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EVALUATING THE VAPOR SHIFT CONCEPT IN AGRICULTURE

Diploma Thesis

Diplomarbeit

zur Erlangung des akademischen Grades

Diplomingenieur

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12. Dezember 2008

Abstract

Globally growing population figures indicate an increasing pressure on water resources in foreseeable future. Agricultural water consumption for producing food is by far the largest human water use. A long term prediction by Falkenmark et al. (2004) suggests a global water deficit for food production of 5800 km y^{-1} annually by 2050. To minimize this deficit, one strategy amongst others, is to shift unproductive soil evaporation towards productive plant transpiration, a so called “vapor shift”. Such a shift should also improve crop water productivity. A conceptual approach by Falkenmark et al. (2004) suggests achieving water savings of 330 km^3 y^{-1} by 2050. To reach this, three options are mentioned: 1.Reducing early season soil evaporation, 2.Increasing canopy cover, 3.Increasing yield levels and thus improving crop water productivity.

In a first step the thesis evaluates the global estimates by means of an online literature search. Field experiments, which are separating green water fluxes on a seasonal scale, were collected to build up a database. 13 experiments mainly for wheat and maize resulted in a water deficit reduction potential of a vapor shift that is 37 % lower, than estimated by Falkenmark et al. (2004). Possible reasons are different climatic and environmental conditions of the database experiments. Currently there still is a lack of field experiments which separate soil evaporation from plant transpiration. Empirical data confirms increasing yield levels to contain a great improvement potential for crop water productivity.

The second part of the evaluation acts on a local scale and uses the agro hydrological model SWAP. An optimization of planting density and application of a mulch layer were chosen as two potential agricultural measures to achieve a vapor shift. Crop, weather and soil data for an Indian region was available for parameterization and to create a realistic model simulation. The simulation results demonstrated the difficulty to consider a shift from soil evaporation to plant transpiration without a variation in total evapotranspiration. The evaluation showed that a model simulation using SWAP can be an appropriate tool for checking the crop water productivity improvement potential of an agricultural measure on a local scale.

Preface

Prior to our one year studies at the Wageningen University my plans did not foresee to write a final thesis abroad. In December 2007 Klaas Metselaar offered me to start working on a thesis with him as a supervisor. After assessing advantages and disadvantages, I decided to take the opportunity and never regretted my decision.

My thanks to Klaas for getting me enthusiastic about the subject of the thesis and for his guidance through this widespread and complex topic. Klaas showed me how to continue when standing on the crossroads of a decision and that there are mostly at least three possibilities to choose from. Thanks also to Jos van Damn for the spontaneous helpful discussions concerning SWAP. I also want to thank my partner Petra for helping me with the structure of my work and for keeping up the patience until its finalization. Last but not least I want to thank Prof. Klik for his cooperation during the completion of the thesis.

Stefan Schmidt

November 2008

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1 Introduction

1.1 Relevance and Background

To show the relevance of the concept of vapor shift the starting point is an example in the North China Plain (NCP) that demonstrates the scope of the problem. The NCP has an area of 320000 km^2 and produces 50 % of the nations wheat and 33 % of its maize. Potential evapotranspiration ET_p exceeds the annually rainfall with 450 to 650 mm. The region is dominated by the monsoon climate and the distribution of the annual rainfall is very uneven, with 70 % falling from July to September. The water deficit is especially acute during the dry and windy spring season. For centuries local farmers accommodated the deficit by only producing two to three crops every two years. Since the late 1970's there has been improvement and development in irrigation facilities which lead to a double cropping system. Two crops, winter wheat and summer maize, are grown every year to meet the growing food demand of the Chinese population, which grew from the early 1980s to the beginning of the 21st century with about 300 mio people to a magnitude of 1,3 bio people (Enzyclopedia Britannica 2008). 64 % of the irrigated area relies on groundwater use and massive extraction has lead to a decline of the groundwater table, on average 1 m decline annually. Because water demand for urban and industrial water use also increased, this leads to a serious water shortage and to a competition for water in the NCP between different areas. The result is a negative feedback; there is more water needed to produce an increasing yield, but actually there is less available.
This example shows how important it is to use the water resource more effective and thus to improve the efficiency of water use. Compared to industrial and domestical use, agriculture is consuming a lot more water. Therefore the focus possibly will be on improving the efficiency of water use in food production. Because the pressure on the resource water increases with growing population and thus growing food demand, Falkenmark et al. (2004) suggest three main ways of increasing agricultural production.

a) Expand the cultivated land
b) Increase cropping intensity and the number of harvests over time
c) Improve yields of grain or biomass per unit land

These three means are important not only for agricultural development, but also to deal with natural resource use. To find a compromise for balancing water resources between humans and nature will be a challenge in the near future. Due to intensifying water scarcity we will be confronted with the trade off of water and land use from ecosystems to agriculture. Expanded cultivated land will involve a shift of ecological water functions to production of food on cultivated land and thus is the worst strategy in terms of a sustainable ecohydrology. Cropping intensities have increased progressively over the last century in all farming systems of the world (Falkenmark et al. 2004). Systems of continuous and more intense cultivation will require additional fresh water, which may affect ecosystems that depend on that water. The third way of improving yields respectively producing more food per unit of soil and water is assumed to be the strategy with the least impact on water dependent ecosystems. Therefore a hopeful option is to apply sustainable management practices that achieve to produce more crop from available water. To put it in other words, the aim is to produce a greater amount of "crop per drop" of water in future.

As the third strategy is assumed to be the most sustainable, it is chosen as the topic, worthwhile to investigate in this master thesis. The introductory example demonstrates the urgency for ongoing research and especially for practical action with regard to improvement of water productivity.

To further explain the "crop per drop" improvement, the expression of the so called vapor shift has to be introduced. The basic idea of vapor shift is to reduce the vertical water flow that is considered to be unproductive, the bare soil evaporation between the crop rows and to shift these savings to the productive plant transpiration that is directly proportional to plant growth and thus yield. This approach constitutes the starting point of the thesis. Falkenmark et al. (2004) estimate the magnitude of the global potential of this real "crop per drop" gain with 330 km^3 y^{-1} for the year 2050. This would account for about 6 % of the total worldwide water deficit of 5800 km^3/y that has to be found to avoid undernourishment (Falkenmark et al. 2004).
On a regional scale it can be crucial to improve water use efficiency in agriculture to meet a growing food demand. For global organizations like the FAO or the UNO it is definitely worth investigating aspects of water use efficiency using conceptual approaches, as water scarcity will become a serious problem in foreseeable future and estimates, even if they are rough, identify a need for action.

Frequently used crop and water balance terms will be designated with their abbreviations further on, except for the conclusions respectively the summary and outlook. The first time they appear in the text, the full term will be announced. The list of symbols in the annex gives information about used abbreviations.

1.2 Research Objectives and Questions

Global estimates such as those quoted above are generalizations and their credibility has to be evaluated and analyzed. The estimates of the magnitude of vapor shift provided by Falkenmark et al. (2004) are based on data and a conceptual approach. These are evaluated and analyzed in Chapter 3. What are the critical points of the concept and are the used assumptions acceptable? In Chapter 3, the global estimate provided by Falkenmark et al. (2004) is checked using experimental data. To do so, a database was built and calculations are compared with the original approach. For this reason a review of literature was done and experiments that deal with the separation of soil evaporation and plant transpiration were collected and analyzed.

In a next step the scale of the analysis was changed from global to local. From the empirical analysis the focus changed to very specific measures for one site and climate. Planting density and mulching as two effective measures to gain more “crop per drop” were chosen for investigation, using the hydrological model SWAP. Why these two measures were picked, will be explained at the end of Chapter 3.
Chapter 4 represents the second part of the practical evaluation. The main questions to be addressed in this Chapter are: What is the effect of a varying planting density and a mulch layer on crop and water balance terms? What consequences do the results of the simulation have for the basic concept of “vapor shift”? Which deficiencies do the simulations have in terms of the description of the physical process and in terms of the data available for parameterization?

1.3 Research Methodology

1.3.1 Methodology of evaluating the global Estimates of the Vapor Shift Concept

Initial Search Strategy

The first idea of the search strategy was to pick out two frequently grown crops that are well investigated. One limitation was to concentrate the investigation on rainfed agriculture and to cross out irrigation experiments and measures. Field production without the support of irrigation, relying completely on natural precipitation, is called “rainfed” agriculture (Ehlers and Goss 2004). Therefore a climate criterion for experiments to be included in the database was set as: precipitation (*P*) equals about evapotranspiration (*ET*), respectively $P >= ET$. In the case where irrigation is necessary because of the uncertain and unequal distribution of precipitation in time, only the experiments with sprinkler irrigation were picked, as this method was most comparable to rainfall. The search was restricted to online articles. Searches were executed using SCOPUS.; to a lesser extent Web of Science and CAB-abstracts.

Adaptation of the initial Search Strategy

The literature search strategy had to be adapted for the following reasons. The climatic criterion to include only experiments without irrigation respectively sprinkler irrigation was canceled because experiments retrieved were mainly done in environments and climates where water is the scarce factor. In most cases *ET* was larger than precipitation and thus necessary to irrigate. It is logical that most research addressing the split up of evaporation (*E*) and transpiration (*T*) fluxes is done in environments, where water is the limiting factor for crop production. Beside wheat and maize also millet (sorghum), cotton and barley were included to increase the available data. The literature was extended to also include articles not available online.

1.3.2 Methodology of evaluating the Vapor Shift Concept with a numerical Simulation on a local Scale

The model, Soil Water Atmosphere Plant (SWAP) is used as a tool for evaluation on a local scale. SWAP simulates transport of water, solutes and heat in unsaturated/saturated soils. It is the successor of the SWATR model which originates from 1978. The model was created by the Soil Physics, Ecohydrology and Groundwater Management Group in cooperation with the Integrated Water Resources Management group, both at Wageningen University and Research Centre. The model can be described as deterministic, physical, semi empirical and agro hydrological. It is written in the programming language FORTRAN and to solve the differential flow equations it uses the finite differences method.
There are two main input modules available in SWAP concerning crop growth. WOFOST and a simple module where seasonal leaf area index (*LAI*) development is prescribed and independent of variation in water availability. With the implementation of WOFOST (a dynamic explanatory model for crop growth with descriptive elements) in SWAP version 2, it became possible to describe the dynamics of plant growth with its physiological and physical processes in a more realistic way (Dam and Malik 2003).

Data from Sirsa District, India was used to build up a realistic model for investigation of water balance terms in relation to planting density (*PD*). It was also tried to build in a mulch layer to estimate the potential of this measure for the site specific conditions. Weather data from 1991 to 2002 as well as soil and plant input data were taken from Dam and Malik (2003). Nutrient availability, which can constitute a major constraint for crop growth, is assumed to be optimal. This assumption is required because fertilization effects are not included in SWAP. Following parameters are variables in the simulation runs: methods for calculating actual soil evaporation (E_a), irrigation criterion, *PD*, vertical discretization of the soil profile. The intention of this small scale investigation is to give information on the magnitude for a possible vapor shift for the specific circumstances and measures. In addition the dynamics of crop and water balance terms are investigated. This is done with regard to a changing *PD* respectively a mulch layer.

2 Theory of describing the Processes involved in Soil Evaporation

2.1 Introduction

In Chapter 2.2 a short overview and explanation of the physical process of vertical upward water fluxes will be given. The aim this Chapter is to describe the influencing factors of the water fluxes. Mechanisms and processes that have to be accounted for when describing transpiration respectively evaporation, are also mentioned. Although this is of less interest for global estimates, it should give an impression of the huge gap between physical reality viewed on a small scale and global predictions which act on a very rough scale.

In Chapter 2.3 the basic approach of viewing water balance terms will be explained. There is a simple approach used in the “vapor shift concept” by Falkenmark et al. (2004). and a more differentiated approach described to me personally by Wim Bastiaanssen. The differentiated approach is of crucial interest as in further chapters this concept is used repeatedly. Especially on a local scale a more differentiated view on crop and water balance terms is assumed to be useful.

In Chapter 2.4 the vapor shift concept itself is introduced. The conceptual approach for the so called “vapor shift” is taken out of the article “Water for Food and Nature in Drought-Prone Tropics: Vapour Shift in Rain-Fed Agriculture” (Rockstrom 2003) respectively the book “Balancing Water for Humans and Nature: The New Approach in Ecohydrology” (Falkenmark et al. 2004). The approach will be explained and suggested practical measures to reach a more effective use of water will be listed in Chapter 2.4.2.

2.2 Physical Process Description concerning Plant Transpiration and Soil Evaporation

2.2.1 Evapotranspiration, Canopy Interception, Plant Transpiration and Soil Evaporation

a) General Aspects

The conceptual approach distinguishes between green and blue water flows. Blue water flow is the visible liquid water flow moving above and below the ground as surface or subsurface runoff. Green water flow is defined as the invisible flow of vapor to the atmosphere and equates to the commonly used term evapotranspiration.(Falkenmark, et al. 2004)

b) Evapotranspiration

Frequently evaporation and transpiration are summarized with the term evapotranspiration *ET*. When looking more exactly at *ET*, in addition to plant *T* and soil *E*, interception is a third component (equation (1)). Intercepted rainfall is evaporating from the leaf surfaces and reduces *T* during this drying cycle due to a more humid microclimate in the canopy and therefore a decreased evaporative demand.

(1). $$ET=I+E+T$$

On different temporal scales these mentioned components vary strongly. Within a fraction of a second cloud cover can change sunshine and radiation conditions and therefore the evaporative demand. On a daily basis the *ET* follows the course of radiation. There is also a strong seasonal dependency typical for global circulations and specific, climatic conditions. Possibly there is also a long term variation due to climatic change. This thesis focuses on seasonal scale processes.

Over the past 20 years the emphasis has been on the Penman method, modified Penman methods and the Penman Monteith methods to calculate *ET* (Burt et al. 2005). The aim of these methods is to calculate the reference crop evapotranspiration (ET_{ref}). As input data these equations need weather components of solar radiation, relative humidity, wind speed and air temperature (Burt et al. 2005).

The FAO Irrigation and drainage paper 56 provides a good summary of how crop coefficients in conjunction with reference *ET* measurements are used to determine *ET* for the crop (ET_c). It also presents a crop coefficient procedure that computes both *E* and *T* components of crop *ET*.

There has been done a lot of research in the field of *ET*, especially in developing equations that describe the biophysical process as exactly as possible. The constraint with many of them is that they just can be used for climatically similar regions. The FAO chose the Penman Monteith equation as the standard method, due to the fact that it is more or less applicable globally. It has also been observed that it can under- respectively overestimate ET_c, therefore an adaptation or adjustment can be necessary. (For instance in the North China Plain ET_c is underestimated by the Penman-Monteith equation. Therefore the crop coefficient $K_c=ET_c/ET_0$ is higher than that recommended by Allen et al. (1999).

c) Canopy Interception

Interception losses are well appreciated in the forestry and hydrology literature, but receive far less attention in the water balance of agricultural crops. (Leuning et al. 1994) Evaporation from soil and wet plants will reduce air and leaf temperatures (cooling effect), humidify the air and thus reduce *T* rates relative to dry soil conditions. Both rainfall and irrigation events lead to increased canopy humidity while intercepted water is evaporating. This contributes to a reduced E_a from the soil and plant *T* caused by interception. This temporary cooling effect may reduce E_a and *T* by 20 – 35 %.(Burt et al. 2005) If the leaves are wet from rain or dew this water evaporates directly from the plant surface and it is generally accepted that *T* begins when the interception storage is emptied, and the plant surface is dry. When *LAI* is greater than 1, there are high interception losses and rainfall is less effective to replenish the soil with water, particularly when rain falls as intermittent, light showers.(Leuning et al. 1994) The idea of reducing “unproductive” soil evaporation by managing crops for early canopy closure will be introduced in this thesis furthermore. An increased canopy cover would also mean greater rainfall interception losses and therefore reduced replenishment of soil water. The focus of investigation will not be on such effects, although the chosen model the modeling part (Chapter 4) accounts for the influence interception.

d) Plant transpiration

Transpiration, in botany, is the loss of water by evaporation in terrestrial plants (Kijne et al. 2003). The process is driven by a difference in matric potential between soil and the atmosphere. The root hairs respectively the stomata cells constitute the interface of the transpiration path, passing the soil and plant respectively the plant and the atmosphere. Transpiration serves several functions in plant growth. Firstly the ascent of sap from the roots to the leaves provides the moisture necessary for the diffusion of carbon dioxide (CO_2) into and oxygen (O_2) out of the stomata. Secondly the upward sap flow provides nutrients to the leaves. Additionally transpiration has a cooling effect for the plant at high temperatures.

Usually the portion of soil water between field capacity and permanent wilting point is considered as transpirable. If water is freely available at the leaf surface, the transpiration rate is primarily controlled by the atmospheric demand. The type and stage of the canopy control *T* as well as the amount of precipitation reaching the soil surface and consequently the water content in the soil profile (Hurtalova' et al. 2001). *LAI*, root density distribution, distribution of soil water and soil hydraulic functions are the factors that determine root water uptake and thus *T*. Transpiration is considered as the productive part of the green water flows because it directly contributes to plant growth and thus yield.

e) Soil evaporation

Definition:

"Evaporation is the process whereby liquid water is converted to water vapor (vaporization) and removed from the evaporating surface. Water evaporates from a variety of surfaces such as rivers, lakes pavements, soils and wet vegetation." (Allen et al.1999)

Furthermore in this thesis the term evaporation always refers to the actual soil evaporation E_a. If evaporation refers to other surfaces, it will be explained explicitly.

Factors determining soil evaporation:

- **Plant physiological factors:**
  Leaf area index, density of the canopy over the plant height, planting density, rooting depth, root distribution.
- **Soil properties:**
  Texture, structure, water conductivity, water holding capacity, water content.
- **Meteorological factors:**
  Evaporative demand, wind speed, temperature.

Most parameters in the crop-soil–system are variable and not constant, therefore it is very difficult to build up a general model for *E* and *T* partitioning over a wide range of sites, soils and seasons. Eastham and Gregory (2000) state that the quantification of *E* rate is difficult, since it can change significantly over relatively short time scales, in response to:

- Changing E_p
- Precipitation
- Crop water uptake
- Canopy development

A common approach of modeling soil evaporation from an initially wet soil profile assumes evaporation occurring in two distinctive stages. The two stage evaporation model by Ritchie (1972) is a widely used approach. The constant rate stage is assumed to be limited by the movement of water from the soil surface to the atmosphere. Thus soil evaporation is limited only by the supply of energy to the surface (sun intensity, wind, air humidity). The falling rate stage is supposed to depend strongly on the hydraulic soil properties because evaporation is limited by the movement of water through the soil to the surface.

2.2.2 Partitioning between Transpiration and Soil Evaporation

Based on the partitioning of potential evapotranspiration (ET_p) into potential evaporation (E_p) and potential transpiration (T_p), a first estimate of the maximum relative amount involved can be based on the leaf area index (*LAI*), and its relation to E_p. By using potential values water stress is factored out. The magnitude of *LAI* has a strong influence on the shading effect and the light extinction of the canopy and therefore restricts the possible radiation that reaches the soil surface. Additionally there is an interaction between the canopy and E_a in crop rows, which is explained with the buildup of a boundary layer that affects the advective air stream, the turbulent mixing and thus the soil evaporation rate.

<u>Definition of *LAI* according to Ehlers and Goss (2004):</u>

The total green area of one side of a leaf as a ratio of one unit of soil surface area. Therefore *LAI* is a dimensionless value.

A common approach to describe the relative loss E_p/ET_p respectively the relative productive part of evapotranspiration is an exponential function according to Goudriaan (1977):

$$(2).\qquad E_p = ET_p \cdot e^{-\kappa_{gr} LAI}$$

E_p is the potential evaporation rate of a soil under a standing crop in mm.

κ_{gr} is the dimensionless extinction coefficient for global solar radiation.

$$(3).\qquad T_p = ET_p (1 - e^{-\kappa_{gr} LAI})$$

Figure 1 represents the course of equation (2) and (3). In literature the attempt to use the unproductive amount of soil water (evaporation) for productive transpiration is referred to as "vapor shift". Figure 1 illustrates the influence of *LAI* on the partitioning of the green water fluxes. If there are no constraints (water, temperature, nutrients etc.) concerning crop development, *LAI* normally increases continuously over the season. 100 % soil evaporation is occurring at emergence of the crop. During crop development there appears to happen a trade off between soil evaporation and plant transpiration. During the season there possibly is a different evaporative demand of the atmosphere depending on climate conditions. Due to this fact, not just the percentage partitioning of the green water fluxes can vary, but also the values in absolute terms. For instance, there is negligible soil evaporation occurring in climates with cool winters. Low temperatures and therefore low atmospheric evaporative demand keep E_p low.

