a \rightarrow \infty$  then Equation [2.8] becomes  $\frac{\Delta T}{T} = \frac{\Delta g_s}{g_s}$ .

available. A regression line is drawn through the points with reliability intervals of 95%. Two publications provide such deviating results (for potato and barley) that we left them out of the analysis.

This data shows that, with every 100 ppm increase in atmospheric CO<sub>2</sub> concentrations, stomatal conductance goes down by an average of:

- 9.3 ± 1.5% for grass and herbal crops;
- 6.8 ± 2.5% for woody crops and trees;
- 11.8 ± 1% for C<sub>4</sub> crops (based on very few observations).

Taken together, these results suggest that if atmospheric concentrations of CO<sub>2</sub> are doubled in 2100, we can expect a reduction in conductance  $g_s$  in most C<sub>3</sub> plants of about 15 – 40%.

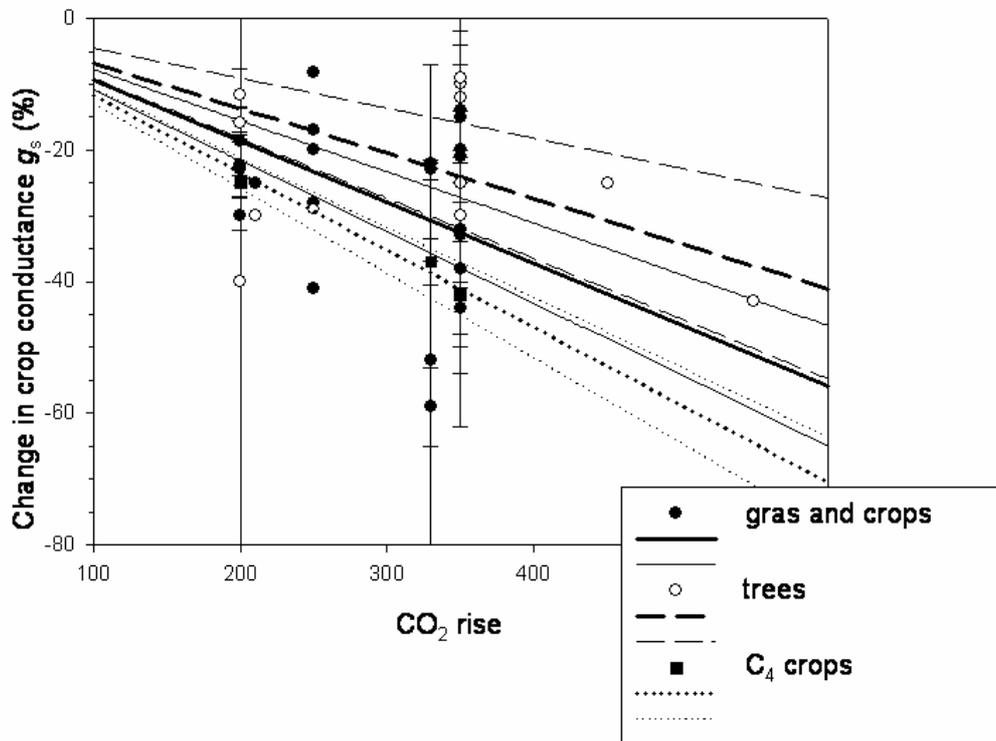


Figure 4-1. Observed effects of increased CO<sub>2</sub> concentrations on crop conductance  $g_s$  (~ stomatal conductance), with standard errors and regression lines with 95%reliability intervals. See also the text and Table 4-1.

Table 4-1. Observed effects of CO<sub>2</sub> increases on conductance  $g_s$ . Figures marked with an asterisk (\*) are derived from evapotranspiration measurements.

Vegetation/species	[CO <sub>2</sub> ] ppm	$\Delta g_s / g_s$ (%)	$\sigma$ (%)	Reference	Crop height (cm)	Photosynthesis type
Potato	680	-59	6	Cure & Acock (1986)	30	C <sub>3</sub>
Potato	700	-32	30	<i>fide</i> Bunce (2004)	20	C <sub>3</sub>
Alfalfa	700	-15		<i>fide</i> Bunce (2004)	50	C <sub>3</sub>
Birch	700	-10	10	Beerling et al. (1996)	1000	C <sub>3</sub>
Birch	800	-25*		Wayne et al. (1998)	100	C <sub>3</sub>
Beech	700	-12	10	Beerling et al. (1996)	1000	C <sub>3</sub>
Beans	700	-38	10	<i>fide</i> Bunce (2004)	50	C <sub>3</sub>
Tree	550	-15.9	2.4	Ainsworth & Long (2005)	1000	C <sub>3</sub>
<i>Brassica campestris</i>	600	-41		Mishra et al. (1999)	20	C <sub>3</sub>
<i>Brassica carinata</i>	600	-8.3		Mishra et al. (1999)	20	C <sub>3</sub>
<i>Brassica juncea</i>	600	-20		Mishra et al. (1999)	20	C <sub>3</sub>
<i>Brassica nigra</i>	600	-28		Mishra et al. (1999)	20	C <sub>3</sub>
Douglas fir	550	-40	43	Apple et al. (2000)	150	C <sub>3</sub>
Oak	700	-30	10	Beerling et al. (1996)	1000	C <sub>3</sub>
Elder	600	-29		Liang et al. (1995)	150	C <sub>3</sub>
Elder	900	-43		Liang & Maruyama (1995)	150	C <sub>3</sub>
Forb	550	-18.7	5.1	Ainsworth & Long (2005)	50	C <sub>3</sub>
Barley	680	-52	30	Cure & Acock (1986)	100	C <sub>3</sub>
Barley	700	-33	8	<i>fide</i> Bunce (2004)	50	C <sub>3</sub>
Grass	550	-22.2	5	Ainsworth & Long (2005)	20	C <sub>3</sub>
Grass	550	-24.9	7.2	Ainsworth & Long (2005)	50	C <sub>4</sub>
Grass	700	-33		<i>fide</i> Bunce (2004)	20	C <sub>3</sub>
Peat bog	560	-25*		Heijmans et al. (2001)	20	C <sub>3</sub>
Young tree	700	-25	3	Medlyn et al. (2001)	150	C <sub>3</sub>
Legume	550	-22.9	4.1	Ainsworth & Long (2005)	50	C <sub>3</sub>
<i>Lolium</i>	700	-20*		Schapendonk et al. (1999)	20	C <sub>3</sub>
Maize	680	-37	3.5	Cure & Acock (1986)	200	C <sub>4</sub>
Aspen poplar	560	-30		Noormets et al (2001)	200	C <sub>3</sub>
Soya	680	-23	1.5	Cure & Acock (1986)	50	C <sub>3</sub>
Soya	700	-25*		Serraj et al. (1999)	50	C <sub>3</sub>
Shrub	550	-11.6	3.9	Ainsworth & Long (2005)	200	C <sub>3</sub>
Wheat	680	-22	15	Cure & Acock (1986)	50	C <sub>3</sub>
Adult tree	700	-9	5	Medlyn et al. (2001)	2000	C <sub>3</sub>
Winter wheat	700	-21*		Dijkstra et al, (1999)	50	C <sub>3</sub>
Summer wheat	550	-30		Hunsaker et al. (2000)	50	C <sub>3</sub>
Summer wheat	600	-17		Agrawal & Deepak (2003)	50	C <sub>3</sub>