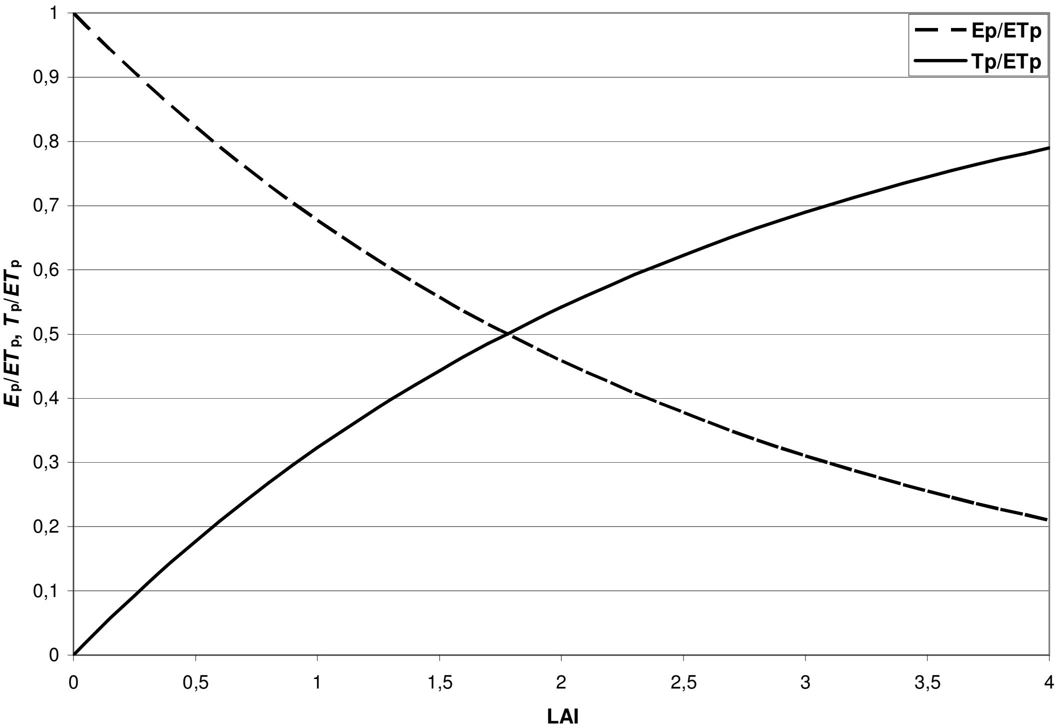

Figure 1 Relative potential evaporation respectively transpiration versus leaf area index according to Goudriaan (1977) with $\kappa_{gr} = 0.39$

2.2.3 The Influence of the Clothesline Effect on Transpiration and Soil Evaporation

Plant stands with a small *LAI*, a low *PD* and a low plant height experience a high E_a and a low *T*. This is due to the fact that a greater percentage of radiation reaches the soil surface in between the crop rows. After the surface has dried, sensible heat is formed. The heated air is transported advectively to the canopy. The vapour pressure deficit (e^*-e) increases and therefore also plant *T*. This process of increasing *T* without raising net assimilation but leaving it at the level set by radiation is called the clothesline effect.

Ehlers and Goss (2004) state that the clothesline effect increases the unproductive *T* to the same extent that the soil surface becomes desiccated and E_a declines. The phenomena of the clothesline effect appears both at micro scale, for instance between a crop row in a sparsely planted cereal and at the local scale of small crop expanses. Neighboring surfaces with a different roughness or an unequal albedo may enhance this advective transport of air. The above described effects have not been investigated exhaustively. Their magnitude and their influence on crop growth in sparsely planted cereals remains a topic for future research. The clothesline effect is mentioned for the sake of completeness, but will not be investigated further in the thesis.

2.3 Approach of viewing Crop Water Productivity respectively Water Use Efficiency

a) Approach of Falkenmark et al.

In order to understand the basic approach of “vapor shift”, an explanation of used assumptions is necessary, respectively definitions of crop water balance terms must be given. Falkenmark et al. (2004) present calculations with concrete numbers, from which the theoretical assumptions are derived. The time scale of the definition for water productivity is annual just considers rainfed agriculture, is not integrative and thus does not include other water uses (industrial, domestic etc.). The spatial scale used is the field. Falkenmark et al. (2004) refers to these definitions.

First introduction is water use efficiency (*WUE*) respectively crop water productivity (*CWP*). In principle both designations describe the relation between *Y* and *ET.* This is the definition preferably used by agronomists respectively hydrologists who aim to produce sufficient food and to optimize water use on a field scale.

Several definitions in literature can be found for this term, which can lead to interdisciplinary confusion and misunderstanding. For instance an irrigation engineer who aims proper water allocation would define *CWP* as *Y* over irrigation supply. Whereas a river basin policy maker who is interested in maximizing profits defines *CWP* as $/*ET.* A plant physiologist who wants to utilize light and water resources would choose the dry matter production over *T* as a definition (Dam and Malik 2003). Mathematically *WUE* can be seen as the average slope of the *Y(ET)*-curve evaluated at the yield of interest.

(4). $$WUE_{mat} = \frac{\Delta Y}{\Delta ET}$$

Most experiments found in literature give cumulative *Y* and actual *ET* values over the whole growing period of the cereal. The concept by Falkenmark et al. (2004) also refers to seasonal values. In this thesis *WUE* in kg/m³ refers to the view of agronomists respectively hydrologists and is defined as the relation of total saleable, seasonal yield (*Y)* to cumulative, seasonal, actual evapotranspiration (ET_a).

(5). $$WUE = \frac{Y}{ET_a}$$

As Y/ET_a is a biological response ratio rather than an efficiency term, many scientists are referring to the term Crop Water Productivity (*CWP*). Monteith criticized the *WUE* term and pointed out that no theoretical limits exist as reference, as should be the case for efficiency in an engineering sense (Evans and Sadler 2007). Therefore the term *CWP* is possibly more adequate for describing the relation.

In this thesis the definition of *CWP* is ET_a/Y in $m^3\ kg^{-1}$, which refers to the concept of Falkenmark et al. (2004). The authors do not clearly state if *Y* or total aboveground biomass (*BM*) is used for the definition. Most common unit for *CWP* and *WUE* is $kg\ m^{-3}$, which is reasonable, because if the magnitude increases, this means an improvement. Falkenmark et al. (2004) use $m^3\ kg^{-1}$ to define *CWP*, which can lead to confusions, since a decreasing value means an improvement. For the reason of a better comparability of the concept of Falkenmark et al. (2004) and to investigate the water balance terms of the more differentiated approach, both expressions (*CWP,WUE*) were retained.

In order to do the global estimates with the concept another water productivity term has to be introduced. The productive green water productivity or transpiration productivity (see equation (6)) WP_T in $m^3\ t^{-1}$ or mm ha t^{-1}.is the relation of seasonal transpiration to saleable yield. It is assumed that WP_T is difficult to influence within a given ecosystem setting, and is largely determined by crop physiology and climatic conditions (Falkenmark et al. 2004). Therefore on average WP_T is considered conservative for a specific climate and crop. Although in physical reality WP_T differs between different crops and varieties of the same crop. For the estimate of the global potential of a vapor shift WP_T is considered constant, despite its obvious variation on a big scale.

(6). $$WP_T = \frac{T}{Y}$$

(7). $$CWP = \frac{1}{WUE} = \frac{ET_a}{Y} = WP_T \frac{ET_a}{T}$$

CWP is the crop water productivity containing the seasonal actual green water flux per saleable yield in $m^3\ kg^{-1}$ or mm ha t^{-1}

Falkenmark et al. (2004) state that the possibility of achieving a vapor shift mainly lies in the improvement of *T/ET*. A constant WP_T implies that increasing *T/ET* also raises the *Y* level and therefore improves *CWP* without additional total *ET*. The described definition of *CWP* respectively *WUE* is a simplification of a more differentiated approach explained below.

b) Differentiated Approach of viewing water use efficiency

To assume productive green water productivity constant, factors out the relation of *Y* to total above ground biomass (*BM*). This relation known as harvest index (*HI*) is assumed to be subject to dynamic changes with varying agricultural practice. Out of personal communication with Wim Bastiaanssen a more differentiated approach was obtained, which divides WP_T into harvest index (*HI*) times transpiration efficiency (*TE*). A similar conceptual approach was also found in an article by Turner (2004) and its origin is unclear. This more differentiated approach seems to be more suitable for investigation in chapter 4, where the expectation is a varying *PD* not just to influence *T/ET* but also the yield component and therefore *HI*.

$$(8).\qquad WUE = \frac{Y}{ET_a} = HI * TE * T / ET_a = \frac{Y}{BM} * \frac{BM}{T} * \frac{T}{ET_a}$$

Due to improvement of agricultural practices and introduction of new cultivars, *HI* experienced considerable improvement the last decades. The 20th century was probably the century of improvement in *HI,* while in future focus possibly is on T/ET_a , when improving *WUE.* The differentiated approach considers two oppositional parameters with an adequate accuracy. *Y* normally needs to be maximized while water use by ET_a should be minimal if water is scarce.

Transpiration efficiency

TE is assumed to be constant for a certain vapor pressure deficit and a certain crop according to the current state of the art of science. This approach was first put into the form of an equation by Bierhuizen and Slatyer (1965) and it is assumed to be valid for various climates. The vapor pressure deficit is the difference between saturated vapor pressure of the air (*e**) and the actual vapor pressure (*e*). *e*-e* varies during the course of the day, from day to day and also seasonally. Increasing the deficit lowers *TE*. The common used approach is shown in equation (9).

$$(9).\qquad TE = \frac{BM}{T} = \frac{k_c}{(e* - e)}$$

k_c is assumed to be constant for a specific crop. k_c is higher for C_4 (maize, sorghum, sugarcane etc.) than for C_3 plants (wheat, barley etc.). C_4 crops transpire more efficiently then C_3 crops, assuming an equal vapor pressure deficit. Species that have the C_4 pathway of photosynthesis have higher *TE* than C_3 plants. C_4 plants tend to have a higher temperature optimum and grow in the warmer periods of the year with high vapor pressure deficits. The selection of genotypes with the ability to grow in cooler temperatures has allowed them to be grown in temperate regions, where their higher *TE* can result in higher yields than C_3 species on the same amount of rainfall. Thus also the selection of species can be a means to improve *Y* and *WUE*.
Payne (2000) states that k_c is not really a constant because environmental factors also have an influence. For instance an observation was that drought can increase e.g. k_c of pearl millet. There are also physiological responses that might increase k_c during water stress, including increased conversion efficiency of photosynthates to biomass because of greater starch production and the proportionally greater effect of partial stomata closure on reducing water flux than on reducing CO_2 flux. It is also well known that k_c decreases when nutrient deficiency is severe (Payne 2000).

As (e^*-e) increases in sparse canopies relative to that of dense canopies, *TE* is linearly reduced. Figure 2 below gives an example for that fact. As plant spacing increases from narrow to wide, the slope of *BM/T* decreases and so does *TE*.
This assumption will be evaluated by a variation in planting density in chapter 4.

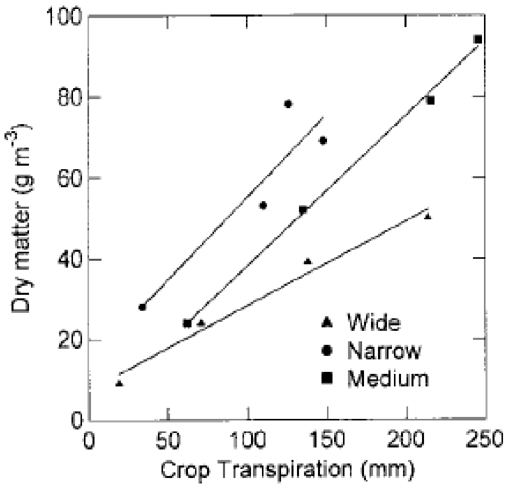

Figure 2 Relation between biomass and transpiration of pearl millet as affected by plant spacing (Payne 2000)

To what extent is *TE* constant and therefore not influencing *WUE* will be evaluated both in chapter 3 and 4.

2.4 The Vapor Shift Concept

2.4.1 The basic Idea of shifting Soil Evaporation towards Plant Transpiration

CWP shall be improved by increasing T/ET_a. Falkenmark et al.(2004) state that a reduction of the non productive evaporation flow can serve to reach this improvement. To visualize the assumptions Figure 3 shows the assumed dynamics of the vapor flows in mm plotted as a function of *Y* in t ha^{-1}. In principle there are three options to achieve a higher T/ET_a respectively a lower E_a/ET_a ratio and thus to use the green water flow more effective.

1) Early season soil evaporation
   To reduce early season E_a that occurs from bare soil before full emergence of the crop. The magnitude is determined by the intercept of the evaporation line with the ordinate in Figure 3. An improvement means to shift the intercept downwards the y - axis.

2) Increased canopy cover
   Reduction of non productive E_a in favor of productive *T* as a result of increased canopy cover, which is determined by the slope of the evaporation line in Figure 3. An improvement shall be achieved by increasing the slope of the *E* course respectively turning the curve downwards.

3) Increasing yield levels
   To improve the T/ET_a ratio by progressively increasing yield levels through improved agricultural management. Moving along the *T* line in Figure 3 will improve the relation E/ET_a and T/ET_a, but also increase total *ET*.

The theoretical expected course of the green water flows suggests that while *T* increases linearly with increased plant growth and *Y*, *E* generally decreases progressively with increased canopy cover as a result of shading.
Only early season E_a and increased canopy cover are assumed to be a true “crop per drop” improvement and thus a “real vapor shift”. Increasing the *Y* level also increases T/ET_a, but requires more consumptive water with every increment of yield for a *WUE* improvement. Falkenmark et al. (2004) hold that experience shows that improved management can result in a raise of *T* and *Y*, while *ET* stays constant or is reduced.

They remark that in hot and dry environments with sparse crop stands and low *LAI* (< 2 m^2 m^{-2}) it is difficult to reduce *E* in favor of *T*, due to a low shading effect of the canopy and a high energy influx through advection. Unfortunately this also indicates that "vapor shifts" are most difficult to achieve in agricultural systems with present low *Y* rates (< 2 t ha^{-1} corresponding to about LAI = 2 m^2 m^{-2}) and high food demands, the savannas. But exactly these agro eco systems would be in most need of such a shift.

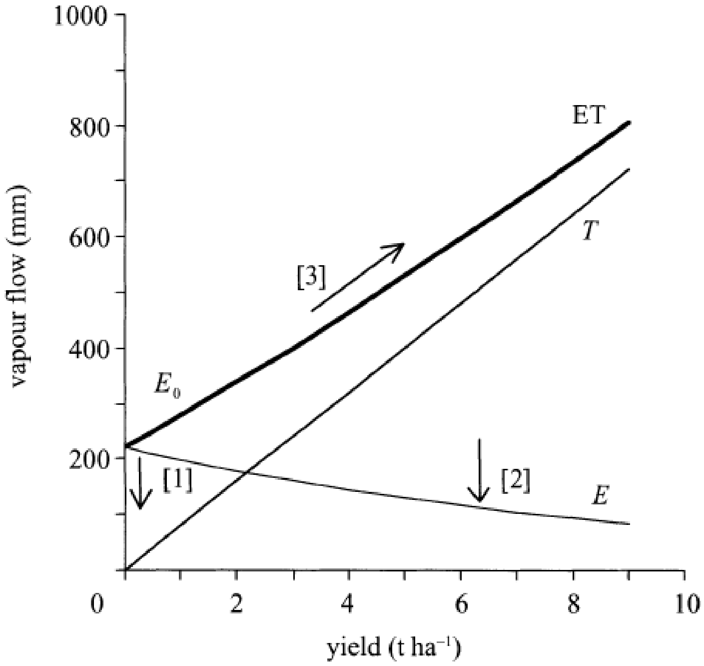

Figure 3 Theoretical course of the green water flows over yield, principal options for improving crop water productivity (Falkenmark et al. 2004)

A crucial assumption for the concept is to consider *CWP* respectively *WUE* with a dynamic character over the *Y* range, especially in the lower ranges. Generally it is supposed that about 1500 m^3 (150 mm ha^{-1}) of consumptive green water is required to produce an additional ton of grain. This conservative view would picture *CWP* as a parallel line to the x – axis in Figure 6 respectively Figure 7. Falkenmark et al. (2004) state, that instead the amount of green water required will actually decrease with every *Y* increase. The decrease in water requirement is largest in the lower *Y* range, where E_a is assumed to be highest. This dynamic character of the *CWP* – *Y* relation can be seen in Figure 4 and Figure 5. The *CWP* course in these two figures differs due to different used units. The illustrations show *CWP* in kg mm^{-1} ha^{-1} in Figure 4 and in m^3 t^{-1} in Figure 5.

Falkenmark et al. (2004) argue that there is a certain *Y* - level (4 - 5 t ha^{-1}) above which little E_a is occurring. From this threshold on the whole remaining green water flow for every incremental *Y* increase then is productive *T*. At high *Y* levels *CWP* may therefore be constant and the common, general approach of a constant *CWP* increase with additional rise of the *Y* is valid. Rockstrom (2003) argue that for the vast majority of farmers in the world this assumption does not apply, instead they operate at the dynamic *Y* range between 0.5 and 3.0 t ha^{-1}. Thus the *CWP* course indicates a great improvement potential.

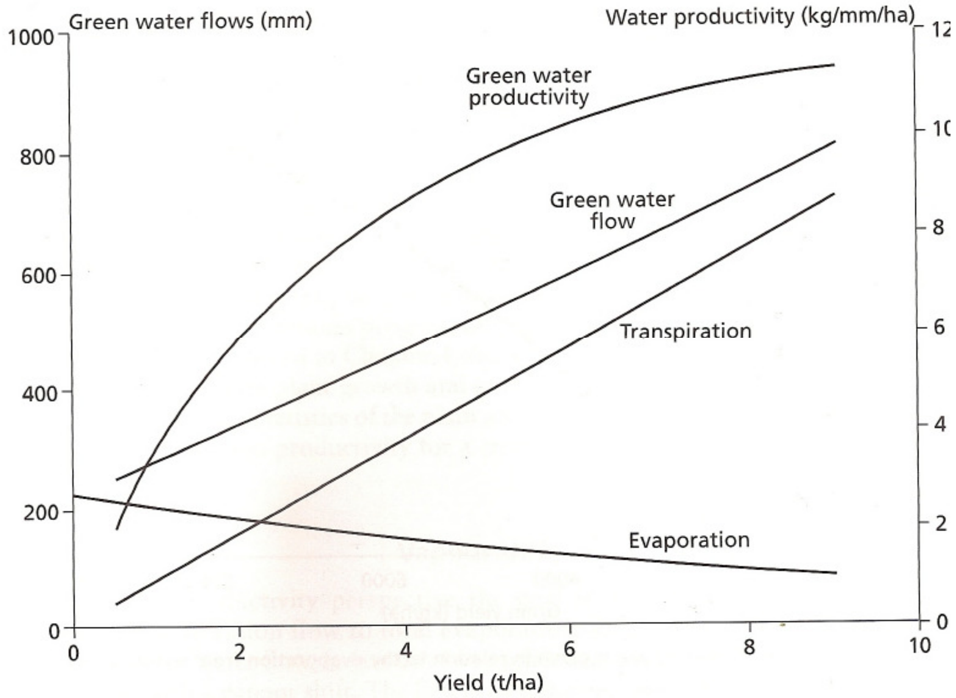

Figure 4 Green water flows as a function of yield and the dynamic character of the crop water productivity (Falkenmark et al. 2004)

The data of Figure 5 originates from ET_a - flow and *Y* observations for different tropical grains and the calibrated *CWP* - function is described in equation (10). WP_T is assumed to amount 800 m^3 t^{-t} respectively 80 mm ha t^{-1} and b = -0.3.

A simple *CWP* model was developed (shown as the line in Figure 5) and calibrated against the empirical observations.

This *CWP* function can not be interpreted as a regression line with the aim of achieving the best statistical correlation, but instead it is a biophysically based function that distinguishes E_a and T flow and their principle influence on Y and CWP dynamics.

$$(10). \qquad CWP = \frac{WP_T}{1 - e^{bY}}$$

b is a constant, that determines the rate of decline in E_a with increased crop canopy and therefore the Y level at which E/ET_a reaches its minimum.

Rockstrom (2003) states that b is climate dependent. $b > -0.3$ in dry and hot climates with high turbulence due to sparsely cropped systems, indicating that E_a will remain a high portion of total green water flow when Y progressively increases. Whereas in cooler and more moist systems with denser vegetation $b < -0.3$.
Because there is a variation in WP_T between different crops and varieties of the same crop, each combination of crop and environment will generate its own *CWP-Y* function.

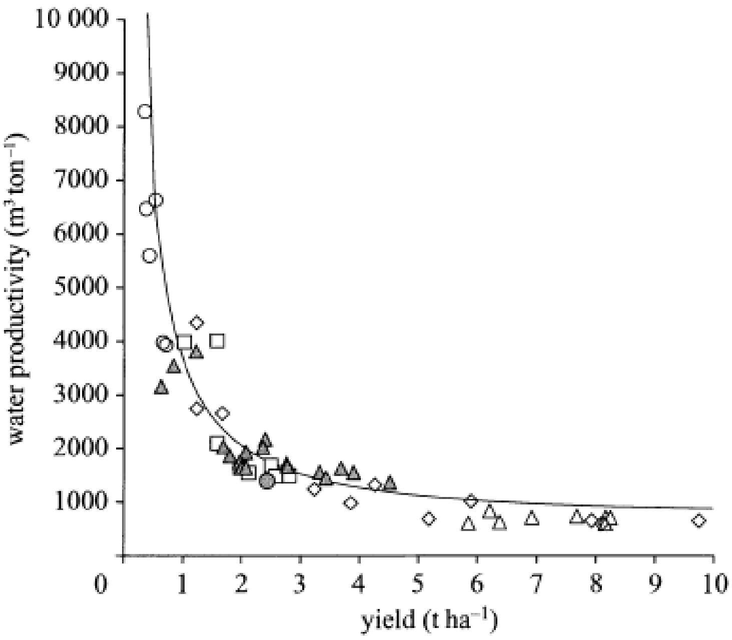

Figure 5 Crop water productivity as a function of yield, open squares, tropical grains; closed circles, maize; open triangles, sorghum; open diamonds, maize; closed triangles, millet; open circles, millet. (Rockstrom 2003)

2.4.2 Management Possibilities to reach a Vapor Shift

To give an overview of possible measures for reduction of the predicted green water deficit by 2050, management strategies are listed below in Table 1. First column describes the principle option of achieving an improvement of water productivity. The process in the second column refers to Figure 3. The basic form of the table is taken from Falkenmark et al. and completed with additional information. The effect of each measure is additionally explained below the table.