### 4.3 Models for stomatal conductance

There are various models for predicting stomatal conductance  $g_s$  in relation to the environment. A classic and still-used model is that of Jarvis & Stewart (Jarvis, 1976; Stewart, 1988). This empirical model calculates the conductance by multiplying a maximum value with a number of reduction functions, including one for CO<sub>2</sub>-sensitivity. Since each reduction function has to be adjusted to the data, this model will provide good prediction for most vegetations. *However, this model is of limited value for extrapolations in time, and for generalizations.*

Another type of model integrates the various sensitivities into one equation with fewer empirical parameters, making it easier to evaluate the interactions and extrapolations. Models of the type used by Ball-Berry (see Jacobs, 1994) express conductance as a function of photosynthesis rate, CO<sub>2</sub> concentration and atmospheric humidity; combined (for details, see Jacobs & De Bruin, 1997):

$$g_s = g_c + 1.6 \frac{A_n}{C_s f(e_s^* - e_s)} \quad [4.1]$$

In which:

- $g_c$  minimum conductance of the epidermis of leaves when stomata are closed (m s<sup>-1</sup> or μmol m<sup>-2</sup> s<sup>-1</sup>)
- $A_n$  net photosynthesis (which in turn depends on radiation, nutrient availability, temperature, CO<sub>2</sub> and  $g_s$  itself) (μmol m<sup>-2</sup>s<sup>-1</sup>)
- $C_s$  CO<sub>2</sub>-concentration on the leaf surface (μmol m<sup>-3</sup> or μmol mol<sup>-1</sup>)
- $f$  function of atmospheric humidity deficit on the leaf surface ( $e_s^* - e_s$ )
- $e_s$  vapour pressure in the atmosphere on the leaf surface (Pa)
- $e_s^*$  saturated vapour pressure on the leaf surface (Pa)

There has been a lot of discussion in the literature about the validity of Equation [4.1], because it appears to be a physiological-mechanistic model, and is often described as such, and yet very little is known about the underlying mechanism. In practice the model seems to work well for a wide range of vegetation types, and with little variation in parameters. It can therefore be seen as a well-chosen empirical method to practically describe how stomatal conductance depends on CO<sub>2</sub> and atmospheric humidity on the leaf surface. It follows from this that  $g_s$  can only be determined through iteration (repeated calculation, mathematically). Medlyn et al. (2001) compared experimental results, as described in Chapter 3, with predictions of both the Jarvis- Stewart model and the Ball-Berry model. Both models seem to work well; the Ball-Berry concept seems to describe all the measurements particularly well, and also to predict changes from doubling CO<sub>2</sub> concentrations well. The study by Jacobs & de Bruin (1997) also analyzes this concept in adapted form, and integrated into a boundary layer model. The projected *change in  $g_s$*  in this study is around -30% with a doubling of CO<sub>2</sub>, which is within the experimental margin of -15 to -40% mentioned in §4.2.

#### 4.4 Calculating evapotranspiration at plot level

For a prediction of changes in evapotranspiration at plot level, measurements on stomatal conductance  $g_s$  have to be fed into an evapotranspiration model which also simulates the aerodynamic conductance in the boundary layer  $g_a$ .

The most relevant approaches to the evapotranspiration calculations are those of:

$$\text{Penman-Monteith: } IET = \frac{sQ + g_a \times (e_z^* - e_z)}{s + g(1 + g_a/g_s)} \quad [4.2]$$

$$\text{Priestly-Taylor: } IET = a \frac{s}{s + g} Q \quad [4.3]$$

$$\text{Makkink: } IET = a \frac{s}{s + g} K \downarrow \quad [4.4]$$

In which:

- ? evaporation heat of water (J kg<sup>-1</sup>)
- $ET$  evapotranspiration (kg m<sup>-2</sup>s<sup>-1</sup>)
- $s$  temperature-dependant gradient of the saturated vapour pressure curve (Pa K<sup>-1</sup>)
- $Q$  net radiation (W m<sup>-2</sup>)
- ? temperature-dependant psychrometric constant (Pa K<sup>-1</sup>)
- $e_z$  actual vapour pressure in the atmosphere at altitude  $z$  (Pa)
- $e_z^*$  saturated vapour pressure in the atmosphere at altitude  $z$  (Pa)
- $a$  constant (-)
- $a$  constant (-)
- $K?$  incoming shortwave (global) radiation (W m<sup>-2</sup>)

*The variable  $g_s$  in these equations is the effective total stomatal conductance of the entire vegetation (the same, therefore, as the crop conductance).*

Equation [4.2] provides a good description of local evapotranspiration, given the necessary variables measured at a certain height above a homogeneous crop. This equation is *the* standard procedure in scientific research. The quantities in [4.2] vary continually, especially the atmospheric humidity deficit ( $e_z^* - e_z$ ), the temperature and the conductance.

The aim of this study is to research the CO<sub>2</sub> sensitivity of  $ET$ , and not that of  $?ET$ . In other words: we still have to divide the equation by  $?$ . However, this evaporation heat is only sensitive to temperature, and will therefore have no influence on the results of this study, since temperature is not taken into consideration. N.B.: in the Drought study of Beersma et al. (2004) the effect of temperature on  $?$  is very small, perhaps even negligible (e.g.: at a temperature of 10 °C,  $?$  decreases 0.1% with every temperature rise of 1 °C).

Equations [4.3] and [4.4] give a particularly reliable value for the evapotranspiration of a crop if  $a$  and  $a$  can be assumed to be constant and if advection is negligible. The atmospheric humidity deficit and the

conductance are implicitly included in these constants and may vary as long as they vary little in proportion to each other. It is easy to demonstrate that for the Priestly-Taylor constant (Moors et al., 1996):

$$a = \Omega \left( 1 + \frac{g_a D_a}{sQ} \right) \quad [4.5]$$

In which  $\Omega$  represents McNaughton & Jarvis's (1983) coupling factor, i.e. the vegetation-atmosphere coupling (see §2.4). If  $\Omega$  is not far from 1 then [4.3] or [4.4] are the most applicable, and evapotranspiration can be estimated from a previously determined crop factor, the radiation and the temperature. This is the case with a smooth vegetation surface, a low wind speed, and a high stomatal conductance. Equation [4.4] has the advantage that it requires few measurements and that it prevents problems in the winter, with a positive evapotranspiration in spite of a negative energy balance. It is routinely used by the KNMI. It is important to stress that, just as is the case with the equation of Priestly-Taylor ([4.3]), we cannot assume that the atmospheric humidity remains constant when we use the Makkink equation, and that by implication, the equation includes advection and all feedback from the boundary layer that plays a role in the empirical determination of crop factors. *Like the Priestly-Taylor equation, the Makkink equation is very suitable for interpolation, but for the reasons given, less suitable for use in climate scenarios in which radiation, temperature and humidity vary.*

However, it is possible to use Equation [4.5] to research the sensitivity of the crop factor to variations in  $g_a$  and  $g_s$  and to make predictions about future crop factors. Both these sorts of analysis were made by Jacobs & de Bruin (1992, 1997). These studies were carried out for various conditions (high wind speed combined with deep boundary layer and vice versa; rough and smooth surfaces). They made use either of Equation [4.2] (without boundary layer feedback), or of a fully linked boundary layer model, in which the effect of  $g_s$  on Equation [4.3] and [4.4] was investigated. The results of a sensitivity analysis with [4.2] can also be expressed as a sensitivity in  $a$ , or  $\partial E / \partial Q$ . Jacobs & De Bruin (1997) analyzed a model that was fully linked to the boundary layer, Equation [4.1] and a photosynthesis model. The study estimates the changes in  $g_s$  and in crop factor for various climates, whether or not feedback from the boundary layer or atmospheric humidity is taken into account.

We have drawn up Figure 4-2 from Jacobs & De Bruin (1992). It shows that *the sensitivity of evapotranspiration to  $g_s$  in the first place depends on the aerodynamic conductance, or the roughness of the surface. In the second place, the boundary layer determines the sensitivity for  $g_s$ : the boundary layer tempers the sensitivity* (compare the boundary layer model and Penman-Monteith in Figure 4-2). Finally, the figure shows that this sensitivity depends on the value of  $g_s$  itself: with higher stomatal conductance, sensitivity is lower, because the link with the atmosphere is weaker ( $g_s / g_a$  is higher). The effect is therefore not linear, and a reduction in  $g_s$  as a result of an increase in  $\text{CO}_2$  has a bigger and bigger effect on evapotranspiration. Well-irrigated and non-stressed vegetation has a relatively high stomatal conductance. For this study we can therefore use sensitivities from Figure 4-2 that are on the high side of  $g_s$ . We can deduce from Figure 4-2 that:

- for a smooth surface (such as short grass), the transpiration changes by 15-20% of the change in  $g_s$ ;
- for a rough surface (such as forest), the transpiration changes by 40-75% of the change in  $g_s$ .

From Jacobs & De Bruin (1992) it appears that, within these two ranges, the lower percentage represents cases in which the boundary layer plays a greater role, and the higher percentage a highly advective situation.

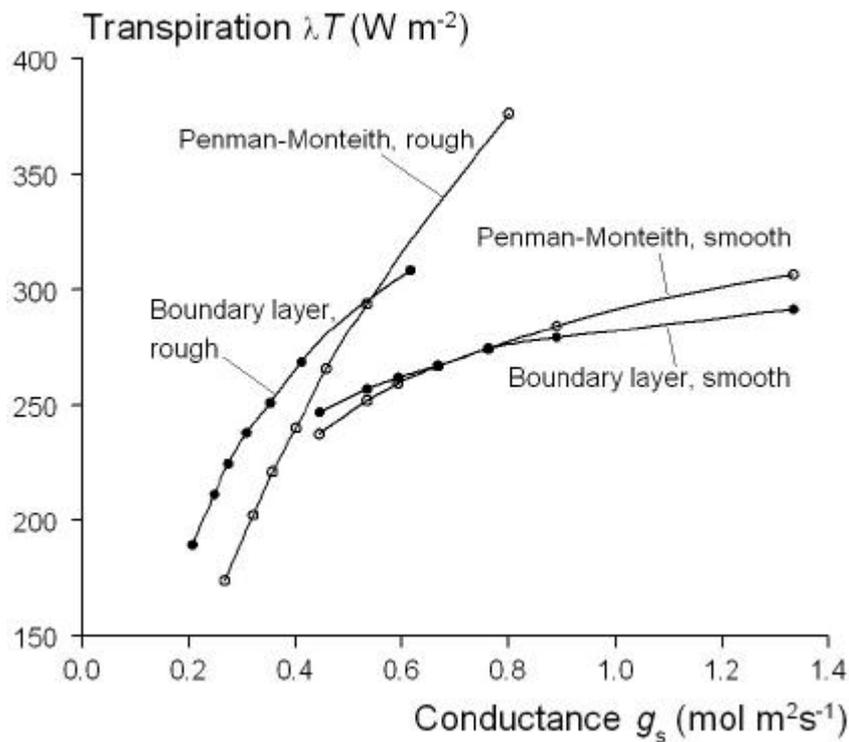


Figure 4-2. The sensitivity of the transpiration to crop conductance  $g_s$  under conditions such as Jacobs & De Bruin (1992) describe. A re-plotting of data from this publication.

#### 4.5 Calculation of CO<sub>2</sub> effect at plot level

With the information about effects of CO<sub>2</sub> on  $g_s$  from §4.2, and the effects of roughness and boundary layers on the sensitivity of evapotranspiration from §4.4, we can now estimate the effect at plot level.

In §4.2 we showed for example that when CO<sub>2</sub> concentrations go up by 100 ppm, the  $g_s$  of grass and herbal crops goes down by an average of 9.3%:  $\Delta g_s / g_s = -0.093$  per 100 ppm. In §4.4 we came to the conclusion that the transpiration from a smooth surface changes by 15-20% - an average of 17.5% - of the change in  $g_s$ :  $(\Delta T / T) / (\Delta g_s / g_s) = 0.175$ . Combining these two factors gives an average decrease in transpiration of 1.6% per 100 ppm ( $0.093 \times 0.175$ ). Making various combinations of crop type and roughness, and taking uncertainties into account, we end up with the transpiration sensitivities  $S$  for CO<sub>2</sub> rise, set out in Table 4-2.  $S$  is defined here as the relative change in transpiration caused by a CO<sub>2</sub> rise of 100 ppm.

We now have to consider two other aspects before we can determine the effect on evapotranspiration: (1) the share of transpiration in the evapotranspiration,  $F^T$ , and (2) the lai-effect of CO<sub>2</sub>-rise, mentioned in §2.1 (positive feedback on  $ET$  via increased Leaf Area Index, see also Figure 2-7).

Table 4-2. Transpiration sensitivities  $S$  (percentages; min = minimum, max = maximum).  $S$  is defined as the relative change in transpiration caused by a CO<sub>2</sub> rise of  $\Delta CO_2 = 100$  ppm. Reduction of stomatal conductance  $g_s$ , taken from §4.2. In these figures the temperature in the boundary layer is assumed to be constant.