Falkenmark et al.(2004) state that by improving the T/ET_a ratio by the suggested management options will normally imply a simultaneous "vapor shift" if the climate and agricultural opportunity is there.

Water productivity strategy	Process	Management options	Effect
Vapor shift	(I)Early season evaporation	Dry planting Mulching Conservation tillage Multiple cropping Optimum planting density	Quick crop establishment Reduced evaporation flow Less soil exposure to atmosphere Maximize canopy cover Reduced evaporation flow with regard to the climate
	(II)Reduce evaporation flux with increased canopy cover	Multiple cropping Mulching Windbreaks Agro forestry High planting density	Reduced energy inflow through advection Reduced energy inflow through advection Reduced energy inflow through shading
Improve T/ET ratio, increase yield levels	(III)Increase plant water uptake Maximize productive green water flow	Improved crop varieties Water harvesting Soil and water conservation Soil fertility management Conservation tillage Multiple cropping Optimum planting density	Dry spell mitigation Maximize infiltration and water holding capacity Maximize plant water uptake Maximize infiltration water holding capacity and rooting depth Maximize transpiration Maximize transpiration

Table 1. Management strategies to improve green water productivity

To minimize early season soil evaporation several cultural practices are suggested. At dry planting respectively dry seeding, farmers are sowing into dry soils. The seeds emerge on the opening rains of the season and thereby gain several days more growth than would be the case if they waited to sow until after the rain (Turner 2004). A mulch layer acts like an insulating layer and therefore reduces the energy inflow through advection and hence the evaporation flow. Within an increased canopy cover it also operates beneficial by retaining soil moisture between the crop rows.

Conservation tillage practices aim to leave a protective mulch cover at the soil surface. Inversion and soil disturbance are minimized by sowing the seeds with the use of narrow tines. The effect that contributes beneficial to a “vapor shift” can be explained by less soil exposure to the atmosphere. Additionally infiltration, water holding capacity and rooting depth increases. At zero tillage systems soil tillage is completely omitted, confined just for the action of seed drill.

Multiple cropping strategies shall maximize the canopy cover, reduce the energy inflow through advection and therefore decrease E_a in favor of T. There are several options to achieve that:

- Double cropping:
  A second crop is planted after the first has been harvested, e.g. winter wheat and summer maize. The crop season is fully exploited without a fallow period.

- Intercropping
  An additional crop is planted in the spaces available between the main crop. E.g. pearl millet with cow pea in semiarid west Africa.

- Relay cropping
  The second crop is started amidst the first crop before it has been harvested.

An optimum in planting density is not mentioned as a management option by Falkenmark et al. (2004) but in the thesis considered as a improvement possibility that requires low effort. Assuming that water availability is not restrictive in a certain climatic and soil specific environment a magnitude of stand density respectively a distance between the crop rows should exist, which leads to an optimum of *WUE.*

Agro forestry, windbreaks and hedges have a reduction effect of the wind speed near the soil surface and therefore energy inflow through advection decreases, which acts positively on the T/ET_a ratio.

Improving crop varieties has been a successful measure to enlarge crop production in the 20th century. In future crop genetic manipulation possibly contains a considerable potential for *CWP* improvement. For field application selected crop varieties with growth characteristics and tolerances, e.g. heat, salinity etc., can be matched to site specific conditions.

Depending on the genetic and environmental interaction, genetic improvement will play a major role, but is unlikely to create major shifts in *WUE*. The potential of giving an immediate return on research is greater in cultural and management practices.

Genetic improvements are likely to bring the greatest increases in yield and hence in WUE in water limited environments in the 21 century, but the role of management in increasing yield in the past and in the future should not be overlooked.

Water harvesting can be a proper measure to reduce dry spell mitigation; therefore water availability is secured during all crop development stages.

Improving soil fertility management can have a positive effect on water use efficiency. Applying fertilizer can be a proper measure to ensure early canopy formation. Fertilized crop earlier forms a closed canopy than crop without manure if water scarcity is not the constraint. This approach needs to be used cautiously, because in some cases the vegetative phase may result in early depletion of stored soil water and lead to insufficient water availability during grain filling.

E.g. an experiment by Allen (1990) with barley resulted in an 10 % reduction of E_a by applying fertilizer, from 77 % to 67 % of total ET_a. The impact on ET_a was little during this examination.

3 Practical Evaluation of the global Estimates using the Vapor Shift Concept

3.1 Introduction

The basic approach introduces global assumed crop growth and water scarcity data on which estimates of Falkenmark et al. (2004) are based. Chapter 3.2 also introduces detailed research questions for the evaluation of the vapor shift estimates.
In Chapter 3.3 empirical gained data from literature is compared to theoretical assumed green water over yield courses of the concept. Ranges of E_a/ET_a and *WUE* found in literature will be introduced. Each suggested option of the concept; early season E_a, increased canopy cover and increasing yield levels, will be analyzed in chapter 3.3.1, 3.3.2 respectively 3.3.3. The focus in chapter 3.3.4 will be on *LAI* and its relation to E_a/ET_a. In a final step conclusions and deficiencies of the evaluation are explained.

3.2 Basic Approach

Table 2 presents the basic assumptions concerning crop growth, population growth and water requirement data on a global scale and is used to contextualize the potential contribution of a vapor shift to reduce global water deficit. The last column indicates calculation steps that are done within the table. The estimates are taken from Falkenmark et al. (2004) and are partly based on FAO future predictions. The predictions expect *Y* level of major rainfed cereal crops to increase from currently 2.1 t ha^{-1} to 3.5 t ha^{-1} in 2050. *Y* growth is expected to increase by 2.5 % between 1995 and 2030 and by 1.5 % between 2030 and 2050. The global cultivated area is also assumed to increase from currently 466 to 600 mio ha within the next 50 years. The growth rate of cultivated area from 0.09 % is expected to be reduced to 0.05 % from 2030 on. Global production therefore should increase from currently 1200 mio t ha^{-1} to 1900 mio t ha^{-1} in 2030 and 2100 mio t ha^{-1} in 2050. (*Calculation for the current production of cereals could not be reproduced. Multiplying position 1 with position 5 from results in 979 mio t ha^{-1}. Either there is a mistake by Falkenmark et al. (2004) or the calculation is done different and not explained in detail.)

World population is estimated to increase from currently about 5.7 E+09 to 9.7 E+09 people in 2050. Averaged present water use for human diets (agricultural green water use) is estimated to account for 1200 m³ c^{-1} y^{-1}. Because currently about 800 mio people are still suffering from undernourishment, the level of desired water needs is set to 1300 m³ c^{-1} y^{-1}. From these figures a current total green water use for food of 6800 km³ a^{-1} is derived. Irrigation is assumed to contribute 1800 km³ a^{-1} and rainfed agriculture 5000 km³ a^{-1}. Still there is a lack of 2200 km³ a^{-1} to eradicate current undernourishment which would result in a total green water demand for food of 9000 km³ a^{-1}. A population figure for 2050 and a higher assumed water need for human diets result in a water requirement for food of 12600 km³ a^{-1} in 2050. Subtracting the contribution of irrigated and rainfed agriculture leaves an estimated water deficit of 5800 km³ a^{-1} by 2050.

Real "vapor shift" measures (early season E_a and increased canopy cover) are assumed to minimize this water deficit by 330 km³ a^{-1}, this is equivalent to 5.7 % of the total deficit. Present E_a/ET_a is assumed to amount for about 50 % of the green water flow. Improvements in agricultural and management practices should decrease E_a/ET_a to 0.31 by 2050. The focus of the estimates is on the major cereals in developing countries where the dominant share of tropical agriculture takes place. In these regions E_a losses are expected to be high and thus also the potential for improvement.
The estimates of Table 2 have several uncertainties. The difficulty in predicting population figures, growth rates in cereal production and estimates of cultivated area grows with an increasing, considered period of time. The improvement potential of a global vapor shift is based on figures, which are compared with experiments found in literature. The arising question is, if the figures hold for a check with experimental data.
A literature search resulted in 13 experiments that allowed a separation of soil evaporation and plant transpiration. Also other relevant data concerning *CWP* was collected to build up a database for answering the research questions.

Pos.	Magnitude	Unit	Remark	Calculation
1	2,1	t/ha	Average yield level of major rainfed cereal crops currently	input
2	2,5	%	Growth rate of yield level between 1995 and 2030	input
3	1,5	%	Growth rate of yield level between 2030 and 2050	input
4	3,5	t/ha	Average yield level of major rainfed cereal crops in 2050	input
5	466	mio ha	Global cultivated area currently	input
6	0,09	%	Growth rate of cultivated area between 1995 and 2030	input
7	0,05	%	Growth rate of cultivated area between 2030 and 2050	input
8	600	mio ha	Global cultivated area in 2050	input
9	1200	mio t/y	Global production of cereals currently	1 x 5 *
10	1900	mio t/y	Global production of cereals in 2030	input
11	2100	mio t/y	Global production of cereals in 2050	4 x 8
12	5,7E+09	people	Population currently	input
13	9,7E+09	people	Population in 2050	input
14	1200	m³/c.y	Present water needs for human diets	input
15	1300	m³/c.y	Desired water needs for human diets	input
16	1800	km³/y	Consumptive irrigation water currently	input
17	5000	km³/y	Consumptive water in rainfed agriculture currently	input
18	6800	km³/y	Total green water use for food currently	12 x 14
19	2200	km³/y	Water need to eradicate current undernourishment	input
20	9000	km³/y	Desired total green water use for food currently	18 +19
21	12600	km³/y	Water requirement for food in 2050	13 x 15
22	5800	km³/y	Water deficit that has to be minimized by 2050	21 - 18
23	1000	km³/y	Contribution of irrigation	input
24	4800	km³/y	Contribution of rainfed agriculture	22 - 23
25	**330**	**km³/y**	**Potential contribution of a "vapor shift"**	input
26	**5,7**	**%**	**Percentage of the water deficit by 2050**	25 / 22 *100
27	**0,57**	**kg/m³**	**Estimated *WUE* currently**	input
28	**0,80**	**kg/m³**	**Improved *WUE* by 2050**	input
29	**0,49**	**-**	**Estimated E_a/ET_a ratio currently**	input
30	**0,31**	**-**	**Improved E_a/ET_a ratio by 2050**	input

Table 2. Crop growth, population growth, water requirement data and the potential contribution of a vapor shift to reduce global water deficit

Research questions

The main aim is to find a reasonable order of magnitude for seasonal E_a for a preferably broad range of different climatic regions in order to get a good average value for evaluation. The indicated wide range (Chapter 3.3.1) of E_a/ET_a indicates that it is difficult to find a reasonable mean value for evaluation. With regard to E_a it is tried to distinguish between the development stages (initial, crop development, mid season, late season) of the plant in detail. Of special interest is to find an order of magnitude for early season E_a. The course of the theoretical approach and the experiments will be compared and is shown with the same arithmetic chart. Theoretical assumptions will be analyzed and their relevance will be questioned critically.

An idea is also to get quantitative information about *WUE, HI, TE, Y, PD* and *LAI*. *LAI* is of crucial interest. Which relation is found in field experiments between *LAI* and E_a/ET_a respectively T/ET_a? What does the relation between LAI over DAS look like? Possible shortcomings of the concept respectively the estimate will be analyzed and it is tried to give an outlook for further research on this topic.

3.3 Analysis and Discussion

3.3.1 Analysis and Discussion: general

The search resulted in papers describing 43 experiments, from which just 13 allowed a seasonal separation of T and E_a. Although other investigations dealt with the topic of separation of vertical water fluxes respectively minimization of soil evaporation, unfortunately they gave no information about seasonal magnitudes. The data was stored in a database using Microsoft “excel” as a tool for further analytical work. The database is used for investigation of water balance terms, for showing possible relations among them and for evaluating the estimations of the concept presented by Rockstrom (2003) respectively Falkenmark et al. (2004).

The climatic characteristic of experimental data can be described with type C (temperate) respectively B (dry) according to Koeppen classification (Kastanek, 2005). 11 experiments were undertaken in a humid temperate climate, mainly Mediterranean. This fact has to be kept in mind during evaluation, as Falkenmark et al.(2004) state that the greatest potential of “vapor shift” lies in tropical rainfed agriculture, which can be classified with an A climate (tropical).

The examination starts with a comparison of the course of green water flows over *Y* with the theoretical assumed courses in Figure 3. Dashed lines in Figure 6 indicate the predicted theoretical trend of the flows.

A linear regression line is fitted to the data points, the fit in the case of ET_a (R^2 = 0.63) and T (R^2 = 0.75) is reasonable. E_a indicates a great scatter especially in the low *Y* ranges till about 3000 kg ha^{-1}, thus the regression coefficient (R^2 = 0.06) is very low. The regression line is even ascending, which is in contradiction to Figure 3. It is striking that the scatter of all fluxes seems to be bigger in the lower *Y* ranges.

The experimental factors varying are *PD*, row spacing, sowing date, irrigation criteria, mulching, different soil textures respectively the application of fertilizer. Due to soil, climatic conditions and water availability the green water flow is influenced by a large number of parameters. At higher *Y* ranges with sufficient water and nutrient availability and increased *LAI*, the climatic influence on E_a is possibly lower and therefore also its scatter. Perhaps a closer canopy reduces the variation in soil evaporation.

Two data points in the upper left section in Figure 6 are striking due to low *Y* levels despite a high ET_a flow. This experiment was done at the ICARDA institute in Northern Syria with the purpose of investigating the influence of two different row spacings on E_a. Although precipitation would have been sufficient, low *Y* levels were caused due to a frost period prior to anthesis with night temperatures dropping between -5 and -10° C on twelve nights.

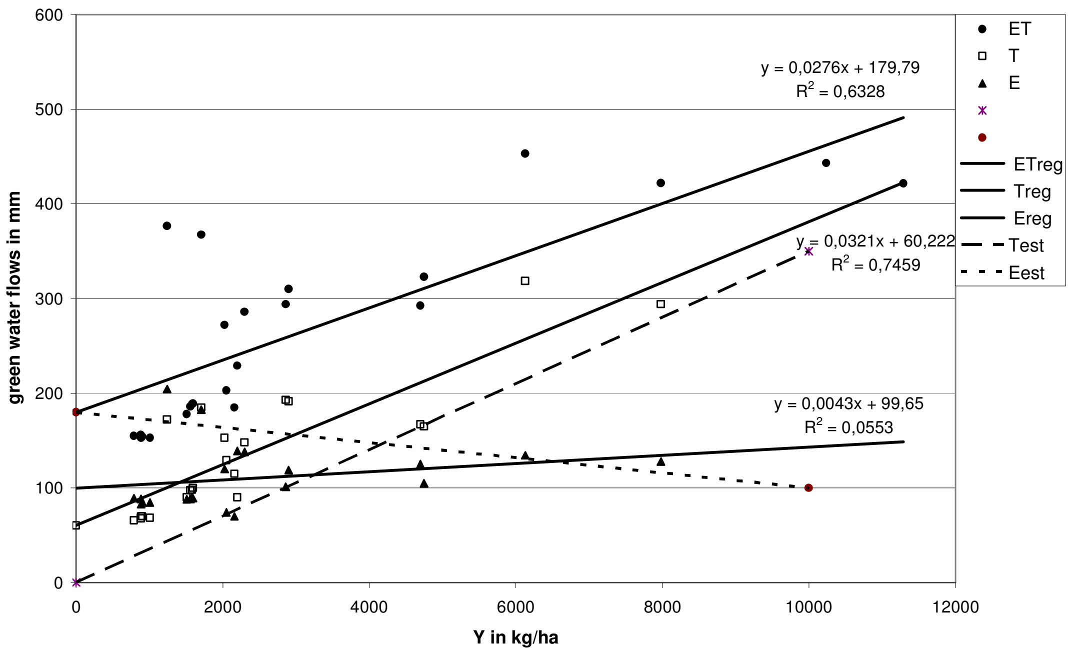

Figure 6 Green water flows as a function of yield from the database, linear regression of the experimental data

The theoretical approach by Falkenmark et al.(2004) suggests a linear course for all green water fluxes as a function of yield. Experimental data shows that this linearity hardly holds for a broad range of different environmental conditions. Probably the bigger the scale of investigation, the bigger is the scattering of data points and the more difficult it is to fit a conceptual function.

Table 3 lists averaged water balance and crop terms from the database. The value for *WUE* lies in the range suggested by Zwart and Bastiaanssen (2004). Differentiating between the two main crops found in the literature search, results in an average value for WUE_{wheat} = 1,00 ± 0.26 kg m^3 (19 values) and WUE_{maize} = 1,88 ± 0.67 kg m^3 (5 values). This approximately corresponds with the median values of WUE_{wheat} = 1.15 kg m^{-3} and WUE_{maize} = 1.88 kg m^{-3} proposed by Zwart and Bastiaanssen (2004). Considering *Y,* the standard deviation already indicates a great variation. The maximum respectively the minimum value accounts for 11298 respectively 792 kg ha^{-1}. Especially E_a, E_a/ET_a and WP_T will be of interest for further evaluation.

parameter	unit	average values	standard deviation
ET_a	mm	296	98
T	mm	167	83
E_a	mm	120	34
E_a/ET_a		0,44	0,14
WUE	kg/m³	1,13	0,54
CWP	m³/t	882	414
TE	kg/mm ha	51,4	10,3
WP_T	m³/t	597	56
Y	kg/ha	3356	2940
HI		0,34	0,12

Table 3. Average values plus standard deviation of water balance and crop terms

Below, possible ranges for *WUE* and E_a/ET_a from other authors give an idea of the order of magnitude and are useful for comparison with the database. Obviously both for the fraction of E_a and for *WUE* a wide range exists.

- ***E/ET*** **range**

30 – 60 % of total *ET* (Xie et al. 2005)

20 – 70 % of the total *ET* (Zhang et al. 1998)

14 – 75 % of total *ET* (Asseng et al. 2001)

A mean value of 110 mm for seasonal E_a is suggested by Asseng et al. (2001) with a possible range from 30 to 170 mm, depending on the seasonal rainfall and soil type. These wide ranges indicate the difficulty respectively the uncertainty that is related with a global estimate of the saving potential of E_a.

- ***WUE*** **range**

To give an idea of the magnitude of *WUE* in kg m^{-3} respectively *CWP* in m³ t^{-1}, ranges for the chosen main crops are listed below (values for *CWP* in brackets):

According to the FAO33 (Bentvelsen and Branscheid 1979):

Wheat: 0,8 - 1,0 (1250-1000)

Maize 0,8 - 1,6 (1250-625)

According to (Zwart and Bastiaanssen 2004):

Wheat 0,6 - 1,7 (1667-588)

Maize 1,1 - 2,7 (909-370)

3.3.2 Analysis and Discussion: early Season Soil Evaporation

Table 4 illustrates figures used for comparison of the estimates by Falkenmark et al. (2004) and the built up experimental database.

pos.	Falkenmark et al	database	unit	Δ (%)	calculation
1	150	77	mm	49	input
2	20	10	mm	50	*1* x3/100
3	13	13	%	-	input
4	200	100	m³/ha	-	*2*/1000x10000
5	600	600	mio ha	-	input
6	**120**	**60**	**km³/y**	**50**	*4* x5x10^6/10^9

Table 4. Reduction potential of early season soil evaporation, Falkenmark et al. (2004) versus the experimental database

First question that arises when checking the potential of the early season E_a is its possible magnitude. Falkenmark et al. (2004) constitute that a value of approximately 150 mm is common for tropical cereals. This is about double the value suggested by the database with 77 +/-26 mm (Table 4 pos. *1*). In the analysis it is tried to establish a value for pre anthesis E_a. There are just five experiments whose data presentation allowed such a separation of E_a and T.

The basic concept does not suggest a clear definition for early season E_a. Is the threshold a determined development stage like e.g. the anthesis or is more appropriate it to define a certain *LAI* level? The latter approach is maybe more adequate, but still remains the question of the threshold value. In literature recommendations of authors range from *LAI* = 2.0 to 3.0; above which T and E_a varies little with increasing *LAI* and thus the possibility of influencing it. Possibly the magnitude depends on climate and environmental factors. For instance at a dry and windy climate with intensive net radiation the critical value for *LAI* is on the upper side of the range. Whereas in moderate climates it is shifted towards lower values. It stays questionable and the value for early season E_a constitutes an uncertainty for the global estimate.

Another figure that has to be viewed critically are the suggested 20 mm ha^{-1} respectively 13 % reduction potential of early season E_a (Pos. *2* and *3* in Table 4). This potential summarizes the measures of mulching, improved timing of sowing, conservation tillage and intercropping. For instance Zhang et al. (2005) suggest reduction potential of E_a with mulch of 10-15 %. This would affirm the magnitude of the basic concept, but only constitutes a range for one certain regional climate and environment (the North China Plain, classification results in a dry B climate according to Koeppen). The reduction potential seems to be limited, as the evaporative demand can not be influenced and it is especially high in hot and dry environments.