	Change in conductance		Roughness of the vegetation					
			Smooth			Rough		
	$\Delta g_s$	$\sigma$	min	mean	max	min	mean	max
Herbal	-9.3	1.5	-1.2	-1.6	-2.2	-3.1*	-5.3*	-8.1*
Woody	-6.8	2.5	-0.6*	-1.2*	-1.9*	-1.7	-3.9	-7.0
C <sub>4</sub>	-11.8	1.0	-1.6	-2.1	-2.6	-4.3*	-6.8*	-9.6*

\* These combinations occur seldom or never.

### The transpiration share

The transpiration share  $F^T$  is mainly determined by vegetation cover. Suppose the transpiration of a well-developed crop constitutes 80% of the total evapotranspiration (Figure 2-3), and that the 20% evaporation in  $ET$  is not sensitive to CO<sub>2</sub>, then the decrease, per 100 ppm CO<sub>2</sub> rise, in  $ET$  in our previous example is not 1.6%, but  $0.8 \times 1.6 = 1.3\%$  instead. So, in order to compute effects on evapotranspiration we have to know the transpiration share  $F^T$ . This share may vary with the seasons, depending on vegetation cover. In winter, fields usually lie fallow so that  $F^T = 0$ . In winter, potential evapotranspiration is also low so that  $ET$  is less sensitive to  $F^T$ . On the other hand, grasslands have a high cover throughout the year and, with that,  $F^T$  is permanently high too.

With the integrated soil-water-atmosphere-plant model SWAP (Van Dam, 2000) we calculated for 10 successive years (1980-1990) and on a soil without moisture stress, the  $F^T$  of four crops: potato, maize, grassland and wheat. The results are shown in Figure 4-3 and Appendix II, with mean values per decade. Table 4-3 that was derived from Appendix II gives the average  $F^T$ -values for the summer season and for the winter season. On the basis of this we define the following two categories:

- Grasslands and other short, lasting vegetations (like heather), with an  $F^T$  value of 80% throughout the year.
- Agricultural fields and other deciduous vegetations (like deciduous forests and gardens), with an  $F^T$  value of 60% on average, 80% in the summer season and 10% in the winter season. Also evergreen conifers

(such as spruce) are in this category because their high interception loss in winter causes a low  $F^T$ .

It may seem that this rules of thumb estimate the transpiration share of wheat too high, but this may not be the case since we did not consider the effect of a second crop, which is often planted by farmers for green manuring. So, for a parcel of wheat  $F^T$  is probably higher than we computed with the SWAP model.

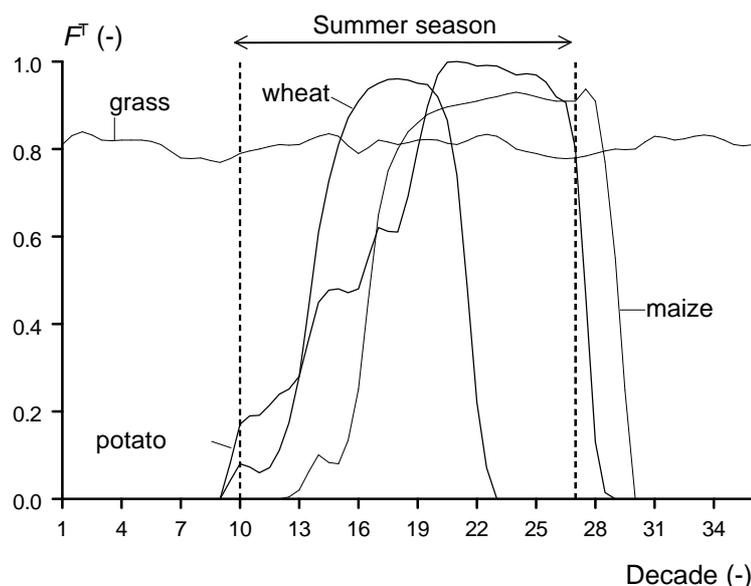


Figure 4-3. Course of transpiration share  $F^T$  in the evapotranspiration of four crops: potatoes, maize, grassland en wheat. Based on average simulated decadal figures of transpiration and evapotranspiration (1980-1990), see Appendix II.

Table 4-3. Mean transpiration share  $F^T$  of four crops, for the whole year, summer season (decade 9-27 = 1 April - 30 September), and winter season (decade 1-8 and 28-36).

	Potatoes	Grass	Maize	Wheat
Year	0.61	0.81	0.63	0.49
Summer	0.81	0.81	0.79	0.67
Winter	0.06	0.80	0.15	0.02

#### The lai-effect

In the literature it has been suggested that  $CO_2$  rise may stimulate Leaf Area Index to such an extent, that this may nullify the effect of a lower stomatal conductance: wue-effect and lai-effect fully compensate each other and the net-effect is that evapotranspiration remains the same. Poorter & Navas (2002) show in a meta-analysis comprising a large number of experiments, that biomass can increase tens of percents when  $CO_2$ -concentration doubles.

However, according to the authors the results do not tell us how biomass increases in natural conditions outdoors, since these large effects on biomass were measured on well ventilated pots in which plants had enough space to use the extra CO<sub>2</sub> for their growth. Experiments with monocultures, in which plants compete, showed a small biomass response.

In order to reliably estimate effects on biomass or LAI, we have to rely on FACE studies. Bunce (2004) gives a review of his own FACE experiments and those of others, in which effects on LAI of CO<sub>2</sub> supply (550-700 ppm) have been measured. From the crops studied, there was no (Beans, Cotton, Orchard grass - *Dactylis glomerata*, Potatoes, Sorghum, Winter barley, Winter wheat) or just a small (<10%; Rice, Summer wheat) observed increase in LAI. In the latter case, the small increase occurred at the beginning of the growing season. An exception was Soya bean, on which an average increase of 27% was observed, throughout the growing season. However, according to a simulation with a soil-vegetation-atmosphere model (Wilson et al., 1999), this increase had no effect on evapotranspiration.

According to Bunce (2004) “the lack of response of LAI to elevated CO<sub>2</sub> in most crop species under field conditions is somewhat surprising and suggests that leaf area growth often is not carbon limited under field conditions”. For our study this means *that we can neglect the lai-effect*.

Bunce (2004) makes a number of statements about the response of crops that are worth mentioning:

- In stands of crops, interception of radiation is generally nearly complete at a LAI of about 3, and evapotranspiration changes little above a LAI of 3 or 4.
- In naturally ventilated plant canopies additional shaded leaf area contributes little to *ET* partly because shaded leaves receive not much radiation, but also because a greater leaf area results in humidification of the air as well as a reduction of wind speed inside the canopy.
- In artificially ventilated systems additional leaf area can result in a higher *ET* because the supply with blowers of CO<sub>2</sub> enriched air causes a lower humidity and a higher wind speed inside the canopy. Therefore, results of such experiments cannot be simply extrapolated to the field.
- Many annual crops spend a substantial fraction of the growing season with a LAI of <3. Therefore during this period LAI could be stimulated and, with that, *ET* as well. As we discussed, however, in most cases there is no effect on LAI and in cases there is any, it only has a small impact on *ET*. According to Bunce (2004) the small response of *ET* might be due to the lower soil evaporation than in the ambient CO<sub>2</sub> treatment.

### *Effects on evapotranspiration*

Now that we know the transpiration share and that we may neglect the lai-effect, we can calculate the decrease of evapotranspiration as a result of CO<sub>2</sub> level rise by ? CO<sub>2</sub>:

$$\frac{\Delta ET}{ET} = \frac{\Delta CO_2}{100} \times F^T \times S \quad [4.6]$$

With the aid of this equation, the two categories for transpiration share mentioned on page 39, and the transpiration sensitivities of Table 4-2, we have drawn up Table 4-4, showing the evapotranspiration decrease in terms of percentage for 2050 and 2100.

Table 4-4. Calculated decrease of evapotranspiration in 2050 en 2100 due to a CO<sub>2</sub> level rise of 150 and 385 ppm, respectively (min = minimum, max = maximum). In these figures, temperature in the boundary layer is assumed to be constant.

Vegetation	F <sup>T</sup>	Roughness of the vegetation					
		Smooth			Rough		
		min	mean	max	min	max	max
<b>2050 (+150 ppm)</b>							
<i>Year</i>							
Short grasslands	0.8	-1.4	-2.0	-2.6	-3.7*	-6.4*	-9.7*
Fields, conifers	0.6	-1.1	-1.5	-1.9	-2.8*	-4.8*	-7.3*
Deciduous, shrubs	0.6	-0.6*	-1.1*	-1.7*	-1.5	-3.5	-6.3
C <sub>4</sub> crops	0.6	-1.5	-1.9	-2.3	-3.9*	-6.1*	-8.6*
<i>Summer</i>							
Short grasslands	0.8	-1.4	-2.0	-2.6	-3.7*	-6.4*	-9.7*
Fields, conifers	0.8	-1.4	-2.0	-2.6	-3.7*	-6.4*	-9.7*
Deciduous, shrubs	0.8	-0.8*	-1.4*	-2.2*	-2.1	-4.7	-8.4
C <sub>4</sub> crops	0.8	-1.9	-2.5	-3.1	-5.2*	-8.1*	-11.5*
<i>Winter</i>							
Short grasslands	0.8	-1.4	-2.0	-2.6	-3.7*	-6.4*	-9.7*
Fields, conifers	0.1	-0.2	-0.2	-0.3	-0.5*	-0.8*	-1.2*
Deciduous, shrubs	0.1	-0.1*	-0.2*	-0.3*	-0.3	-0.6	-1.0
C <sub>4</sub> crops	0.1	-0.2	-0.3	-0.4	-0.6*	-1.0*	-1.4*
<b>2100 (+385 ppm)</b>							
<i>Year</i>							
Short grasslands	0.8	-3.6	-5.0	-6.7	-9.6*	-16.5*	-24.9*
Fields, conifers	0.6	-2.7	-3.8	-5.0	-7.2*	-12.4*	-18.7*
Deciduous, shrubs	0.6	-1.5*	-2.7*	-4.3*	-4.0	-9.0	-16.1
C <sub>4</sub> crops	0.6	-3.7	-4.8	-5.9	-10.0*	-15.7*	-22.2*
<i>Summer</i>							
Short grasslands	0.8	-3.6	-5.0	-6.7	-9.6*	-16.5*	-24.9*
Fields, conifers	0.8	-3.6	-5.0	-6.7	-9.6*	-16.5*	-24.9*
Deciduous, shrubs	0.8	-2.0*	-3.7*	-5.7*	-5.3	-12.0	-21.5
C <sub>4</sub> crops	0.8	-5.0	-6.4	-7.9	-13.3*	-20.9*	-29.6*
<i>Winter</i>							
Short grasslands	0.8	-3.6	-5.0	-6.7	-9.6*	-16.5*	-24.9*
Fields, conifers	0.1	-0.5	-0.6	-0.8	-1.2*	-2.1*	-3.1*
Deciduous, shrubs	0.1	-0.2*	-0.5*	-0.7*	-0.7	-1.5	-2.7
C <sub>4</sub> crops	0.1	-0.6	-0.8	-1.0	-1.7*	-2.6*	-3.7*

\*These combinations hardly occur in practice.

## 4.6 Discussion

### *Comparison with measurements*

Measurements of evapotranspiration decreases in cases of CO<sub>2</sub> increases of 200 ppm are according to Table 3-1 6.5% on average, with a standard deviation of 3.5% (including experiments under conditions of drought stress and nutrient poverty). If we calculate the decrease at 200 ppm according to the method described in §4.5, excluding unrealistic combinations of vegetation and aerodynamic resistance, we obtain a value of between 2 and 11% (see sheet 'calculations' in the data base). Like Table 3-1, in our method a C<sub>4</sub> plant and trees have a relatively high value, whereas the low value is computed for the other agricultural fields. So, *measurements seem to confirm the usability of the calculation method presented here.*

### *Comparison with model simulations*

The effect on evapotranspiration of doubling of CO<sub>2</sub> level has been simulated in a number of studies. According to our method, 2×CO<sub>2</sub> leads to an evapotranspiration reduction of 3.3-6% of short grasslands and aerodynamically smooth C<sub>4</sub> crops. High crops like maize are not that smooth, aerodynamically, so that the reduction will be somewhat higher.

Bunce (2004) discusses five model studies in which the stomatal conductance depends on environmental conditions, such as CO<sub>2</sub> concentration and moisture stress. With one-dimensional soil-vegetation-atmosphere models, a reduction of *ET* was simulated at 2×CO<sub>2</sub> of 1-2% for Alfalfa, 2-5% for Orchard grass, 5-9% for Soybean, and 0-9% for Maize. A reduction of *ET* of 2.3-3.5% for all vegetation was simulated with a Ball-Berry model of stomatal conductance ([4.1]), linked to a Global Circulation Model (GCM). According to Bunce (2004) these studies suggest that doubling atmospheric CO<sub>2</sub> would probably reduce *ET* by a few percent, but probably by <10%.

With a one-dimensional model Grant et al. (2001) simulated a 9% reduction of evapotranspiration of Wheat, sufficiently supplied with water and nutrients. Also using a one-dimensional model, Riedo et al. (1999) simulated reductions of 6 and 11 % for two grasslands in the Alps. Given soil texture (loam) and species composition (Orchard grass, Perennial ryegrass - *Lolium perenne*, Tall oatgrass - *Arrhenatherum elatius*), both grassland probably had enough water and nutrients.