13 % reduction potential applied on the magnitude of E_a in the database results in an absolute value of 10 mm ha^{-1}. Pos. *4* in Table 4 shows the absolute reduction potential per ha. Multiplying this with the predicted cultivated area of 600 mio ha in 2050 (Pos. 5 in Table 4) results in a global annual early season vapor shift of 60 km³ y^{-1}. This accounts for only 50 % of the potential constituted by Falkenmark et al. (2004) (Pos. *6* in Table 4). Total season E_a of the database accounts for 120 mm, which is still 20 % lower then the value suggested for early season E_a suggested by Falkenmark et al.(2004).

3.3.3 Analysis and Discussion: increased Canopy Cover

This chapter focuses on the evaluation of shifting E_a towards T due to increased canopy cover. The estimates of Falkenmark et al. (2004) and those based on the database are summarized in Table 5. The basic concept suggests that 49 % of the green water flow is E_a. The result of collected experiments amounts to 44 ± 14 %, which constitutes a difference of 5 %. Taking the median values of proposed ranges of E_a/ET_a from chapter 3.3.1 results in about 45 %. Thus it seems to be reasonable to assume an average value that is positioned in the range of 40 to 50 %.

Negative values in the calculation indicate an increase of a flow, due to the fact that a reduction is assumed desirable and therefore seen as positive. Within the prediction of Falkenmark et al. (2004) there is a global reduction potential of E_a = 214 km³ a^{-1} due to increased canopy cover. Compared to this estimate, the database results in a global potential of 151 km³ a^{-1}; this constitutes a difference of 29 %.

Reduction potential of E_a/ET_a due to increased canopy: 18 %		Falkenmark et al.		database	
parameter	**unit**	**currently**	**2050**	**currently**	**2050**
E_a/ET_a		0,49	0,31	0,44	0,26
Y	t/ha	2,1	3,5	2,1	3,5
WP_T	mm.ha/t	80	80	60	60
$T = WP_T*Y$	mm	168	280	126	210
$T/ET_a = 1 - E_a/ET_a$		0,51	0,69	0,56	0,74
ET_a	mm	329	406	225	284
$E_a = ET_a - T$	mm	161	126	99	74
ΔE_a	**mm**	**36**		**25**	
ΔE_a	**m³/ha**	**356**		**252**	
applied on 600 mio ha	**km³/y**	**214**		**151**	
ΔET_a	**mm**	**-76**		**-59**	
ΔET_a	**m³/ha**	**-764**		**-588**	
applied on 600 mio ha	**km³/y**	**-458**		**-353**	

Table 5. Global vapor shift potential due to increased canopy cover: 18 %, Falkenmark et al.(2004) versus database results

The estimate also includes a FAO predicted *Y* increase from 2.1 to 3.5 t ha^{-1}, which implies an increase in total ET_a. The global annual increase of ET_a amounts to 458 km³ y within the basic assumption in contradiction to 353 km³ y^{-1} for the database, which is 23 % less. An additional 458 km³ y^{-1} would even increase the water deficit by 7.9 %, that has to be minimized by 2050 (5800 km³ y^{-1}). This constitutes a considerable rise in consumptive water resources and therefore it is critical to view an increased canopy cover in combination with *Y* increase as vapor shift measure that reduces water deficit.

Despite of this, the order of magnitude of E_a reduction seems to be comparable, there are great uncertainties with $\Delta E_a/ET_a$. The same estimate was done in Table 6 with an E_a/ET_a reduction potential accounting for 10 % instead of 18 % by 2050. The minus indicates even a global increase in E_a accounting for 55 km³ y^{-1}. This constitutes a difference in soil evaporation flow of 126 % to the basic assumption.

There is a threshold for the reduction potential value below which the E_a in absolute terms is increasing despite E_a/ET_a is decreasing. This limit was detected both for Falkenmark et al. (2004) and the database at about 12 %. Above this threshold the assumption of a reduction of the absolute value of E_a is valid. Below the threshold soil evaporation flow is negative and thus increasing.

Reduction potential of E_a/ET_a for the database due to increased canopy: 10 %			
		currently	2050
E_a/ET_a		0,44	0,34
Y	t/ha	2,1	3,5
WP_T	mm.ha/t	60	60
$T = WP_T * Y$	mm	126	210
$T/ET_a = 1 - E_a/ET_a$		0,56	0,66
ET_a	mm	225	318
$E_a = ET_a - T$	mm	99	108
ΔE_a	**mm**	**-9**	
ΔE_a	**m³/ha**	**-92**	
applied on 600 mio ha	**km³/y**	**-55**	
Δ	*%*	**-126**	

Table 6. Global vapor shift potential due to increased canopy cover: 10 %

To illustrate different possible scenarios for E_a reduction, an equation underlying Table 5 and Table 6 was derived. Since both the magnitude of E_a/ET_a and the reduction potential are uncertain factors, the specific estimate is generalized. Derived equation (11) represents ΔE_a as a function of Y, WP_T and $f_E = E_a/ET_a$. Figure 7 illustrates this function for different scenarios. On the abscissa there is the current E_a/ET_a relation and on the ordinate the ΔE_a in km³ y^{-1}, which can either be a reduction (+) or an increase (-). The three graphs illustrate this reduction function for a reduction to E_a/ET_a = 0.2, 0.3 and 0.4 from the current situation, which can be positioned on any point of the x-axis. The intercept of the functions with the x-axis constitute the above mentioned threshold, where ΔE_a is separated either in a reduction or an increase. WP_{T1} and WP_{T2} were both assumed with 60 mm ha t^{-1}, the values for Y_1 = 2.1 t ha^{-1} and Y_2 = 3.5 t ha^{-1} were adopted from Table 2 in Chapter 3.2. f_{E1} varies and $f_{E2} = E_a/ET_a$ (0.2, 0.3, 0.4) matches to the three graphs. For instance, if current f_{E1} = 0.5 is reduced to f_{E2} = 0.2, a global "vapour shift" would amount to ΔEa = +441 km³ y^{-1}. If current f_{E1} = 0.45 is reduced to f_{E2} = 0.4, the vapor shift accounts for ΔE_a = -369 km³ y^{-1}, so to say the soil evaporation flux in absolute terms increases. Equation (11) allows a generation of current and future scenarios for any possible reduction potential, a specific WP_T and certain Y levels.

$$(11). \qquad \Delta E_a = Y_1 \cdot WP_{T1} \cdot \frac{f_{E1}}{(1-f_{E1})} - Y_2 \cdot WP_{T2} \cdot \frac{f_{E2}}{(1-f_{E2})}$$

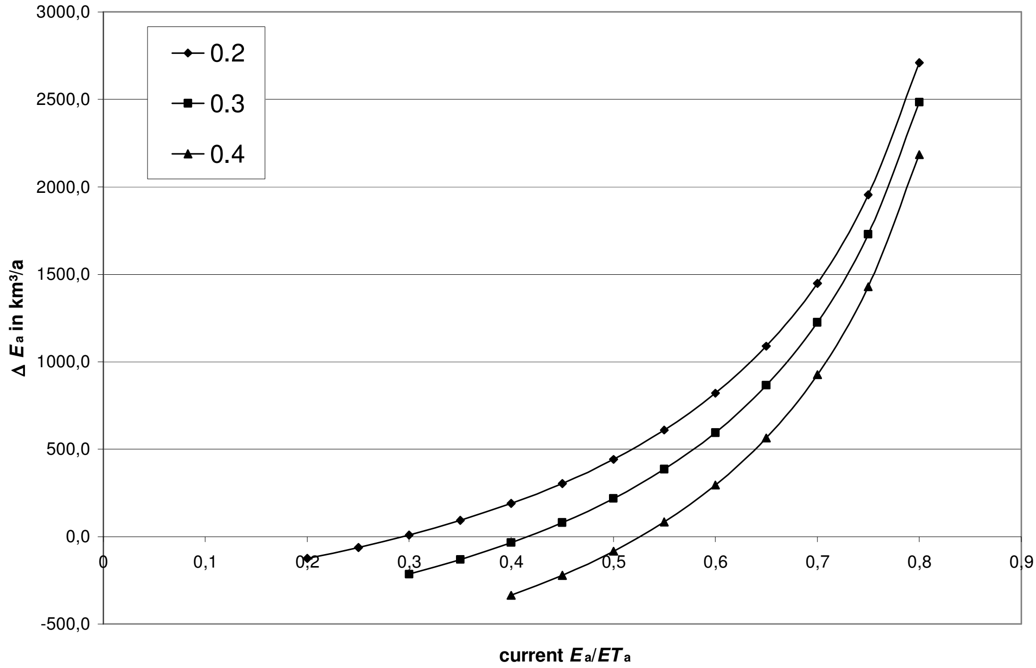

Figure 7 General concept for creating different scenarios of vapor shift potential due to increased canopy cover

3.3.4 Analysis and Discussion: increasing Yield Levels

Increasing *T* respectively ET_a suggests a highly dynamic character of the *CWP-Y* relationship in the low *Y*-ranges till about 4 – 5 t ha^{-1}. Every *Y* increase in this range will improve *CWP* respectively *WUE* more effective than at high *Y* ranges (Falkenmark et al. 2004). The amount of green water required to produce one more ton of grain should actually decrease with every *Y* increase. Collected experimental data shown in Figure 8 confirms the supposed tendency.

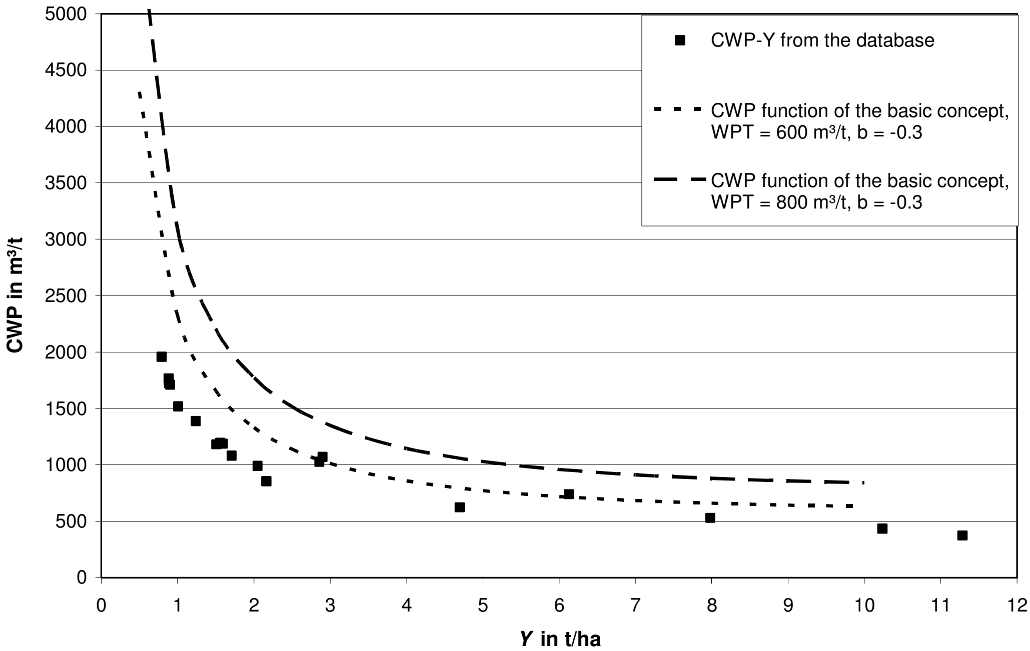

Figure 8 Crop water productivity as a function of yield from experimental data, biophysical crop water productivity - yield function

Figure 8 presents database results within the same arithmetic chart as Figure 5. For reason of comparison *CWP (Y)* from Chapter 2.4.1 is also illustrated in the graph. $CWP = WP_T/(1-e^{bY})$ with $WP_T = 800$ m³ t^{-1} and $b = -0.3$ is represented by upper dashed line in Figure 8. The function underestimates *CWP* due to different climatic conditions (*b* chosen to high) and different cultivars (sorghum, millet maize and other tropical grains instead of mostly wheat and partly maize) which results in a lower WP_T. Choosing $WP_T = 600$ m³ t^{-1} according to the database improves the quality of the fit, but still the function lies above the data points.

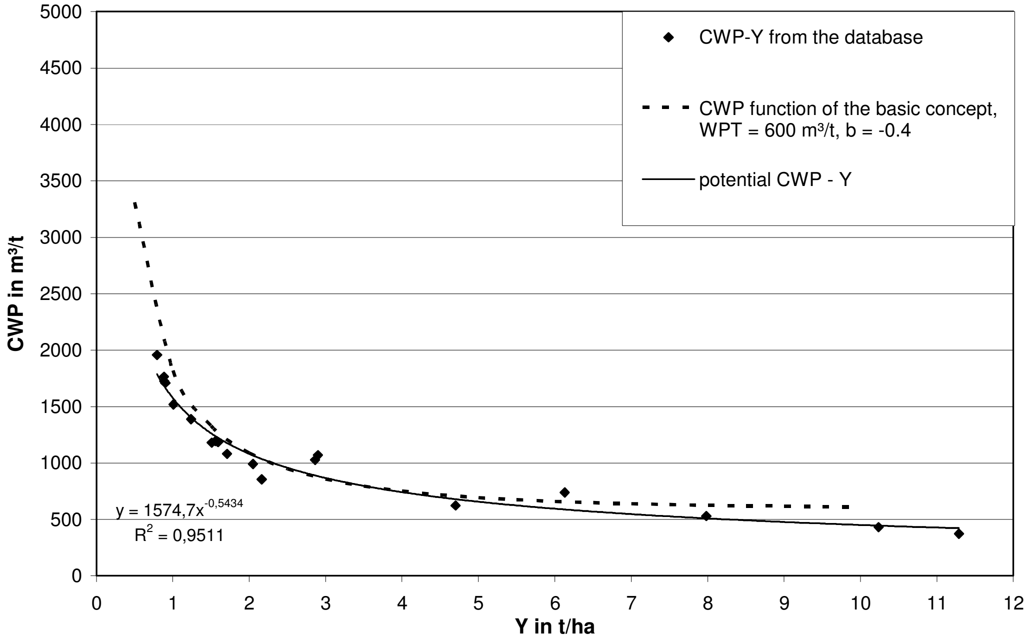

Figure 9 Crop water productivity as a function of yield from experimental data, adjusted biophysical crop water productivity – yield function and fitted regression line

In Figure 9 the constant b was decreased to -0.4, which adapts the function well. Additionally there is fitted a power function with a correlation coefficient R^2 = 0.93. Comparing the graphs also shows a greater dynamic phase in a system with high evaporative demand. If *b* and WP_T increase due to a warmer climate and different cultivars (C_4 instead of C_3 plants), then the shape of the function changes and constancy for *CWP* is shifted towards higher *Y* ranges. Viewing the fitted function in Figure 9 indicates that in temperate climates with systems of lower evaporative demand and where air humidity is retained in the crop stands the static *CWP* mode is reached at lower *Y* levels.

To support the "dynamic" character of the *CWP – Y* relation with numbers, examples will be given for the function fitted to the database in Figure 9. For instance if the *Y* increases by 2 t ha^{-1} from 1 t ha^{-1} to 3 t ha^{-1}, which constitutes a change of 200 %, *CWP* improves by the factor 2.1 respectively by 112%. Viewing the same *Y* increase at a higher range from 5 t ha^{-1} to 7 t ha^{-1}, the improvement of CWP amounts to the factor 1.1 respectively 9 %.

Both in Figure 5 and in Figure 9 *CWP(Y)* seem to underestimate *CWP* at higher *Y* ranges, which indicates a necessity for specification of the mathematical function. At low *Y* ranges, where the greatest potential of improving *CWP* is suspected, the suggested biophysical function seems to match well.

An increase in *Y* also always results in a rise of consumptive water demand; Figure 10 pictures the relation between *CWP* and ET_a for collected experimental data. Despite the scattering, the tendency that an improved *CWP* is related to an increase in ET_a can be observed. A linear regression suggests a three fold improvement of *CWP* from 1500 $m^3\ t^{-1}$ to 500 $m^3\ t^{-1}$ and also indicates a three fold increase in ET_a from about 150 mm to 450 mm. The two parameters are obviously direct proportional.

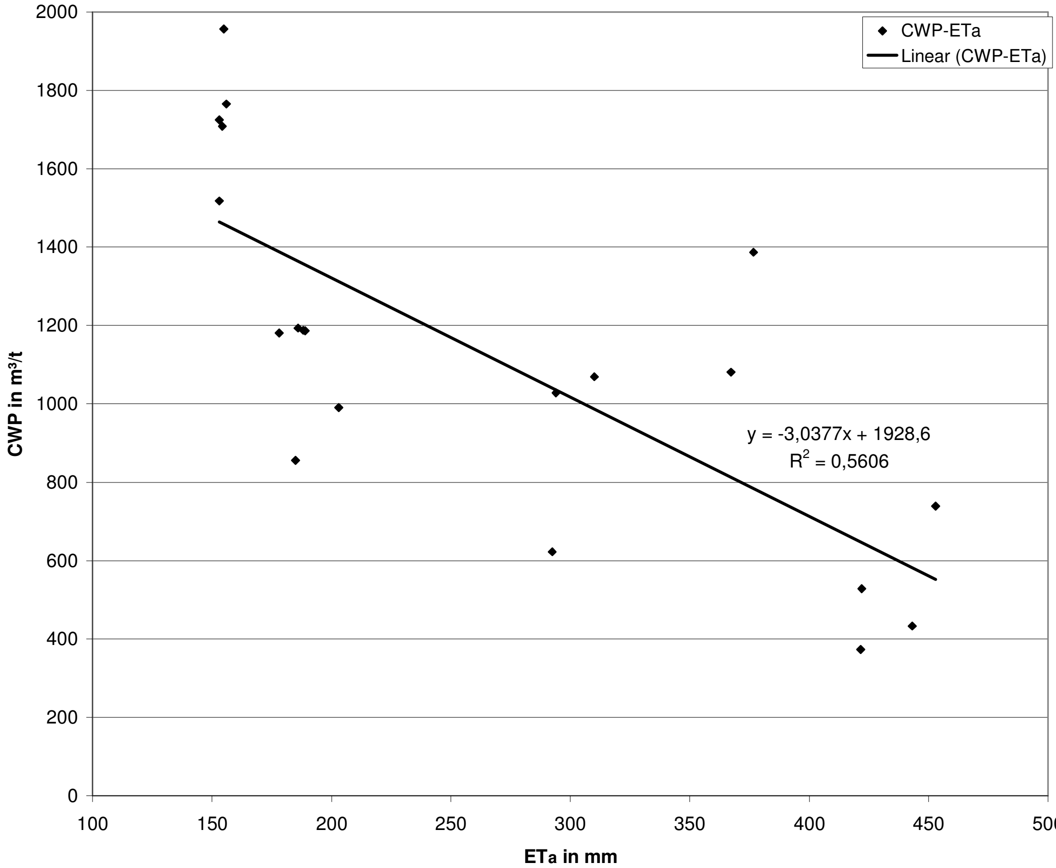

Figure 10 Crop water productivity as a function of actual evapotranspiration for the database results

To summarize the option of increasing *Y* levels: you gain more “crop per drop” by increasing *Y* but it is always combined with the need of an increased drop. An additional consumptive water demand is generated. The challenge will be to achieve *Y* improvements without applying additional water, just by shifting the unproductive E_a towards productive *T.*

3.3.5 Analysis and Discussion: Leaf Area Index

One of the crucial parameters describing the partitioning of E_a respectively T is *LAI*, which was introduced in Chapter 2.2.1. The common approach to describe the relative losses and productive flows with a function of *LAI* are shown with equations (2) and (3), which use the potential green water flows E_p, T_p and ET_p. Collected experimental data gave little information about potential vapor flows. Data of actual green water flows (E_a, T_a and ET_a) was mainly available, but it is not reasonable to evaluate actual green water flows with potential ones, as stress factors minimize the flows within a wide range.

Nevertheless, results from the database approve the tendency of a decreasing E_a/ET_a with increasing *LAI*. Figure 11 shows this context from the collected experimental data (mainly wheat and maize). Maximum, seasonal value of leaf area index (LAI_{max}) is protracted on the abscissa of Figure 11. A greater scattering for the low *LAI* range can possibly occur due to a stronger influence of climatic, atmospheric and soil factors.