Finally, Sellers et al. (1996) used a biosphere model linked to a GCM to calculate for the northern latitudes ((50.4 °N to 72.0 °N) a reduction of *ET* of 2.2 and 4.1%. The low figure (2.2%) is based on the assumption that all the extra carbon is used for extra photosynthesis, the high figure (4.1%) on the assumption that photosynthesis does not change. Since we may probably neglect the lai-effect, the highest figure seems most appropriate.

*The results of these model simulations are in reasonable agreement with the results of our calculation method. Deviations may be due to model assumptions and sub-optimal growth conditions in the simulations.*

#### *Future research*

The predicted evapotranspiration decreases, with all their uncertainties, could be included, whether in these or in more simplified forms, in future hydrological calculations. The predictions for increased evapotranspiration in Beersma et al. (2004) should also be included. Given that the increases are of similar dimensions, we can expect that *the net effect of climate change on evapotranspiration will be small, but that there are many uncertainties*. The type and structure of vegetation plays a big role, with CO<sub>2</sub> temperature and crop evapotranspiration having a bigger effect on rougher (and usually taller) vegetation forms. The uncertainties increase here too, and it is more important for rougher vegetation than for lower, smoother vegetation to integrate evapotranspiration processes explicitly in models.

Finally, we would like to point out that, as mentioned in §2.6, we have left out a number of processes, both on the smaller scale at leaf and stomata level, and on the larger, regional scale. These processes are potentially very influential and it is therefore important to conduct *further studies with integrated models simulating and linking both small-scale and large-scale processes*.



## 5 Conclusions and recommendations

1. The greenhouse and Open Top Chamber experiments described in the literature (Chapter 3) reveal a bigger decrease in evapotranspiration due to increased CO<sub>2</sub> than that which is observed out in the field. In such experiments, the aerodynamic resistance is so reduced by the efficient application of CO<sub>2</sub> enriched air that the transpiration of plants displays an increased sensitivity to CO<sub>2</sub> enrichment.
2. For the Drought study, Doomen & Witte (2004) estimate an evapotranspiration reduction of 5% per 100 ppm increase in CO<sub>2</sub>. Given that this study is based on the experiments mentioned in (1), this reduction figure has to be considered unrealistic and must therefore be rejected.
3. Experimental research into the effect of CO<sub>2</sub> application on evapotranspiration is complicated by various feedback mechanisms, including:
  - Reduction in evapotranspiration increases the vapour pressure gradient from leaf to air through a rise in the leaf temperature and a drop in atmospheric humidity, which in turn stimulates evapotranspiration.
  - Rising temperatures and falling atmospheric humidity levels near the leaves can make the stomata close, causing a further decrease in transpiration. There has been little research into this positive feedback and its effect in practice is highly uncertain.
  - Under nutrient-poor conditions, CO<sub>2</sub> may stimulate plants to extend their root system in order to obtain nutrients, which are then a limiting factor. A larger root system ensures a better supply of moisture, which stimulates transpiration.
  - Rising CO<sub>2</sub> leads to greater above-ground growth, increasing leaf surface area and with it evapotranspiration.
  - On dry soils, evapotranspiration reduction through increased CO<sub>2</sub> ensures that soil moisture is available for longer, which promotes evapotranspiration.
4. Most experimental research has focused on agricultural crops and natural vegetations, probably with a view to consequences for agricultural production and for biodiversity, respectively. For hydrological scenarios in The Netherlands, it is very important that more experimental research is done on common vegetations such as grasslands (dominated by *Lolium perenne*), maize fields and heather. This research should be done using FACE, and should also investigate the increased closing of the stomata as a consequence of reduced atmospheric humidity around the leaves.

The effect of CO<sub>2</sub> on evapotranspiration can be researched using historical lysimeter results, preferably from at least fifty years ago. CO<sub>2</sub>

concentrations have increased so much in the past century that their effect on evapotranspiration must be demonstrable with the help of historical data.

5. For a truly reliable estimate of the effects of changing climate and CO<sub>2</sub> levels, a study should be carried out using a linked soil-water-vegetation-atmosphere model on a landscape scale. Such a model includes the seasonal dynamics of growth and leaf development and is applied to whole regions over at least one year. Only under such conditions can we be sure that the most significant feedback mechanisms are taken into account.
6. In spite of all the uncertainties, we can use the literature study (Chapter 3), model simulations described in the literature (§4.6), and our calculations (Chapter 4; Table 4-4) to give estimates of the reduction in evapotranspiration caused by increases in the CO<sub>2</sub> level of 150 and 385 ppm, which are (§1.2) the averages predicted for 2050 and 2100 respectively: *see Table 5-1*. These estimates take into consideration the aerodynamic roughness of the vegetation (the rougher the vegetation, the better the air mixing and the lower the aerodynamic resistance), the photosynthesis type (C<sub>3</sub> or C<sub>4</sub>) and the moderating influence of nutrient poverty mentioned under point (3).
7. The reduction in evapotranspiration presented in Table 5-1 is more or less the same as the increase in evapotranspiration calculated by the KNMI for scenarios of yearly average temperature increases of 0.5, 1 and 2 °C (Table 1-1: 1.9, 3.9 and 7.8% increase in evapotranspiration). However, when the predicted increase in rainfall (Table 1-1) is taken into account, the expectation is that The Netherlands will become rather wetter, on average (see example calculation on page 48). According to the example calculation, the summer season may become wetter or dryer, depending on the scenario and the value  $c_2$  for the CO<sub>2</sub>-effect. It is only in the 'Drought scenario' that the increase in evapotranspiration by higher temperatures and the reduction of precipitation will yield a large reduction of the precipitation excess, irrespective the CO<sub>2</sub>-effect on evapotranspiration.
8. In view of the fact that the effects on evapotranspiration of temperature increases (Table 1-1) and of CO<sub>2</sub> increases (Table 5-1) are surrounded by large uncertainties, have an opposite result, and are comparable in scale, we recommend that both effects be incorporated, with their margins of uncertainty, in any hydrological risk calculations for different climate scenarios.

Table 5-1. Proposed factor  $c_2$  for the correction of potential evapotranspiration  $ET_p$  (according to Equation(1.3)) for 2050 and 2100 ( $CO_2$  concentration of 150 and 385 ppm respectively)<sup>9</sup>. Presented are the estimated minimal (min), mean and maximum (max) figures for evapotranspiration reduction. Effects on the evapotranspiration of the expected rise in temperature are not taken into account. The relative change in  $ET_p$  amounts  $\Delta ET_p/ET_p = 1 - c_2$ .

Vegetation	2050			2100		
	min	mean	max	min	mean	max
<i>Year</i>						
1. Grasslands, dry + nutrient-poor reserves*	0.99	0.98	0.97	0.96	0.95	0.93
2. Deciduous, shrubs, C <sub>4</sub> crops	0.98	0.96	0.94	0.96	0.91	0.84
3. Other fields, conifers	0.98	0.97	0.95	0.95	0.92	0.88
4. Other nature reserves	0.97	0.96	0.94	0.93	0.89	0.84
<i>Summer</i>						
1. Grasslands, dry + nutrient-poor reserves*	0.99	0.98	0.97	0.96	0.95	0.93
2. Deciduous, shrubs, C <sub>4</sub> crops	0.98	0.95	0.92	0.95	0.88	0.78
3. Other fields, conifers	0.97	0.96	0.94	0.93	0.89	0.84
4. Other nature reserves	0.97	0.96	0.94	0.93	0.89	0.84
<i>Winter</i>						
1. Grasslands, dry + nutrient-poor reserves*	0.99	0.98	0.97	0.96	0.95	0.93
2. Deciduous, shrubs, C <sub>4</sub> crops	1.00	0.99	0.99	0.99	0.99	0.98
3. Other fields, conifers	1.00	0.99	0.99	0.99	0.99	0.98
4. Other nature reserves	0.97	0.96	0.94	0.93	0.89	0.84

\*dry dunes, dry heath

<sup>9</sup> Explanation of how the figures were established:

- The estimates for category 1 and 2 are directly based on Table 4-4.
- Although nutrient-poor and dry nature reserves have, on average, a higher aerodynamic roughness than grasslands, they are assigned to category 1 because nutrient-poverty tempers evapotranspiration reduction.
- Maize is assigned to category 2. This crop is moderately rough, aerodynamically, so less rough than deciduous forest, but, on the other hand, the C<sub>4</sub> photosynthesis increases the sensitivity of maize to CO<sub>2</sub>.
- 'Other fields' have a season dependent transpiration share in the evapotranspiration. Aerodynamically speaking, they are 'moderately rough'. The estimates are averages from the calculation method described in §4.5 of 'smooth' and 'rough' for grasslands. Coniferous trees are assigned to category 3 because of their low transpiration share, which is caused by a high interception rate.
- Category 4 got the same transpiration share as that of grassland (80%), but an aerodynamic roughness just between 'smooth' and 'rough'.

**Example calculation : effects on precipitation excess in 2050**

Approximately 800 mm of precipitation falls in The Netherlands every year, and approximately 550 mm of moisture evaporates under good water supply conditions, giving a precipitation excess of 250 mm yr<sup>-1</sup>. (www.knmi.nl).

For short grassland, Table 5-1 gives a reduction in evapotranspiration through the CO<sub>2</sub>-effect of 2% for 2050 (c<sub>2</sub> = 0.98). If we adopt the market optimist’s scenario (Table 1-1: increase in precipitation of +1.5%, increase in evapotranspiration through higher temperatures of +1.9% (c<sub>1</sub> = 1.019)), then the precipitation excess for this grassland in 2050 will be 5%: 800×1.015 - 550×1.019×0.98 = 263 mm. The table below can be put together in the same way, for different climate scenarios and c<sub>2</sub>-values.

In the table below, figures for the summer season are based on a precipitation of 400 mm and an evapotranspiration of 500 mm; positive values indicate a decrease of the evapotranspiration excess.

It is of course a rough calculation method, but it does indicate that most scenarios suggest that The Netherlands will become somewhat wetter *on average*. To accurately calculate the effects on the actual evapotranspiration and the precipitation excess, a model for unsaturated zone is needed, e.g. SWAP or MOZART. Models like NAGROM, MONA and MOZART could be used to investigate how evapotranspiration, the precipitation excess and the hydrology of The Netherlands change in various climate scenarios (including other precipitation, potential evapotranspiration, and downwardly adjusted crop factors).

*Predicted increase in precipitation excess (%) in different climate scenarios (with average temperature rises as in Table 1-1), for correction factors c<sub>2</sub>.*

Scenario	Year			Summer		
	c <sub>2</sub> =0.95	c <sub>2</sub> =0.97	c <sub>2</sub> =0.98	c <sub>2</sub> =0.95	c <sub>2</sub> =0.97	c <sub>2</sub> =0.98
Market optimist (+0.5 °C)	+12	+7	+5	+20	+10	+4
Controller (+1 °C)	+12	+8	+6	+15	+5	-1
Environmentalist (+2 °C)	+14	+9	+7	+5	-6	-11
Drought (+2.3 °C)	-39	-45	-47	-170	-180	-190

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# I List of symbols

$a$	Makkink constant (-)
$A_n$	net photosynthesis ( $\text{mol m}^{-2} \text{s}^{-1}$ )
$c_1$	factor for the temperature effect (Table 1-1) (-)
$c_1$	factor for the $\text{CO}_2$ -effect (-)
$C$	$\text{CO}_2$ -concentration ( $\text{mol m}^{-3}$ or $\text{mol mol}^{-1}$ )
$C_s$	$\text{CO}_2$ -concentration on the leaf surface ( $\text{mol m}^{-3}$ or $\text{mol mol}^{-1}$ )
$e_0^*$	saturated vapor pressure in the substomatal space (Pa)
$e_s$	vapor pressure in the atmosphere on the leaf surface (Pa)
$e_s^*$	saturated vapor pressure $s$ on the leaf surface (Pa)
$e_z$	vapor in the atmosphere at height $z$ (Pa)
$e_z^*$	saturated vapor in the atmosphere at height $z$ (Pa)
$E$	evaporation ( $\text{kg m}^{-2}\text{s}^{-1}$ or $\text{mm d}^{-1}$ )
$ET$	evapotranspiration ( $\text{kg m}^{-2}\text{s}^{-1}$ or $\text{mm d}^{-1}$ )
$ET_a$	actual evapotranspiration ( $\text{kg m}^{-2}\text{s}^{-1}$ or $\text{mm d}^{-1}$ )
$ET_p$	potential evapotranspiration ( $\text{kg m}^{-2}\text{s}^{-1}$ or $\text{mm d}^{-1}$ )
$ET_p^*$	potential evapotranspiration from the vegetation, corrected for both the temperature effect and the $\text{CO}_2$ effect ( $\text{kg m}^{-2}\text{s}^{-1}$ or $\text{mm d}^{-1}$ )
$ET_{\text{ref}}$	reference evapotranspiration according to Makkink ( $\text{kg m}^{-2}\text{s}^{-1}$ or $\text{mm d}^{-1}$ )
$f$	crop factor (-)
$F_T$	share of transpiration in the evapotranspiration (-)
$g_a$	aerodynamic conductance ( $\text{m s}^{-1}$ or $\text{mol m}^{-2} \text{s}^{-1}$ )
$g_c$	minimum conductance of the epidermis of leaves with closed stomata ( $\text{m s}^{-1}$ or $\text{mol m}^{-2} \text{s}^{-1}$ )
$g_s$	stomatal or crop conductance ( $\text{m s}^{-1}$ or $\text{mol m}^{-2} \text{s}^{-1}$ )
$K?$	incoming shortwave (global) radiation ( $\text{W m}^{-2}$ )
$LAI$	Leaf Area Index (-)
$M_w$	molecular mass of $\text{H}_2\text{O}$ ( $\text{kg mol}^{-1}$ )
$Q$	the available energy ( $\sim$ net radiation energy) ( $\text{W m}^{-2}$ )
$r$	diffusion resistance ( $\text{s m}^{-1}$ )
$r_a$	aerodynamic resistance ( $\text{s m}^{-1}$ )
$r_g$	crop resistance ( $\text{s m}^{-1}$ )
$r_s$	stomatal resistance ( $\text{s m}^{-1}$ )
$R$	universal gas constant ( $\text{J mol}^{-1}\text{K}^{-1}$ )
$R_T$	transpiration ratio (-)
$s$	temperature-dependant gradient of the saturated vapor pressure curve ( $\text{Pa K}^{-1}$ )
$S$	transpiration sensitivities $S$ for $\text{CO}_2$ rise, defined as the relative change in transpiration caused by a $\text{CO}_2$ rise of 100 ppm (-)
$t$	absolute temperature (K)
$T$	transpiration ( $\text{kg m}^{-2}\text{s}^{-1}$ or $\text{mm d}^{-1}$ )
$T_p$	potential transpiration ( $\text{kg m}^{-2}\text{s}^{-1}$ or $\text{mm d}^{-1}$ )
$wue$	water use efficiency (-)
$a$	Priestly-Taylor constant (-)