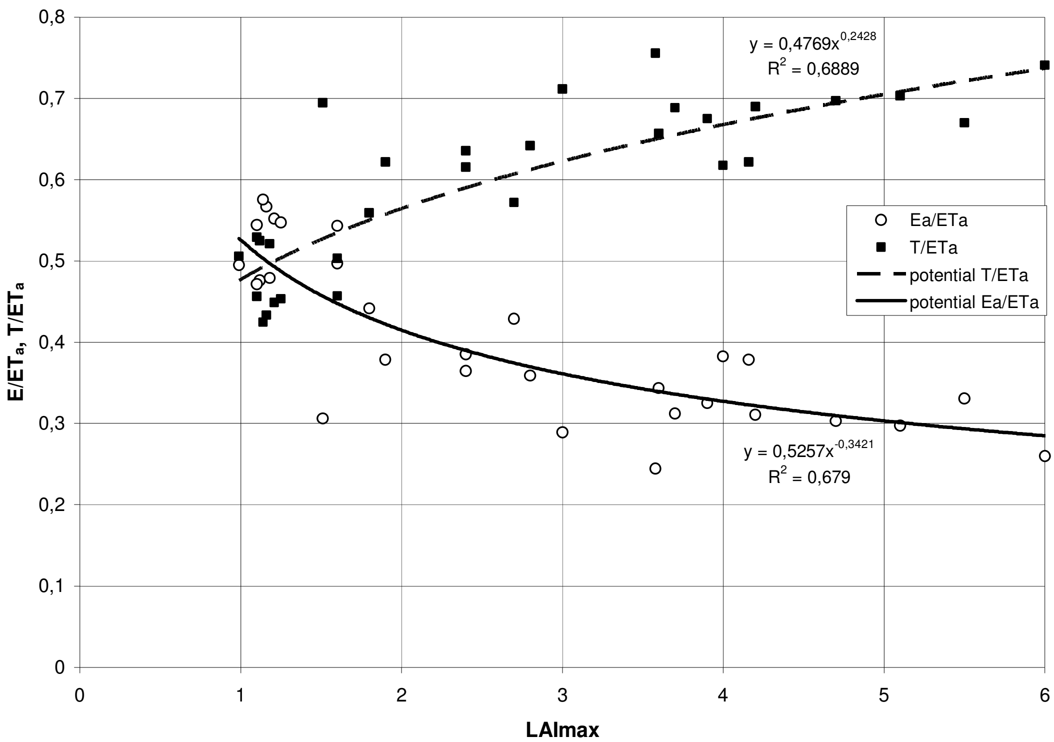

Figure 11 Actual relative evaporation respectively transpiration versus maximum leaf area index for mainly wheat and maize

A *LAI* threshold of 2 is set, which about corresponds to a *Y* limit of 2 t ha^{-1} (see Figure 12). A regression in Figure 12 suggests that *Y* increases linearly with *LAI* (R^2 = 0.9).

Assuming the "vapor shift potential" lies in the low *Y* ranges, the average values below this threshold can be compared with the estimates done in chapter 3.3.3 (increased canopy cover), see Table 7. E_a/ET_a for wheat amounts to 0.50 ±0.06 and for all crops to 0.49 ±0.08 at *LAI* < 2. This corresponds well with the assumption of E_a/ET_a = 0.49 by Falkenmark et al. (2004). The estimate calculates with a reduction potential of 18 % and supposes the order of magnitude with about 20 %.

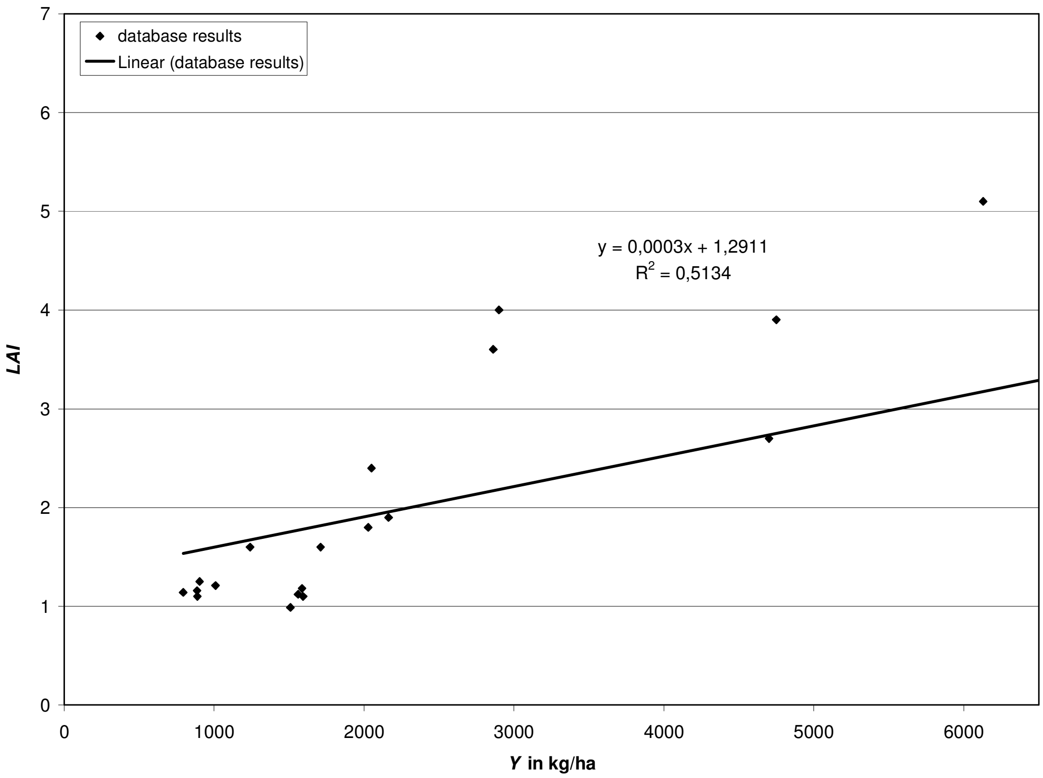

Figure 12 Relation of maximum leaf area index and yield for wheat from the database

The database suggests, that E_a/ET_a on average amounts to 0.32 ± 0.04 for wheat and 0.33 ± 0.05 for all crops when LAI > 2. This constitutes a reduction potential of 18 respectively 17 % due to an increased canopy cover. Thus the comparison of the estimate by Falkenmark et al. (2004) with the database confirms the assumptions concerning the magnitude of the "vapor shift potential" due to an increased canopy cover. Although there is no definition for a certain *LAI* threshold value and it is set arbitrary, above investigation takes away the uncertainty of the reduction potential concerning E_a/ET_a.

E_a/ET_a	wheat		all crops	
	LAI < 2	LAI > 2	LAI < 2	LAI > 2
average	0,50	0,32	0,49	0,33
sd	0,06	0,04	0,08	0,05

Table 7. Average values and standard deviation for actual relative evaporation with a leaf area index threshold of 2

The development of *LAI* during the growing period can be seen as the crucial factor influencing E_a in crop growth. Attention is given to the seasonal course of *LAI*. Leaf area index always seems to follow a similar course with an increase in the early development stages, a peak value at about anthesis (*T* is at its maximum) and a decrease in the post anthesis phase as a result of leaf senescence and the investment of the plant in the reproductive parts instead of the leaves. Figure 13 shows the typical course and indicates how it is influenced by three different plant populations. Persaud and Khosla (1999) investigated the partitioning of soil water losses (E_a, *T*) of corn due to the variation in *PD*. The variation of *PD* (seeding rate) respectively row spacing is assumed to be an easy feasible measure to reduce E_a in favor of *T,* respectively to improve *WUE.* Thus the evaluation in Chapter 4 aims to examine this aspect as a management option for vapor shift.

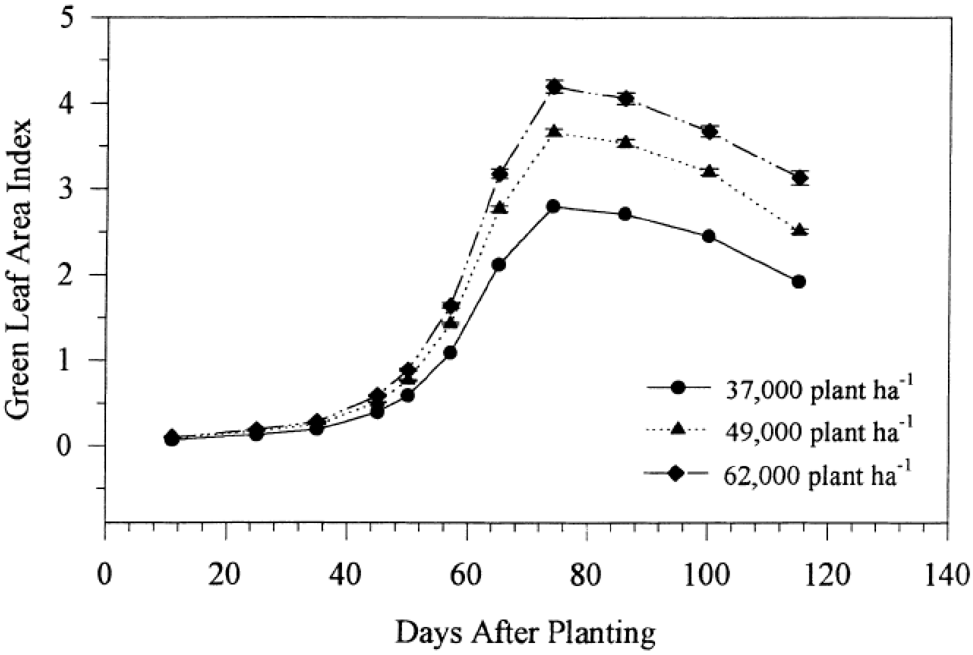

Figure 13 Calculated seasonal course of leaf area index for three different plant populations of corn (Persaud and Khosla 1999)

3.4 Conclusions

To summarize the experimental evaluation of the “vapor shift concept” comparison of the cumulative potential is necessary. The concept of Falkenmark et al. (2004) suggests an overall amount of 330 $km^3\ y^{-1}$ to be possibly saved by 2050 due to reduction of early season soil evaporation and an increased canopy cover. In contradiction the database constitutes 211 $km^3\ y^{-1}$, which accounts for 37 % less.

Early season soil evaporation

For early season soil evaporation the database suggests 60 $km^3\ y^{-1}$ (50 % lower compared to Falkenmark et al. (2004)). Reason for the difference in the magnitude might be caused by analyzing different climatic regions. Falkenmark et al.(2004) suggest a typical value for tropical agriculture (A climate) , where the greatest potential of water savings is assumed to be located. Whereas the experimental data can mostly be associated with C and B climates having a lower evaporative demand of the atmosphere

Reduction potential of early season soil evaporation varies within a wide range dependent on soil, climate and crop properties. It might be a questionable simplification to take one representative value of reduction potential for a global estimate.

A number of management options are suggested by Falkenmark et al. (2004) without allocating an order of magnitude to each measure. As environmental situations are very heterogeneous and a beneficial measure in one climate can even have a detrimental effect in another one it is difficult to estimate a global magnitude for a certain agricultural measure. Possibly it is worthwhile to concentrate on conservation tillage practices in combination with mulching, as one of the management options with the greatest potential in improvement of water use efficiency.

Increased canopy cover

The evaluation of an increased canopy cover to achieve a vapor shift results in a difference of 29 %. Falkenmark et al. (2004) estimate that 214 $km^3\ y^{-1}$ are possible to save by 2050. In contrast the database suggests 151 $km^3\ y^{-1}$. The considerable difference just seems to confirm the great uncertainties that are involved with the estimates on this scale of space an time. The main disagreement is transpirational water productivity, which is 25 % lower for experimental data. A possible reason is the comparison of different crop cultivars in different climate regions within the two calculations. There is a similar problem like at early season soil evaporation. Relative evaporation (E_a/ET_a) varies within a wide range and to pick one value for the estimate again is a questionable simplification.

A reduction of relative evaporation can still mean an increase of actual soil evaporation in absolute values. The conceptual approach in Figure 7 respectively Equation (11) demonstrates that fact. The assumed yield increase from 2.1 to 3.5 t ha^{-1} is critical within the estimate. An increase of yield always is combined with a growing demand of consumptive water. A suggested 214 km^3 y^{-1} "vapor shift" savings imply an increasing total evapotranspiration flow of 458 km^3 y^{-1}. Although water is used more efficient in terms of water use efficiency there is no contribution in minimizing global water deficit. If the calculation is done with a yield increase there might be a trade off from soil evaporation to plant transpiration, but total water consumption will also increase. If actual evapotranspiration varies it is difficult to refer an improvement in water use efficiency to a vapor shift trade off (soil evaporation shifts to plant transpiration) or an improvement in relative transpiration (T/ET_a). Considering the decrease of malnutrition as a main objective, additional water resources have to be generated for agriculture anyway, because the contribution of a vapor shift is just a fraction of the total deficit. Thus it is not relevant to consider increased canopy cover as a "real" vapor shift option or not. Improvement of water use efficiency must be in the foreground, independent of a variation of total evapotranspiration.

Both for early season soil evaporation and increased canopy cover global the estimate of possible saving potentials is risky and not warrantable without viewing the problem more differentiated. Table 8 suggests a subdivision into various Koeppen climate types (Kastanek 2005), where agriculture of crops is assumed to be possible and water can get a limiting factor. For each climate type it would be necessary to gain an average value for early season soil evaporation, either a mean for the main cereals or even partitioned to certain crop sorts.

Af	Tropical rainforest climate
Am	Tropical monsoon climate
Aw	Tropical monsoon climate
BW	Desert climate
BS	Steppe climate
Csa, Csb	Mediterranean climates
Cfa, Cwa	Humid subtropical climates
Cfa, *Cwa*	Maritime temperate climates or oceanic climates

Table 8. Suggestion of a possible climate subdivision for further estimates

Although the data acquisition is a challenge that has to be faced with the suggested subdivision of climates such an improvement would raise the quality of the estimate. Besides the climate there are other factors concerning the uncertainty of the estimate. Population growth data, data concerning increase of cultivated area respectively predicted yield raise constitute a forecast uncertainty. The further the prediction is situated in the future, the greater the uncertainty gets.

Increasing yield levels respectively the crop water productivity yield function

Collected experimental data confirms the exponential shape of the biophysical crop water productivity yield function (*CWP(Y)*). Experimental data shows the low yield range to contain a greater improvement potential of water use efficiency respectively crop water productivity then the high yield range. A low yield increase causes a large improvement in crop water productivity. Depending on the climate and environmental conditions, it might be valid to consider crop water productivity constant above a certain yield level. There is a clear aim of increasing yield levels from small holder farmers with ineffective agricultural practices. By increasing yield levels a vapor shift effect might be included but difficult to unpick. Somehow it is difficult to consider an increased canopy cover and an improvement of crop water productivity by a yield increase as separate options. It might be advisable to adapt the concept and merge these two options.

One of the most obvious management factors which defines leaf area index is planting density. Crop yields often respond to planting density in terms of an optimum response. It is not clearly established which relation holds between water use efficiency and planting density. If vapor shift is to be taken seriously as a production and management option it has to be analyzed both experimentally and theoretically. Therefore a numerical simulation using the hydrological model SWAP was chosen for the evaluation in Chapter 4.

3.5 Constraints and Recommendations concerning the practical Evaluation of the global Estimates

3.5.1 Constraints and Recommendations concerning Data Availability

- **Generally low experimental data availability online**

Originally the idea was to find about 50 to 60 research projects that gave information about a seasonal separation of transpiration and actual soil evaporation. The results of the search contained more than 50 experiments, but just 13 allowed the desired separation of green water fluxes.

For further work on the topic it is advisable to cooperate with regional offices of the FAO. It is in their interest to estimate the potential of vapor shift, the FAO knows exactly where the critical regions are and there is possibly better data availability due to cooperation with agricultural institutes.

- **Data for rainfed tropical agriculture**

Considering the potential of vapor shift to be greatest in tropical agriculture it would have been preferable to focus on these climatic areas. It seems that research of determining evapotranspiration empirically is mainly done in regions where agricultural practices are well developed and water is the limiting factor. Data is hardly available from smallholder farmers with low production rates in rainfed agriculture. Empirical research should be done in agricultural areas where small holder farming systems are predominant.

- **Heterogeneity of the available data**

There is a considerable heterogeneity in the research objectives of the collected experiments. Research on the field of evapotranspiration is dealing with different scales in time and space which makes it somehow difficult to build up a homogenous database. Despite the main aim was to get information about seasonal values for relative soil evaporation, relative transpiration, leaf area index respectively water use efficiency, it would also be desirable to get further information about potential green water flows , yield, total above ground biomass, transpiration efficiency, precipitation, irrigation, interception, drainage and runoff. The collection of desired data was fragmentary.

- **Data for different climatic regions**

As Falkenmark et al. (2004) constitute that their concept is applicable for global predictions; there would have been the necessity to gain information about different climatic regions. The suggested subdivision (Chapter 3.4) into Koeppen climates could be a proper approach.

3.5.2 Constraints and Recommendations concerning the Vapor Shift Concept

- No clear definition of early season soil evaporation.

- Lack of an explicit explanation of the time and space scale in the basic concept. Figure 3 is assumed to illustrate the seasonal green water flows. Contradicting to the conceptual approach the global estimates are done on an annual scale.

- Due to different climate and environmental conditions there is a large scattering of green water flows. Applying the theoretical linear courses on a global scale constitutes a questionable simplification.

- Falkenmark et al. (2004) define transpirational water productivity as the amount of water transpired to produce one unit of biomass but within their calculations they correspond to yield and not to total biomass. That constitutes a contradiction. Generally the description of the concept is lacking of equations.

4 Practical Evaluation of the Vapor Shift Concept on a local Scale using the hydrological Model SWAP

4.1 Introduction

In Chapter 3 the theoretical approach of vapor “shift” with data from experiments was verified. Chapter 4 aims to investigate crop productivity and water balance parameters. The examination focuses on the variation of green water fluxes. In order to do so the hydrological model SWAP-WOFOST version 3_0_3a is used. SWAP was developed at Wageningen University over 30 years and thus is well developed and well known. From the empirical analysis the focus changes to very specific measures for one site and climate. The considered management options are a variation in *PD* respectively the implementation of a mulch layer.

The basic approach gives information about detailed research questions addressed in this part of the thesis. Further the theoretical approach of calculating E_a in SWAP will be explained. The site will be introduced in terms of climate, soil and cultural practices and at last an explanation of the choice respectively the calibration of the parameters for the simulation will be given.

Both the Chapter “Analysis and Discussion Planting Density” and “Analysis and Discussion Mulching” present aspects from literature. The actual analysis compares the results of the simulation with the “vapor shift concept”. Crop and water balance terms with regard to *PD* respectively mulching are examined.

4.2 Basic Approach

4.2.1 Research Questions

The results of the data analysis from carried out simulations shall be looked at in the same way as experimental data and the theoretical approach. A comparison with the simulation results is necessary to detect and evaluate tendencies in water balance terms. This is done in order to get a better understanding of the dynamics of the terms.
What order of magnitude for early season soil evaporation, reduction of E_a due to increased canopy cover and improved *CWP* does the model suggest for winter wheat in Sirsa. What significance do results of the simulation have for the theoretical approach of Falkenmark et al. (2004) and vice versa.

An additional aim is to examine *WUE, HI, TE, T/ET* plus other relevant terms with regard to the more differentiated concept of viewing *WUE* (Chapter 2.3). How does the behavior of crop and water balance terms change due to varying *PD* and a mulch layer. An irrigation criterion had to be implemented and varying water availability affects crop and water balance terms; investigation will also be done on this aspect. It shall be explored if the model suggests an optimum in planting density with respect to E_a losses and *WUE*.

As it turned out there appear difficulties in simulating varying *PD* and a mulch layer with a deterministic model and there are effects which are not accounted for in the simulation run. Deficiencies and constraints of the simulation will be analyzed and a perspective for possible improvements will be given.

4.2.2 Theory of describing the Calculation Procedure of Evaporation in SWAP

a) General

Canopy development and hence *LAI* is crucial for partitioning of the green water fluxes. Crop growth is mainly driven by solar radiation and *LAI*. When assimilation is reduced due to water stress, leaf area will expand less. This directly affects the assimilation in the subsequent period. A reduced *LAI* influences the distribution of potential *ET* over *T* and E_a. This further affects soil moisture flow (personal communication Jos van Dam).
SWAP uses WOFOST as a crop growth routine. WOFOST is a detailed module for all kind of crops. It simulates in detail photosynthesis and crop development, taking into account growth reductions due to water and/or salt stress. It uses the ratio of actual

transpiration and potential transpiration T_a/T_p as reduction coefficient affecting assimilation. SWAP calculates a daily average of the potential transpiration rate, T_p cm/d, taking into account the fraction of the day during which the intercepted water evaporates. During evaporation of intercepted water, the transpiration rate is assumed to be negligible. Water stress and therefore actual transpiration is described by the function proposed by Feddes et al. (1978).
The method of determining the evaporation flux is essential for the carried out simulation, therefore a description of the calculation procedure in SWAP is given below.

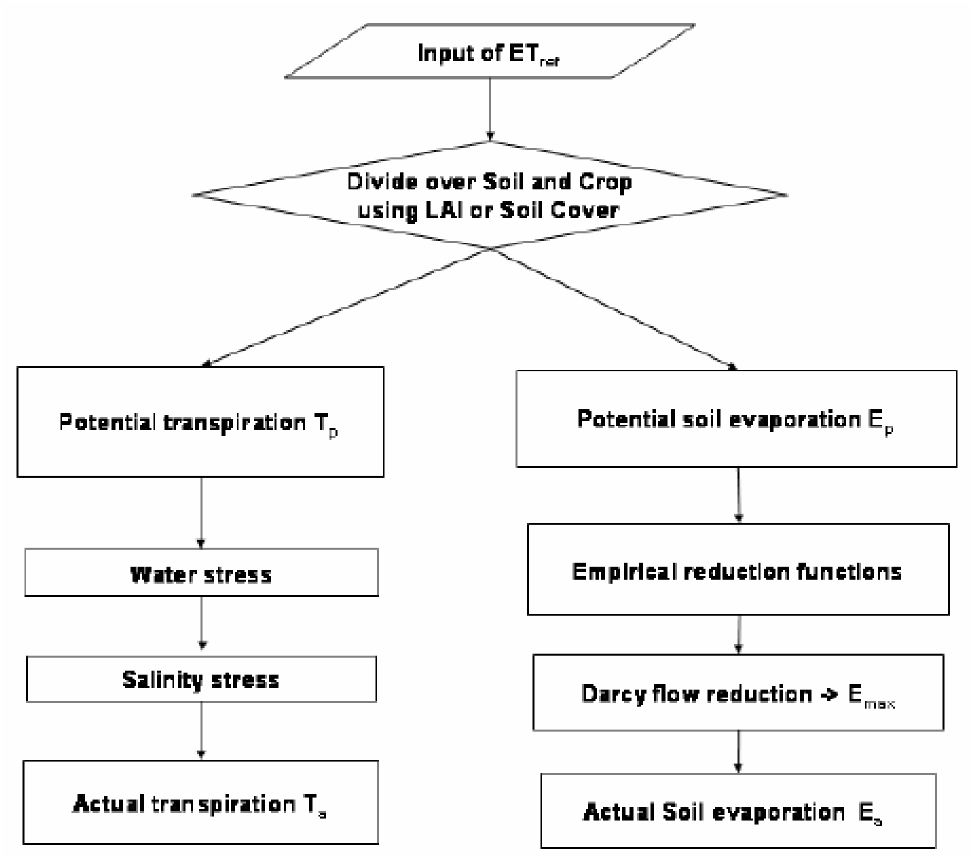

Figure 14 Partitioning of evapotranspiration over crop and soil (Kroes and van Dam 2003)

Figure 14 presents the flowchart which demonstrates the calculation path of *E* and *T* in SWAP. Top boundary condition is determined by the potential evapotranspiration ET_p, which is estimated by the Penman-Monteith equation. This method requires measured climatic data on temperature, humidity, solar radiation and wind speed.

There are three different output fluxes calculated for homogenous surfaces:
ET_{wo} = potential evapotranspiration rate of a wet canopy, completely covering the soil
ET_{po} = potential evapotranspiration rate of a dry canopy, completely covering the soil
E_{po} = potential E rate of a wet, bare soil

ET_{wo} respectively ET_{po} differ in the crop resistance (r_{crop}), which is set to 0 respectively varies from 30-150 s m^{-1}.
In case of E_{po}, r_{crop}= 0 and the reflection coefficient α_r = 0.15. For a wet or a dry crop canopy α_r = 0.23. An additional difference within the calculation of E_{po} is the crop height is set to 0.1 cm.

E_{po} is further used to calculate the potential evaporation rate of a soil under a standing crop, see equation (12).

(12). $$E_p = E_{p0} e^{-\kappa_{gr} LAI}$$

κ_{gr} represents the extinction coefficient for global solar radiation.

(13). $$\kappa_{gr} = \kappa_{df} \cdot \kappa_{dir}$$

κ_{df} is the extinction coefficient for diffuse visible light (0.4-1.1) and κ_{dir} the extinction coefficient for direct visible light, see equation (13).

Calculation of actual soil evaporation (E_a)

Within SWAP there are three options to calculate E_a: using Darcy’s law and using empirical reduction functions of Black et al. (1969) or Boesten and Stroosnijder (1986).

a) Darcy:

$$(14). \qquad E_{\max} = K_{1/2}\left(\frac{h_{atm} - h_1 - z_1}{z_1}\right)$$

Maximum evaporation rate of the top soil
$[E_{\max}]$ = cm d^{-1}
Average hydraulic conductivity
$[K_{1/2}]$ = cm d^{-1}
Soil water pressure head in equilibrium with the air relative humidity
$[h_{atm}]$ = cm
Soil water pressure head of the first node
$[h_1]$ = cm
Soil depth at the first node
$[z_1]$ = cm

Darcy's law overestimates E_a. A steep pressure gradient occurs in reality on the soil surface during the drying process. The problem is to find the correct shape of soil hydraulic functions for this superficial layer, for instance the soil water retention function and the hydraulic conductivity function. (personal communication Jos van Dam). The difficulty is that the hydraulic properties on the soil surface are not directly measurable and it is still not clear to which extent the hydraulic functions, which usually represent a top layer of a few decimeters, are valid for the top few centimeters of a soil.

b) Black:
The empirical method according to Black et al. (1969) suggests that cumulative actual soil evaporation at any stage is proportional to the square root of time following a significant amount of rainfall.

$$(15). \qquad \sum E_a = \beta_1 \cdot \sqrt{t_{dry}}$$

ΣE_a	cumulative actual evaporation during a drying cycle in cm
β_1	Black coefficient in cm $d^{-0.5}$
t_{dry}	time after a significant amount of rainfall in d

β_1 is a soil specific parameter characterizing the evaporation process. β_1 can be either obtained directly from one or two drying periods by measurements with a lysimeter or it can be calculated from the equation below using estimates of θ_0 and θ_i, while the soil water diffusivity D has to be determined experimentally.

(16). $$\beta_1 = 2(\theta_i - \theta_0)(D/\pi)^{1/2}$$

θ_i	initial water content in $cm^3\ cm^{-3}$
θ_0	water content at the boundary in $cm^3\ cm^{-3}$
D	soil water diffusivity in $cm^2\ d^{-1}$

The difficulty of this approach is to get a reasonable value for β_1, since originally the equation was developed for a specific soil (Plainfield sand) and a certain climate. The problem is the general applicability and that a changing atmospheric demand is not being taken into account. Despite the approach assumes a varying E_a flux, it neglects the fact that E_a physically occurs in two stages

c) <u>Boesten and Stroosnijder:</u>
This method accounts for the two stage evaporation process and fluctuations of atmospheric demand. It can be seen as an improvement of the original worked out by Ritchie (1972). In this approach ΣE_a during a drying cycle is directly proportional to the square root of ΣE_p. It contains one soil parameter β_2 in $cm^{0,5}$, and uses the sum of ΣE_p as a time variable.

(17). $$\sum Ea = \sum Ep \ for \qquad \sum Ep \le \beta_2^{\ 2}$$

(18). $$\sum Ea = \beta_2 (\sum Ep)^{1/2} \qquad for \sum \ Ep \ > \ \beta_2^{\ 2}$$

β_2 is determined empirically, it determines the length of the E_p period and the slope of ΣE_a versus ΣE_p in the soil limiting stage. A minimum amount of rainfall is set to reset ΣE_p to zero. P_{net} is the net amount of rainfall reaching the soil.

If $P_{net} < E_p$, that means the daily rainfall excess is not sufficient to moisten the dried soil profile to field capacity, ΣE_p follows from equation (18).

(19). $$(\sum Ep)_n = (\sum Ep)_{n-1} + (Ep - P_{net})$$

n indicates the day number. $(\Sigma E_a)_n$ is calculated from $(\Sigma E_p)_n$ with equation (19) and E_{an} as follows from equation (20):

(20). $$Ea_n = Pnet_n + (\sum Ea)_n - (\sum Ea)_{n-1}$$

On days with excess of rainfall $(P_{net}>E_p)$ $E_{an}= E_{pn}$. The excess of rainfall is then subtracted from ΣE_a.

(21). $$(\sum Ea)_n = (\sum Ea)_{n-1} - (Pnet - Ep)_n$$

Next $(\Sigma E_p)_n$ is calculated from $(\Sigma E_a)_n$ with equation *(21).* If the daily rainfall excess is larger than $(\Sigma E_p)_{n-1}$, then both $(\Sigma E_a)_n$ and $(\Sigma E_a)_n$ are set to zero.

SWAP determines Ea by taking the minimum value of Ep, Emax and if set one of the two empirical functions. The Boesten-Stroosnijder approach seems to describe the physical process of soil evaporation most properly. Although there remains a great uncertainty in the simulation runs as there was no information about the magnitude of the empirical coefficients for the site specific situation in Sirsa.

Variation in relative evaporation (E_a/ET_a) due to changing empirical coefficients:

The challenge of the empirical approaches is the application on a broad range due to their site specific character. To show the influence of a varying empirical coefficient on E_a/ET_a, a simulation run was done over three seasons from 2000 till 2002 for a stand density of 1.80E+06 pl/ha. The chosen crop is winter wheat seeded on the 12th of December and harvested on the 20th of April. Rewetting of the soil starts for Boesten-Stroosnijder from pF = 3.7 and for Black from pF = 4.2 until field capacity. The soil can be described as loamy sand respectively sandy loam with a vertical hydraulic conductivity of 102 respectively 121 cm d^{-1}. Free drainage of the soil profile is chosen as a bottom boundary condition. Figure 15 illustrates the results with E_a/ET_a on the y-axis and changing coefficients on the x-axis. It can bee observed that E_a/ET_a is considerably varying from 0.05 to 0.65 with a changing β_1 from 0.1 to 0.9.

This demonstrates the great uncertainty of the magnitude of simulated soil evaporation when data lacks for determining β_1 empirically.

Both the Boesten-Stroosnijder and the Black coefficient were not determined for the site specific conditions of Sirsa. We do not claim to describe the situation in the field in exactly.

An objective was to examine the dynamics of water balance terms with varying *PD*. It is assumed that tendencies are recognizable independent from the true magnitude of E_a/ET_a and that there is merely a shift of certain functions whereas the form and the character of the relations stays more or less the same. Because the Boesten-Stroosnijder approach describes the soil evaporation process most properly, it was generally chosen for further analyses, although the approaches were also compared.

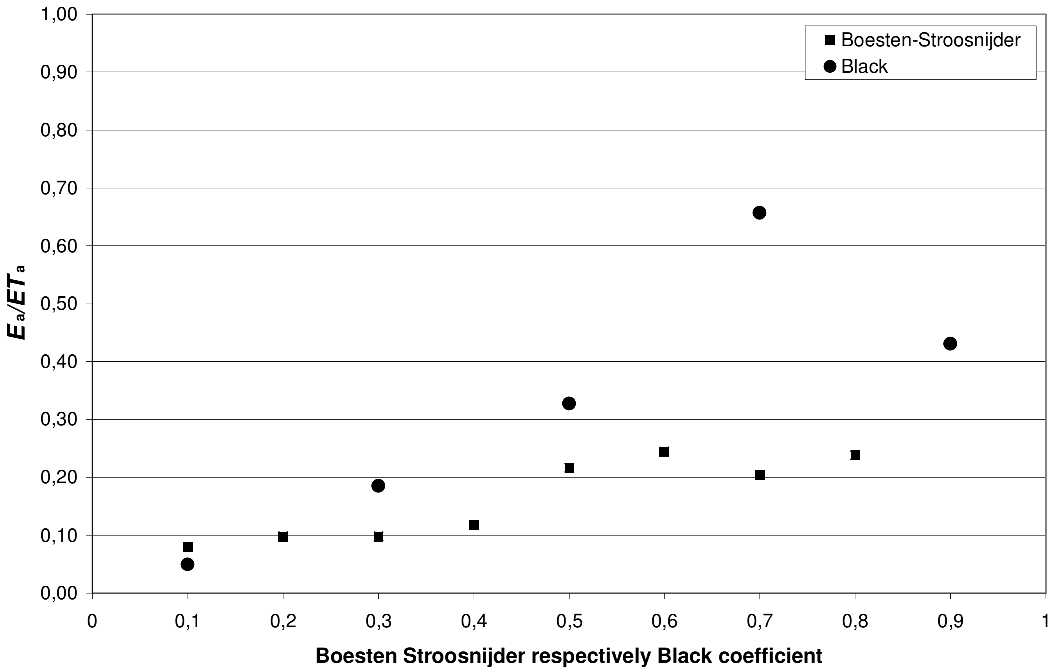

Figure 15 Variation of relative evaporation for winter wheat from 2000 till 2002 due to a varying Boesten-Stroosnijder coefficient (pF = 3.7) and Black coefficient (pF = 4.2), PD = 1.8×10^6 *pl* ha^{-1}

4.2.3 Site Description of Sirsa in Haryana State, India

A short description of the site in terms of climatic and soil conditions with reference and relevance to the simulation run will be given below.

a) Climate characteristic

Sirsa is located in the Western part of Haryana state in India, situated between latitude 29.1º to 30.0º North and longitude 74.2º to 75.3º East. The climate is dry with extremes in temperature and erratic rainfall. It can be characterized as subtropical, semiarid with a continental influence and monsoon. Evaporative demand is high, ET_{ref} accounts for about 4 to 5 times the annual rainfall. Therefore it can be designated as a B climate according to Koeppen classification (Kastanek 2005). B climates are characterized by the fact that precipitation is less than ET_p.
The average annual rainfall from 1990 to 2002 accounts for 367 mm. This amount is highly erratic, both in quantity and in distribution. As 80 % of the annual rainfall occurs during the Monsoon months of July to September a crop production over the whole year without supplemental irrigation is hardly possible. Rainfall for the investigated winter growing season accounts for 46 ±29 mm averaged over 12 seasons. The agricultural year can be divided into four periods: the hot and dry season from March to June, the hot rainy season (monsoon) from July to September, the post monsoon season from October to November and finally the cold season from December to February. January is the coldest month with a mean daily maximum temperature of 21 ºC and minimum temperature of 5 ºC. In the hottest period (May and June) temperatures rise till about 49 ºC and hot winds with low relative humidity cause dust storms.

b) Crop and soil description for Sirsa conditions

Climatic conditions allow a double cropping system with two growing seasons over the year. In addition to a wheat-rice combination a wheat-cotton rotation is very common. The latter combination was chosen for the simulation runs, with wheat in the winter season from beginning of December till end of April and cotton in the summer season from beginning of May till October. Only wheat parameters were varied, while cotton crop was modeled with a simple crop file and parameters kept constant for the entire simulation. The growing season of wheat lasts for 120 to 135 days in this region. Crop yield of wheat in Sirsa experienced a considerable increase from about 1900 kg/ha in 1975 to 3900 kg/ha in 2001. This rise was feasible due to a participation in the “Green

Revolution", which resulted in more irrigation facilities, improved crop varieties and increased fertilizer use. A further food production increase in the district is restricted by the availability of water.

The soil texture in the region is characterized as sandy loam respectively loamy sand. Soil hydraulic functions were available for the stratified soil profiles. Ground water level is more than 3 m below top ground surface which means that there is no influence of ground water to the upper soil layers and the *ET* process.

4.2.4 Parameterization of SWAP for the specific Conditions in Sirsa

In this chapter most relevant settings of the parameters for the simulation runs are described. To create a reasonable simulation, values for parameterization were mainly taken from Dam and Malik (2003) and Heemst (1988). There are fixed and variable parameters. Variation of the variable ones serves for investigation of water balance and crop growth terms. Firstly fixed parameters divided into a crop and soil-water section are described. Secondly, variable parameters are explained; parameterization for calculating E_a and an explanation of the chosen irrigation criteria is given. Further the calibration of *PD* is described and in a final step the implementation of the mulch layer is explained.

a) Fixed crop parameters:

A detailed crop file was specified for winter wheat and a simple crop file for cotton. Constant over 12 seasons from 1991 till 2002 the date of seeding is the 13th of December and of harvest the 20th.of April. Different dates of sowings and harvest like happening in the field are not taken into account. This is also valid for cotton, which is always drilled on 01.05 and yielded on 28.10. There will be no further attention on cotton, as it was just implemented to mimic with the common cropping system practice.

Crop height is related to development stage, which is a function of temperature sum from emergence to maturity. This one dimensional assumption does not take into account dynamic changes of crop growth due to environmental influence. Data for assimilation, conversion of assimilates into biomass, maintenance respiration, partitioning and death rates were adopted from Dam and Malik (2003). Chosen values constitute averages over several cultivars grown in Sirsa.

The following settings for reduction of root water extraction are applied:

- no water extraction at higher pressure heads than -1 cm
- optimum water extraction starts for the top layer at a pressure head of -22.9 cm (pF = 1.36)
- optimum water extraction for the sub layer starts at a pressure head of -22.9 cm (pF = 1.36)
- water uptake reduction starts at high T_p below a pressure head of -1025 cm
- the water uptake reduction starts at low T_p below a pressure head of -2200 cm (pF = 3.34)
- no water extraction is possible at lower pressure heads than -16000 cm (pF = 4.20)
- the level of high atmospheric demand is 1.0 cm d^{-1}
- the level of low atmospheric demand is 0.2 cm d^{-1}
- minimum canopy resistance: 70 s m^{-1}

Rainfall interception is modeled according to Von Hoyningen-Hune and Braden with a coefficient of 0.25 cm. Initial rooting depth was set to 10 cm, maximum daily increase in rooting depth to 0.6 cm d^{-1} and the maximum rooting depth of the cultivar was set to 70 cm.

b) Fixed soil and water parameters

Initial moisture condition was specified in this way, that the final pressure heads were read from the previous SWAP simulation and put as initial values. Ponding, run on and run off are assumed to be negligible. The vertical discretization of the soil profile can be seen in Table 9. A sandy loam in the upper layers and a loamy sand in the lower layers with K_{sat} values of 101.71 cm d^{-1} respectively 120.87 cm d^{-1} is chosen as a typical soil for Sirsa. Six measurements sites in Sirsa suggest K_{sat} values differing by about the factor 100 and the chosen soils lie in the upper range.

soil texture	soil layer	sublayer	height sub layer in cm	depth in cm	number of nodes
sandy loam	1	1	10	0-10	10
sandy loam	1	2	20	10-30	4
loamy sand	2	3	30	30-60	6
loamy sand	2	4	140	60-200	14

Table 9. Vertical discretization of the soil profile

When viewing the results of the simulation runs, it always has to be kept in mind that the output is just for one specific soil profile with certain soil hydraulic functions.
Apart from plant physiological and meteorological factors, varying soil properties are a main factor influencing *Es*. The soil hydraulic parameters pertaining to the soil layers are shown in Table 10. θ_{sat} in cm^3 cm^{-3} is the saturated volumetric water content, θ_{res} in cm^3 cm^{-3} is the residual water content in the very dry range and α respectively n are empirical shape factors. L_{exp} is the exponent in the hydraulic conductivity function. L_{exp} and n are dimensionless.

soil layer	θ_{res} in cm^3/cm^3	θ_{res} in cm^3/cm^3	α in 1/cm	n dimensionless	K_{sat} in cm/d	L_{exp} dimensionless
1	0,01	0,31	0,014	1,29	101,71	-1,67
2	0,01	0,32	0,036	1,19	120,87	-0,87

Table 10. Parameters to describe the analytical θ (h) function by van Genuchten

The initial groundwater level is prescribed at 300 cm below top ground surface and free drainage of the soil profile is chosen as a bottom boundary condition.

c) Variable soil and water parameters

Varying factors of the numerical simulation:

I. Methods for calculating actual soil evaporation (Black, Boesten-Stroosnijder, Darcy)
II. Irrigation criteria
III. Estimate of planting density
IV. Vertical discretization of the soil cover in order to simulate a mulch layer

I. Methods for calculating actual soil evaporation (Black, Boesten-Stroosnijder, Darcy):

The light extinction coefficient (κ_{gr}) for wheat is set to 0.375. It has been shown in chapter 4.2.2, that there is considerable variation in E_a with changing with β_1 respectively β_2, therefore these empirical coefficients constitute an uncertainty factor in estimating the magnitude of E_a. β_1 is chosen from the original approach of Black et al. (1969) with 0.5 cm $d^{-0,5}$, originally it was determined for Plainfield sand. β_2 is set to 0.54 $cm^{0,5}$, which represents the default value in SWAP.

II. Irrigation criteria:

Due to the very dry conditions in the winter wheat season (precipitation accounts on average for 46 ±29 mm over 12 seasons) it is necessary to implement irrigation criteria to simulate a greater yield range and to make crop growth even possible. Without the application of irrigation the simulation suggests yield values mostly below 1(t ha^{-1}). Table 11 describes the chosen irrigation criteria. Different threshold (pF) values are chosen for the start of the irrigation. The irrigation amount selected is rewetting until field capacity. In reality I4 (close to permanent wilting point) and I5 would probably lead to a crop failure. However, the reason why these two criterions are implemented, is to create a wide yield range.

abbreviation	pF	matric potential in cm	range of irrigation amount in mm
I1	3.0	-1000	258 - 315
I2	3.7	-5000	208 - 256
I3	4.0	-10000	missing
I4	4.2	-15000	131 - 168
I5	no irrigation		

Table 11. Description of the irrigation criteria and the range of irrigation amount

III. Estimate of planting density

The possibility to vary planting density in SWAP is the initial total crop dry weight (*TDWI*) in kg ha^{-1}. In a first step *TDWI* has to be translated to a *PD* to get a reference value for further extrapolation. To achieve this equation (22) and (23) are applied. The description of the calculation procedure is described below.

$$(22).\qquad seeds/m^2 = \frac{100\,\frac{plants}{m^2}}{field\_emergence(\%) - death\_rate(\%)}$$

$$(23).\qquad seed\_weight = seeds/m^2 \cdot \frac{W_{1000}}{100} \quad in\_kg/ha$$

W_{1000} in equation (23) constitutes the1000 kernel weight in g / 1000 kernel. Within the different cultivars from data of Sirsa, a calculation suggests an average value for W_{1000} = 38 g/1000 kernel.

Field emergence of cereals is about 60-80 %. Death rate of cereals is about 5-10 %. Field emergence minus death rate is assumed to be 70 %. Seeding weight accounts for 100 kg ha^{-1} (Dam and Malik 2003).

The used assumption is, that the seeding weight approximately corresponds with *TDWI*. With a given seed weight and W_{1000} equations (22) and (23) result in a *PD* of 1.841 × 10^6 pl ha^{-1} for conditions in Sirsa.

The Australian Society of Agronomy recommends a *PD* of 1.0 ×10^6 - 2.0 × 10^6 pl ha^{-1} for wheat. The experimental data base suggests a range from 8.8 × 10^5 - 3.0 × 10^6 pl ha^{-1}. Therefore the range for simulation is chosen from 8.0 × 10^5 - 3.0 × 10^6 pl ha^{-1} and the increment of difference is set to 2.0 ×10^5 pl ha^{-1}.