- ? evaporation heat of water ( $\text{J kg}^{-1}$ )
- ? temperature-dependant psychrometric constant ( $\text{Pa K}^{-1}$ )
- O coupling factor (-)
- $\psi$  water potential (Pa)

## II The transpiration share $F^T$

Mean decadal values of transpiration  $T$  (cm), evaporation  $E$  (cm), and transpiration share  $F^T$  (-), computed with the SWAP model for Potatoes, Grass, Maize and Wheat. Based on meteorological data from weather station De Bilt (1980-1990), and ideal soil conditions (not too wet, nor too dry).

Month	decade	Potatoes			Grass			Maize			Wheat		
		$T$	$E$	$F^T$	$T$	$E$	$F^T$	$T$	$E$	$F^T$	$T$	$E$	$F^T$
		cm	cm	(-)	cm	cm	(-)	cm	cm	(-)	cm	cm	(-)
Jan	1	0.00	2.67	0.00	2.21	0.51	0.81	0.00	2.67	0.00	0.00	2.67	0.00
	2	0.00	3.30	0.00	3.33	0.63	0.84	0.00	3.30	0.00	0.00	3.30	0.00
	3	0.00	3.91	0.00	3.56	0.79	0.82	0.00	3.91	0.00	0.00	3.91	0.00
Feb	4	0.00	5.31	0.00	4.87	1.10	0.82	0.00	5.31	0.00	0.00	5.31	0.00
	5	0.00	5.40	0.00	5.98	1.28	0.82	0.00	5.40	0.00	0.00	5.40	0.00
	6	0.00	4.24	0.00	5.51	1.29	0.81	0.00	4.24	0.00	0.00	4.24	0.00
Mar	7	0.00	6.95	0.00	6.03	1.74	0.78	0.00	6.95	0.00	0.00	6.95	0.00
	8	0.00	7.38	0.00	8.43	2.39	0.78	0.00	7.38	0.00	0.00	7.38	0.00
	9	0.00	10.73	0.00	11.31	3.39	0.77	0.00	10.73	0.00	0.00	10.73	0.00
Apr	10	1.53	7.49	0.17	12.89	3.48	0.79	0.00	7.71	0.00	0.70	7.65	0.08
	11	1.77	7.59	0.19	14.84	3.74	0.80	0.00	8.13	0.00	0.54	7.95	0.06
	12	2.27	7.18	0.24	17.37	4.16	0.81	0.00	7.50	0.00	0.89	7.31	0.11
May	13	3.29	8.41	0.28	19.41	4.41	0.81	0.17	9.11	0.02	3.15	8.30	0.28
	14	6.78	8.44	0.45	24.94	5.18	0.83	1.03	9.02	0.10	12.37	7.81	0.61
	15	8.55	9.35	0.48	25.60	5.43	0.83	0.85	10.20	0.08	25.07	5.91	0.81
Jun	16	9.63	10.30	0.48	21.45	5.66	0.79	3.85	11.65	0.25	24.73	2.43	0.91
	17	13.24	8.01	0.62	25.11	5.46	0.82	14.81	7.91	0.65	29.87	1.69	0.95
	18	13.70	8.76	0.61	22.18	5.34	0.81	24.55	6.03	0.80	26.35	1.21	0.96
Jul	19	25.30	6.24	0.80	25.91	5.82	0.82	32.52	5.08	0.86	30.70	1.66	0.95
	20	30.64	0.85	0.97	24.85	5.45	0.82	32.66	4.22	0.89	28.75	2.42	0.92
	21	33.24	0.10	1.00	27.06	6.20	0.81	36.70	3.95	0.90	20.33	7.18	0.74
Aug	22	29.78	0.23	0.99	24.10	5.05	0.83	33.11	3.13	0.91	2.42	8.72	0.22
	23	30.86	0.43	0.99	25.28	5.26	0.83	34.68	2.88	0.92	0.00	9.53	0.00
	24	26.69	0.69	0.97	22.04	5.41	0.80	30.18	2.33	0.93	0.00	12.01	0.00
Sep	25	19.32	0.67	0.97	15.89	4.23	0.79	21.81	1.82	0.92	0.00	9.51	0.00
	26	14.38	1.30	0.92	11.98	3.42	0.78	16.16	1.55	0.91	0.00	10.87	0.00
	27	11.28	2.87	0.80	10.58	2.90	0.78	14.37	1.38	0.91	0.00	8.95	0.00
Oct	28	1.19	8.09	0.13	9.60	2.52	0.79	12.74	1.24	0.91	0.00	8.52	0.00
	29	0.00	7.86	0.00	7.67	1.91	0.80	5.17	4.17	0.55	0.00	7.85	0.00
	30	0.00	7.10	0.00	6.19	1.50	0.80	0.00	7.07	0.00	0.00	7.09	0.00
Nov	31	0.00	4.22	0.00	4.58	0.91	0.83	0.00	4.24	0.00	0.00	4.22	0.00
	32	0.00	3.95	0.00	3.79	0.82	0.82	0.00	3.96	0.00	0.00	3.97	0.00
	33	0.00	3.21	0.00	2.89	0.59	0.83	0.00	3.19	0.00	0.00	3.19	0.00
Dec	34	0.00	2.11	0.00	2.45	0.49	0.83	0.00	2.13	0.00	0.00	2.13	0.00
	35	0.00	2.83	0.00	2.41	0.57	0.81	0.00	2.84	0.00	0.00	2.82	0.00
	36	0.00	2.97	0.00	2.99	0.69	0.81	0.00	2.93	0.00	0.00	2.96	0.00