To calculate different planting densities, a linear extrapolation is used. Thirteen different *PD* were created for the simulation runs. *PD1* constitutes a low, *PD7* a medium and *PD13* a high stand density.

PD1 = 0.8 × 10^6 pl ha^{-1}	low
PD7 = 1.8 ×10^6 pl ha^{-1}	medium
PD13 = 3.0 × 10^6 pl ha^{-1}	high

IV. Vertical discretization of the soil cover in order to simulate a mulch layer

The original plan of implementing a mulch layer of organic matter consisting of plant residues had to be modified, due to a lack of soil hydraulic properties about organic mulch.

As an alternative, realistic option a sand mulch layer with 2 cm thickness is chosen. The layer was placed on top of the existing soil profile. Its vertical discretization and its soil hydraulic functions are taken from Kroes and van Dam (2003), see Table 12.

soil texture	soil layer	sublayer	height sub layer in cm	depth in cm	number of nodes
sand	1	1	2	0-2	2

soil layer	Θres in cm³/cm³	Θsat in cm³/cm³	α in 1/cm	n dimensionless	Ksat in cm/d	Lexp dimensionless
1	0,01	0.36	0.0452	1.933	52.91	-0,359

Table 12. Vertical discretization and soil hydraulic functions of the mulch layer, parameters to describe the analytical $\theta(h)$ function by van Genuchten

4.3 Analysis and Discussion: varying Planting Density

4.3.1 Introduction

In Chapter 4.3.2 literature statements concerning the effect of varying planting density respectively row spacing on crop and water balance terms are given. In Chapter 4.3.3 the results of the simulation are compared with the assumptions of the “vapor shift concept” by.Falkenmark et al. (2004). The analysis deals with the suggested seasonal green water fluxes as a function of yield, the influence of a changing *PD* on *LAI* and the magnitude of actual early soil evaporation (E_{ae}) for the specific circumstances in Sirsa. Furthermore the vapor shift potential of an increased canopy cover is investigated and the theoretical *CWP(Y)* function is compared to the simulation data from Sirsa.

The more differentiated approach (Chapter 2.3) allows a more detailed view on *HI, Y* and thus *WUE*. The approach is assumed to describe the dynamics of the process of crop growth and vertical water fluxes more exactly. Therefore each term of the more general approach is investigated with regard to a changing *PD* and varying irrigation criteria.

4.3.2 Aspects from Literature concerning Planting Density and expected Changes of Crop and Water Balance Terms prior to the Simulations

Manipulation of ground cover to influence soil evaporation and plant transpiration by altering row spacing and planting density could provide a low input means of adjusting and reducing *E* from a cropped field, thus leading to a more efficient use of water. Generally can be assumed that *Y* and *BM* production increase with rising *PD* to a maximum, then declines in accordance with a parabolic yield-density function (Ogola et al. 2005). At high *PD* it is likely that water becomes a limiting factor for *BM* production due to increased interplant competition. If water is sufficient, light or nutrient availability might become constraining factors.
This assumption might be valid for well watered conditions respectively sufficient rainfall. Whereas under rainfed, water scarce circumstances *BM* production might be reduced due to higher *PD*.

Following statements show how row spacing respectively *PD* affects crop Y and therefore *WUE*.
The compensating relationship between evaporation and transpiration arising from changes in row spacing may have varying effects on grain yields depending on the environment. Where terminal drought is common, early canopy closure is often associated with a rapid depletion of soil moisture reserves, in which case grain yield may be limited by the lack of soil moisture during the post anthesis period. Therefore, when the crop depends on stored moisture for the whole or a considerable part of the season, rapid canopy closure by manipulating row spacing often reduces yield (Yunusa et al. 1994).
Conditions which lead to lower ratios of E_a/ET_a may not necessarily translate to higher yields. Routley et al. (2003) showed that under conditions of low rainfall, more sparse plantings of grain sorghum sown with a skip-row configuration may lead to higher yields by conserving water use during the vegetative stage of the crop, for use of the crop by grain filling. This implies that at very dry conditions , wide row sown wheat may achieve higher yields than wheat sown at narrow row spacing (Eberbach and Pala 2005).
Optimum *PD* depends on rainfall distribution, with low densities being detrimental in well watered environments, but being preferred where the crop relies on stored soil moisture, particularly in areas with little or no rainfall during the growing season and little evaporation from the dry soil surface (Turner 2004).
It seems the optimal *PD* is a compromise between water supply per plant over the growing season and water loss by E_a. Ehlers and Goss (2004) argue that the question

can only be answered for a specific crop in a given climate for given soil properties. Above statements show that a certain optimum of *PD;* for instance in a moderate climate with even rainfall distribution, can have a negative influence on *Y* and *WUE* in dry climates with erratic rainfall. Assuming that water availability is not sufficient over the whole growing period for a great part of small holder farmers in dry climates, the strategy of optimizing *PD* has to be kept flexible and to be adapted by site. *WUE* can obviously change due to a varying sufficiency of water in certain development stages of the crop.

To summarize, a high *PD* is not necessarily associated with improvement in *Y* and *WUE*, although Es may decrease with increasing canopy, depending on the water availability. The more differentiated approach of analyzing *WUE* (Chapter 2.3) is assumed to be more suitable in describing crop and water balance terms. This approach (equation (8)) is written as:

$$WUE = \frac{Y}{ET} = HI * TE * T / ET = \frac{Y}{BM} * \frac{BM}{T} * \frac{T}{ET}$$

It will be discussed in short how terms are expected to change due to varying *PD* prior to the simulation results. Each factor is sensitive to physical and plant physiological interactions and therefore sensitive to a variation of canopy structure. Following comments refer to Chapter 4.3.4, where an investigation is done with regard to changing crop and water balance terms.

- E_a/ET_a

E_a/ET_a is expected to decrease with increasing *PD* due to the fact that an increasing canopy cover increases *LAI* and therefore reduces E_p. Consequently E_a must also decrease.

- Yield, harvest index

Due to the interplant competition for water and light the course of *Y(PD)* should follow an optimum curve, after increasing at low *PD*, declining again at higher *PD*. This should affect *HI* in such a way, that it declines continuously and even steeper in the higher yield ranges.

- *WUE*

WUE is expected to follow an optimum curve with a peak value at a certain *PD*. With increasing *PD* it should decline due to interplant competition for light and water.

4.3.3 Investigation of a varying Planting Density with regard to the Vapor Shift Concept

Falkenmark et al. (2004) do not mention that varying planting density is a management option to achieve a “vapor shift”. Despite it is assumed to be worth investigating with regard to the concept. A change in seeding rate has influence on the canopy cover, E_a/ET_a, Y and therefore *CWP* respectively *WUE*. Early season soil evaporation, increased canopy cover and an improvement of *WUE* due to increasing yield levels are checked for the conditions in Sirsa.

Simulation results have to be compared with the output from the database respectively the theoretical approach by Falkenmark et al. (2004). Therefore two simulations were chosen:

I. Three varying planting densities (*PD1*=low, *PD7*=medium, PD13=high), five different irrigation criteria(I1=well watered, I2, I3, I4, I5=no irrigation) and a Black coefficient β_1= 0.5, time scale:12 seasons

II. 13 different planting densities, irrigation criteria is defined to start from pF = 3.7 till field capacity (I2), E_a is calculated with Boesten-Stroosnijder criteria (β_2 = 0.54), time scale: 12 seasons

a) General investigation of the simulated seasonal green water flows

Data from simulation run I is used to picture vapor flows as a function of yield in Figure 16, which is comparable to the theoretical approach in Figure 3. The graph illustrates the seasonal values of E_a, T and ET_a as a function of Y. The enlargement in Y in the simulation is mainly an effect of the irrigation criteria. In other words, the better the water availability, the higher Y and also the green water flows. The more the soil is depleted by a denser crop stand, the higher is the irrigation amount, according to the irrigation criteria. The course of E_a in absolute terms is suggested as a rise with increasing Y contrary to the theoretical decline of soil evaporation in Figure 3. The increase of E_a in the simulated results is also caused by the larger amount of irrigation application and thus a more wet top soil. Above a Y level of about 1 t ha^{-1} the simulation suggests green water flows to increase linearly. Below that value the linearity does not seem to apply. For all green water flows a steeper increase is suggested in this low Y range.

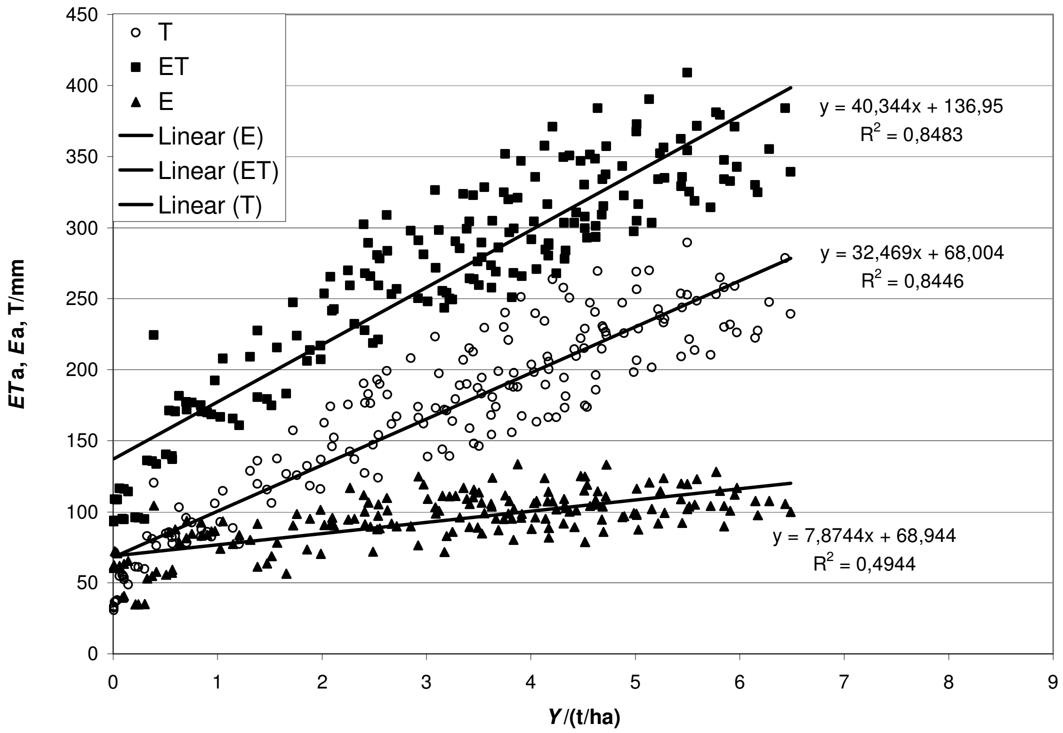

*Figure 16 Simulation results of green water flows for three different planting densities (*PD1,PD7,PD13*) and five irrigation criteria (I1,I2,I3,I4,I5), actual soil evaporation according to Black*

WP_T is assumed to be constant within a given ecosystem setting and should be determined by crop physiology and climatic conditions (Falkenmark et al. 2004). Simulation runs show that for well watered conditions on average for twelve seasons and thirteen planting densities, WP_T accounts for about 47 mm ha t^{-1}. Without irrigation WP_T accounts for 181 mm ha t^{-1} with a larger standard deviation compared to irrigated conditions. Both *T* and *Y* increase due to more available water, but *Y* to a bigger extent. This causes a decrease in WP_T at well watered compared to rainfed conditions. Simulated results are contrary to the basic assumption of a constant WP_T. The model suggests a sensitivity of WP_T to the amount of supplied irrigation water.

b) Leaf area index determines actual early season soil evaporation

The seasonal changing course of *LAI* due to varying *PD* is assumed give information about early season soil evaporation. To get an idea of the magnitude in Sirsa a simulation run with thirteen varying *PD*, one irrigation criteria (I2 = pF3.7) and a Boesten-Stroosnijder coefficient β_2 = 0.54 was chosen. The 1997 and 2002 season plus three different planting densities (*PD1* = low, *PD7* = medium, *PD13* = high) were picked to show the seasonal course of *LAI* with a daily resolution. Figure 17 illustrates *LAI* on the ordinate and days on the abscissa.

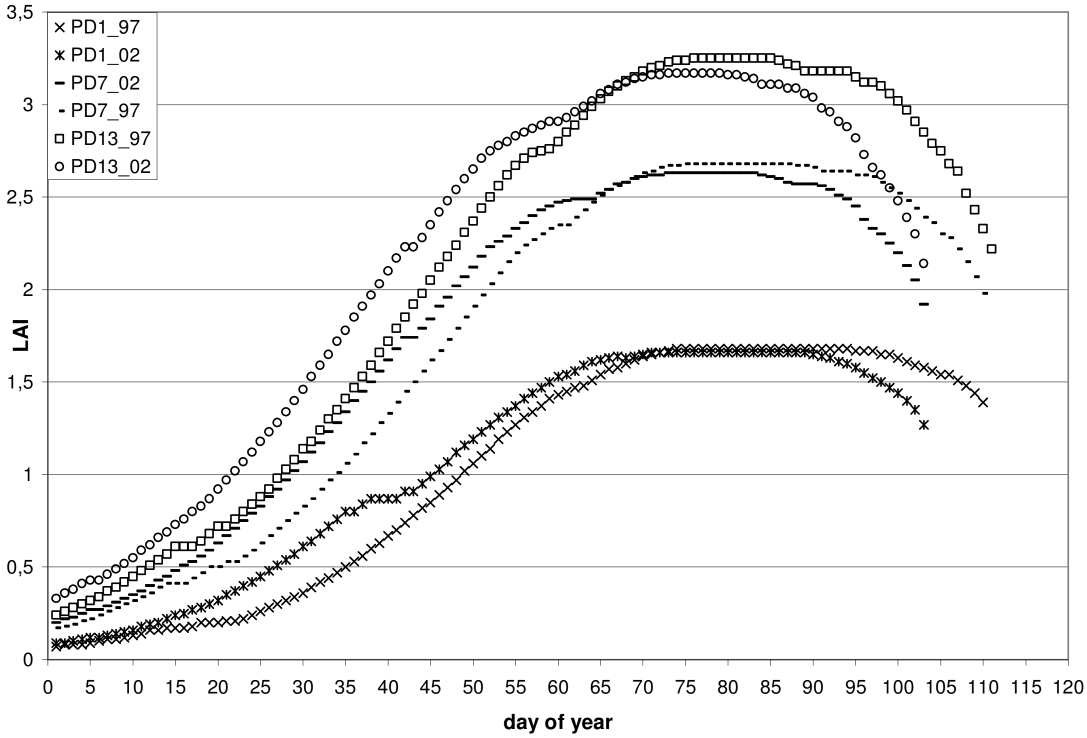

*Figure 17 Seasonal course of leaf area index for irrigation criterion I2 and three planting densities; counting for the days starts with 1st of January, add 20 days to get days after sowing (*DAS*).*

The characteristic is similar for all the curves with a peak value somewhere around day 80 (100 *DAS*). The simulation suggests a considerable increase of LAI_{max} of about 60 % when increasing from *PD1* to *PD7* and of 90 % when increasing from *PD1* to *PD13*. In this simulation run the reason for differences in the courses of *LAI* is *PD* and availability of irrigation water (amount increases with rising *PD*). In reality also fertilization may play a major role.

As no clear definition of actual early season soil evaporation exists we may consider different periods as a threshold value definition.

- Definition of a certain *LAI* threshold. Literature suggests *LAI* values from 2 to 3, depending on climate conditions and crop species.
- Set a certain *DAS* value as a reference, for instance depending on the development stage of crop. At anthesis stage the canopy is fully developed, preanthesis evaporation could be viewed as early season soil evaporation.

Applying these two approaches for the 1997 season and *PD7* results in early season E_a = 17 mm for LAI <= 2 and early season E_a = 18 mm for *DAS* = 80. Values for the 2002 season are even lower, see Table 13.

early season soil E (mm) for LAI<=2		
	1997	2002
PD1	19	9,3
PD7	17	7,6
PD13	17	6,7

Table 13. Magnitude of actual early season soil evaporation in Sirsa for season 1997 and 2002; three planting densities

This constitutes a low value for early season soil evaporation, just about a tenth part of the value suggested by Falkenmark et al. (2004). Possible reasons are, that hardly any rainfall occurs in this growing period, also hardly irrigation as the crop depletes the available soil water and the evaporative demand during winter months is low. So it can be stated that for winter wheat in this region and season (1997 represents a typical rainfall and temperature pattern) there is hardly any early season E_a that could be shifted towards *T*. Consequently there is no option for reduction and therefore improvement of actual early season soil evaporation of the vapor shift concept for these special climate conditions. Also the potential of saving early season E_a for other winter crops is probably negligible. Therefore the focus should preferably lie on summer crops within a further investigation of early season soil evaporation.

c) Increased canopy cover

The course of soil evaporation suggested in Figure 16 indicates the problem already mentioned in the analysis and discussion of increased canopy cover and increasing yield levels of the vapor shift concept (chapter 3.3.3 and 3.3.4). An increased canopy cover cannot easily be separated from additional water demand.
Figure 18 shows E_a as a function of *Y* for three different planting densities. A linear regression suggests a tendency of the slope to decline with increasing *PD*. This course seems to confirm the assumption of the basic concept (see figure 6) but leaves the question how ET_a flow changes.

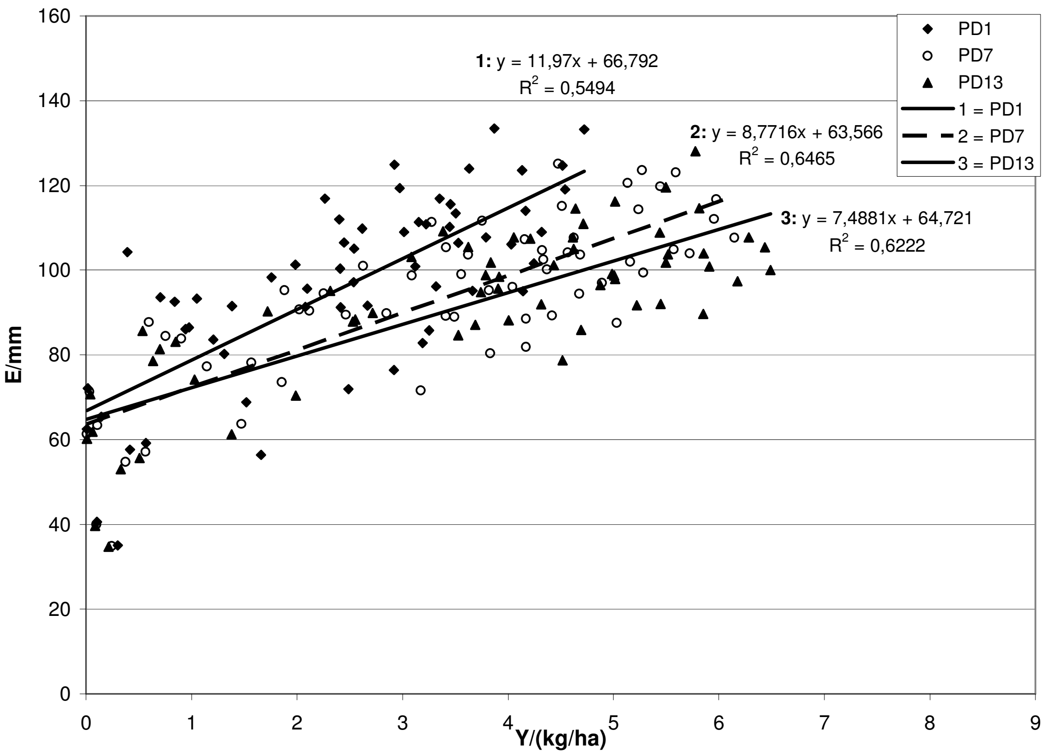

Figure 18 Actual soil evaporation as a function of yield for three planting densities; diamonds = low PD*, circles = medium* PD *and triangles = high* PD

Table 14 illustrates results of simulation run I. The variation of three different *PD* and three irrigation criteria causes the green water flows to change on a 12 year average. The simulation suggests E_a mostly to decrease with rising *PD* independent from the irrigation criteria. *T* always increases with increasing *PD*. *T* increases to a bigger extent than E_a decreases. The difference origins from an increasing ET_a flow for all three stand densities.

Only without irrigation the decrease in E_a with 4.7 mm can be seen as a real “crop per drop” gain, because in this case ET_a hardly changes. But for rainfed (Falkenmark, Rockstrom, and Savenije 2004)conditions in Sirsa a rise in *PD* would act disadvantageous on the already low *Y* level. At field conditions there is no crop development possible with such a low amount of seasonal rainfall (annual twelve year average = 45.6 mm). ΔE in Table 13 represents the possible vapor shift suggested by the simulation. Values constitute the difference of E_a in comparison to *PD1*. The highest potential seems to be reached with 8.6 mm at well watered conditions (I1) and a change from *PD1* to *PD13*. This still is small in comparison to 36 mm suggested by Falkenmark et al. (2004). (see Table 5).

	PD1			
pF	E_a in mm	ΔE in mm	T in mm	ET_a in mm
3,0	118,2	0,0	190,5	308,7
4,0	97,6	0,0	158,3	255,8
no irrigation	68,1	0,0	67,5	135,5
	PD7			
3,0	113,6	4,6	237,3	350,8
4,0	95,6	2,0	192,3	287,9
no irrigation	64,9	3,1	72,1	137,1
	PD13			
3,0	109,6	8,6	257,7	367,3
4,0	97,6	0,0	211,3	308,9
no irrigation	63,4	4,7	74,3	137,7

Table 14. Twelve year average values of green water fluxes for three different planting densities and three irrigation criteria, △E *constitutes soil evaporation savings of* PD7 *and* PD13 *compared to* PD1

To show the possible magnitude of a vapor shift due to increased canopy cover also the results of simulation run II are analyzed. This simulation can be described with thirteen varying *PD*, one irrigation criteria (I2=pF3.7) and a Boesten-Stroosnijder coefficient $\beta_2 = 0.54$.

Figure 19 illustrates the relative *T* as a function of *PD* to indicate the order of magnitude. The vertical scatter per *PD* can be seen as the seasonal variation of climatic conditions over 12 years. The graph shows that the seasonal scatter gets smaller with increasing *PD*. That is possibly caused due to an increasing *LAI* at high stand densities.

The rising course of the 12 year average with increasing *PD* can be described with a logarithmic function ($R^2 = 0.97$). Assuming a change from *PD1* = 8.0×10^5 pl ha^{-1} to *PD13* = 3.0×10^6 pl ha^{-1} results in an improvement of T/ET_a of 7 %. To the same extent E_a/ET_a decreases.

Viewing the water fluxes in absolute terms, again shows that *T* increases to a bigger extent then E_a decreases. Therefore the simulation suggests that the additional plant water consumption and therefore *T* is mainly delivered by a rise in ET_a and partly due to a shift from E_a to *T*.

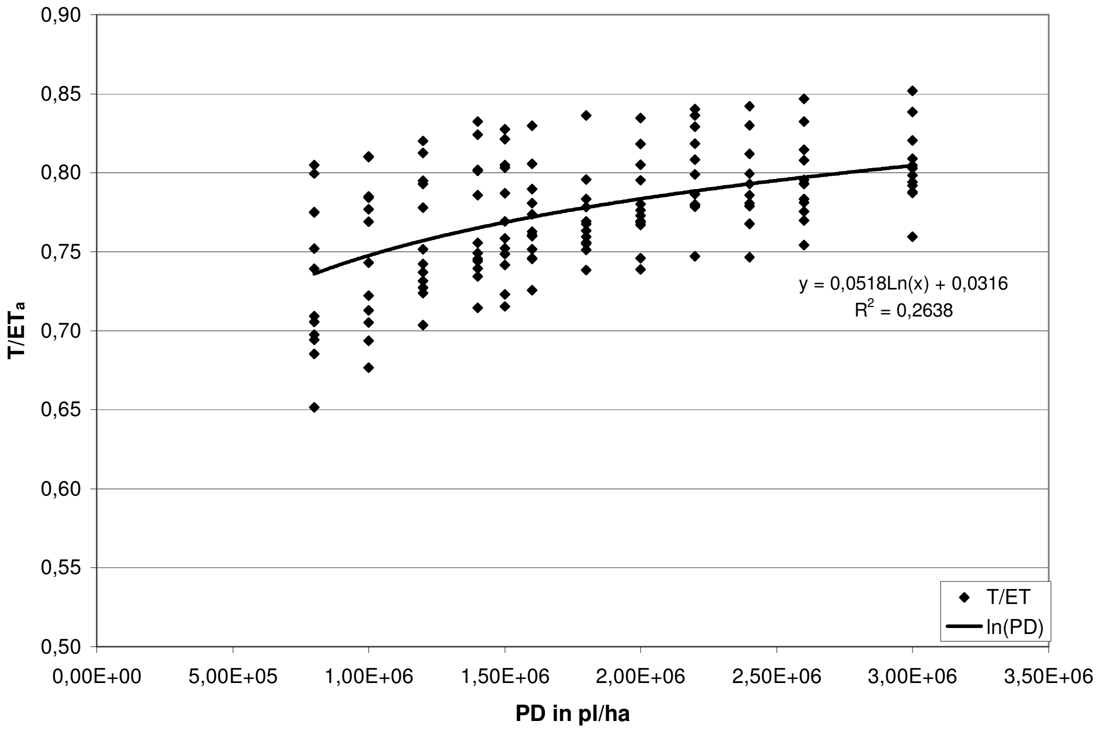

Figure 19 Relative transpiration as a function of planting density for twelve seasons from 1991 till 2002

d) Improving crop water productivity by increasing yield levels

The simulation results suggest a similar course of *CWP* with increasing *Y* when looking at the dynamics of the *CWP-Y* relation, see Figure 20. Obviously the empirical results are located within the range of the simulation run. This indicates that the results for Sirsa fit well to the found empirical data due to the crop type and the climate condition. With increasing *PD* and irrigation criteria (well watered correspond with I1 and I2) data points are shifted to the lower right section of the graph. Yield ranges from almost 0 in dry seasons without irrigation to 6.5 t ha^{-1} for I1 with a high *PD*. The simulation seems to hold the assumption that the greater part of the potential improvement of *CWP* lies in the dynamic low *Y* ranges. In other words, green water flows in agriculture seem to be used more effective in higher *Y* ranges.

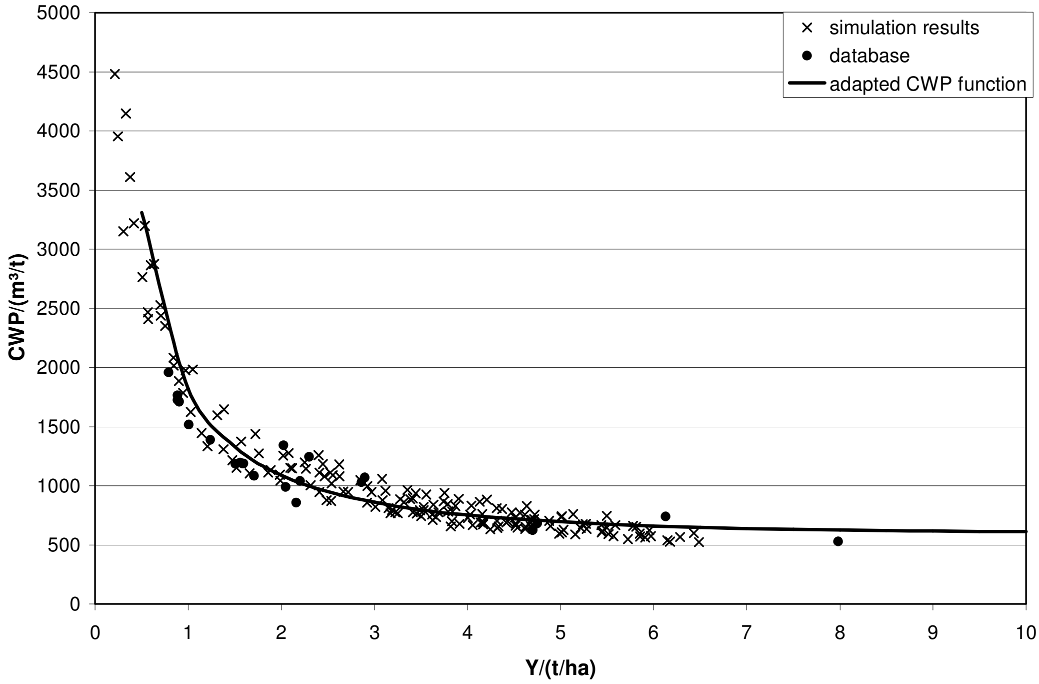

Figure 20 Crop water productivity - yield relation; diamonds: results of the database, triangles: simulation run I (three different planting densities and five irrigation criteria, actual soil evaporation according to Black)

The adapted *CWP*- function with WP_T = 600 m³ t^{-1} and b = -0.4 looks proper, at least in the low *Y* ranges. There seems to occur an overestimation at the higher *Y* ranges. To show the character of the *CWP* – function more clearly an example will be given. Improving yield from 0.5 to 1 t ha^{-1} corresponds with a decrease of *CWP* from 3310 to 1820 m^3 t^{-1} (see Figure 20). This change constitutes a 45 % improvement in *CWP*. Using the same magnitude of *Y* increase from 4.5 to 5.0 t ha^{-1} results in a *CWP* decrease from 719 to 694 m³ t^{-1} which constitutes only a 3.5 % improvement.

4.3.4 Investigation with Regard to the Crop and Water Balance Terms of the more differentiated Approach of viewing Water Use Efficiency

The idea in this chapter is to split up *WUE* respectively *CWP* according to the more differentiated approach (Chapter 2.3) and to view each parameter (*E/ET,HI, TE* and *WUE*) separately with regard to a changing *PD*. Literature and present knowledge suggests a certain course for each factor. The model output will be compared and analyzed.

The figures in this chapter result from simulation run II of Chapter 4.3.3 To remember, the simulation is done for twelve seasons from 1991 till 2002, for 13 different *PD*. E_a is calculated with the Boesten-Stroosnijder criteria ($\beta_2 = 0.54$) and I2 (rewetting from pF=3.7 until field capacity) is chosen as irrigation criteria.

Furthermore some simulations are done, which have exactly the same parameterization than simulation run II, except for the irrigation criterion. An analysis of the influence of irrigation and therefore water availability on crop and water balance terms is done.

a) Variation of actual relative transpiration (T/ET_a) respectively evaporation (E_a/ET_a) due to a varying planting density

The relation between E_a/ET_a and T/ET_a can be described as follows:

$$(24).\qquad T/ET_a = 1 - E_a/ET_a$$

Considering equation (24) shows that viewing the course of E_a/ET_a also gives information about the tendency and magnitude of T/ET_a. Figure 21 shows the course of E_a/ET_a due to a varying *PD*. The vertical scatter of E_a/ET_a per *PD* can be seen as an influence of the seasonal variation of climatic conditions. Each course in Figure 21 shows a decreasing seasonal E_a/ET_a due to increasing *PD*. This tendency is not surprising and was expected prior to the simulation. The results of the model can be explained with an increased light extinction at high stand densities. An increasing *LAI* at high seeding rates decreases E_p (see equation **Fehler! Verweisquelle konnte nicht gefunden werden.**) and therefore also E_a. The simulation suggests the LAI averaged over 12 seasons to increase from 1.54 (SD = 0.22) at *PD1* to 2.96 (SD = 0.31 m) at *PD13*.

The average value for E_a/ET_a declines from 0.27 at *PD1* to 0.20 at *PD13*. Also SD is decreasing from 0.05 at *PD1* to 0.02 at *PD13*, i.e. the seasonal scatter decreases with rising *PD*. The range of E_a/ET_a over 12 seasons varies by 12 % at *PD1* and by 8 % at *PD13;* see Table 15.

Comparing Darcy and Black calculations for actual soil evaporation shows a similar tendency of E_a/ET_a to decline with rising *PD* although the order of magnitude is different. As expected, the Darcy simulation probably overestimates E_a/ET_a with values up to 0.7 at low *PD*. Both at the Black and the Boesten-Stroosnijder simulation it is

striking that E_a/ET_a "jumps" occur in between two *PD* in certain seasons, example given in 1994 from 0.19 at *PD6* = 1.6×106 pl ha-1 to 0.24 at *PD7* = 1.8×106 pl ha^{-1}.
These skips correspond to changes of the irrigation amounts and can be explained by the chosen irrigation criteria. If the irrigation amount is reduced, anomalies of the course are flattened.

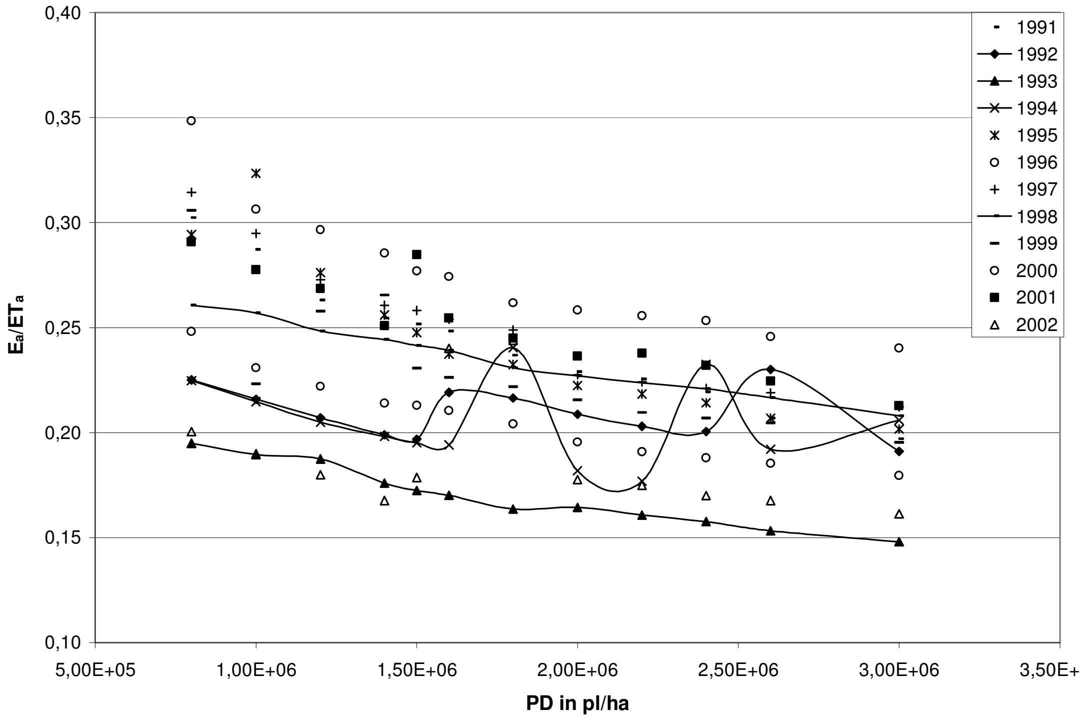

Figure 21 Simulation results: relative evaporation for twelve varying planting densities, vertical scatter constitutes twelve different seasons, irrigation criteria I2, soil evaporation according to Boesten - Stroosnijder

Table 15 shows the influence of the irrigation criteria and *PD* on the vertical scatter, the average of E_a/ET_a and the absolute values of E_a. Under well watered conditions the seasonal influence seems to be minimal. Without irrigation the scatter is larger and appears to stay constant despite a varying *PD*. For the simulation runs can be stated, that the more sufficient the water supply, the higher is the potential of reducing E_a/ET_a due to increased *PD*. This tendency can be recognized, although the effect is very small. For irrigation criterion I2 (pF=3.6) $\Delta E_a/ET_a$ accounts for 7 % and without irrigation $\Delta E_a/ET_a$ accounts for 5 %, when *PD* is almost quadrupled from 8.0 × 10^5 to 3.0 × 10^6 pl ha^{-1}. Despite there is also a reduction in absolute values of E_a, ET_a increases on average by 43 mm from *PD1* to *PD13*.

	irrigation criterion	PD1	PD13
E_a/ET_a seasonal scatter in %	I2 (pF=3.6)	12	8
	I5 (no irrigation)	24	24
E_a/ET_a average ± SD	I2 (pF=3.6)	0.27± 0.05	0.2 ± 0.02
	I5 (no irrigation)	0.35 ± 0.07	0.3 ± 0.06
E_a ± SD in mm	I2 (pF=3.6)	79 ± 16	69 ± 10
	I5 (no irrigation)	46 ± 16	40 ± 15
ET_a ± SD in mm	I2 (pF=3.6)	265 ± 25	308 ± 18
	I5 (no irrigation)	130 ± 28	133 ± 29

Table 15. Simulation results: seasonal scatter and average of relative evaporation, twelve season average actual soil evaporation and evapotranspiration for irrigation criterion I2 and I5 and two different planting densities, actual soil evaporation according to Boesten-Stroosnijder

For the specific case in Sirsa the simulation suggests that an increase in *PD* cannot considered to be a “real” vapor shift”. Although E_a/ET_a and E_a are decreasing respectively T/ET_a is decreasing due to increasing *PD,* there is still the fact that the absolute demand of water is increasing. However, if CWP decreases respectively WUE increases, the same amount of yield in an area can be attained with less water. Due to the chosen irrigation criteria it is not possible to analyze the dynamics of the water flows with a constant ET_a.

b) Variation of yield and harvest index due to a varying planting density

Y respectively *HI* are additional parameters to analyze. Figure 22 shows the variation of *HI* on the y-axis for 13 different planting densities on the x-axis. Again the vertical scatter can be seen as the seasonal influence due to variation of climatic conditions. The simulation course by trend shows a smooth decrease of *HI* with increasing *PD*, which is due a steeper increase of *BM* than of *Y* with rising *PD*. The SWAP/WOFOST simulation proposes a continuous rise of *Y,* which seems to be steeper at low and to flatten at higher *PD*, but without a tendency to decrease again. If *PD* would be increased further, the simulation would probably suggest a constant value for *HI.*

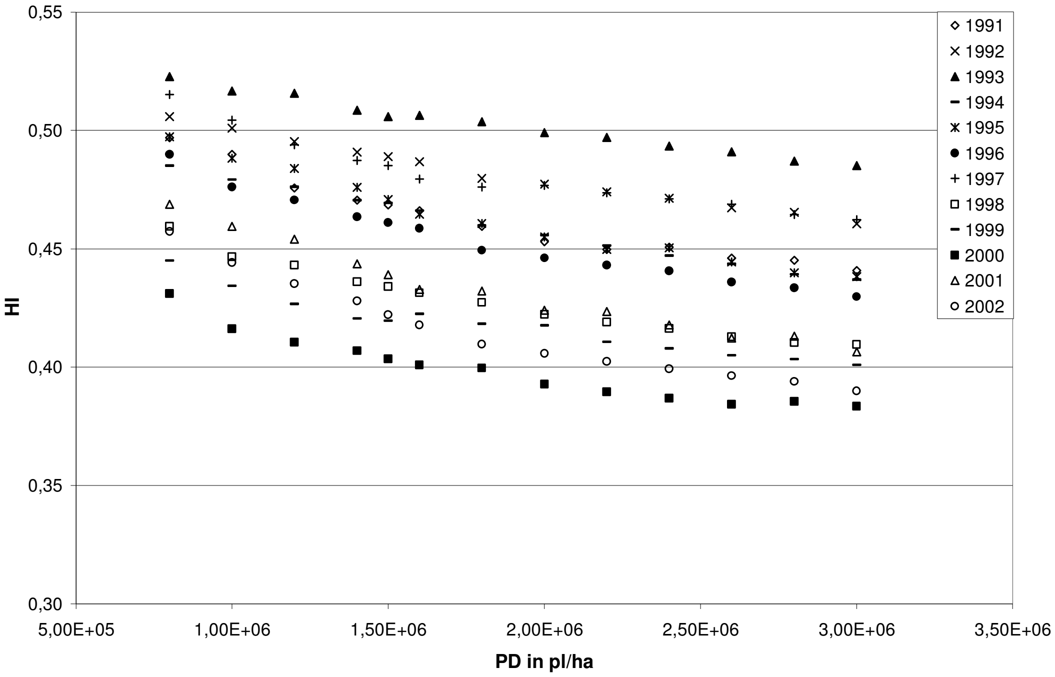

Figure 22 Simulation results of harvest index as a function of planting density, 13 different planting densities, vertical scattering constitutes twelve different seasons, irrigation criteria I2, actual soil evaporation according to Boesten-Stroosnijder

Table 16 presents statistical data for *HI* and *Y* for two irrigation criteria and two different planting densities averaged over 12 seasons. For well watered conditions the seasonal scatter is low and relative constant over the *PD* range, whereas without irrigation the seasonal influence decreases with increasing *PD*. The average reduction of *HI* for pF = 3.6 due to an increase in *PD* from *PD1* to *PD13* accounts for 5 %. At rainfed conditions *HI* is considerable lower and *Y* is even decreasing from 846 kg ha^{-1} at *PD1* to 714 kg ha^{-1} at *PD13*. Rainfall accounts for 46 ± 29 mm averaged over 12 seasons. Despite of this low amount the simulation indicates a crop growth depending on the water stored in the soil in winter. *Y* is mainly lower than 1000 kg ha^{-1}, thus lies in the very low *Y* ranges. *Y* and *HI* are dependent on water supply during different phenological stages of crop growth. The irrigation criteria is adjusted to the matric potential of the soil and different growing stages were thus not taken into account.

	irrigation criterion	PD1	PD13
HI seasonal scatter in %	pF=3.6	9	10
	no irr	30	19
average HI ±SD	pF=3.6	0.48 ± 0.03	0.43 ± 0.03
	no irr	0.19 ± 0.08	0.12 ± 0.05
average Y ±SD in kg	pF=3.6	3977 ± 669	5272 ± 719
	no irr	846 ± 561	714 ± 517

Table 16. Simulation results: Seasonal scattering of harvest index, twelve season average ± SD of harvest index and yield for two irrigation criteria and two planting densities, actual soil evaporation according to Boesten-Stroosnijder

c) Variation of transpiration efficiency due to a varying planting density

In Chapter 2.3 it is argued that an increasing stand density reduces the vapor pressure deficit and therefore increases *TE*. SWAP does not account for that effect as the model does not simulate atmospheric vapor pressure deficit. Biomass production and therefore *LAI* are the main variables determining *TE* in the simulations. For comparison, simulation run I (three different *PD* and five varying irrigation criteria) is chosen and the results are illustrated in Figure 23. The results show that there is proportionality between total aboveground *BM* and *T*. A higher stand density leads to a steeper slope of the fitted regression line, which represents *TE*. The model thus suggests what was expected prior to the simulation; an increasing *TE* with increasing *PD*.

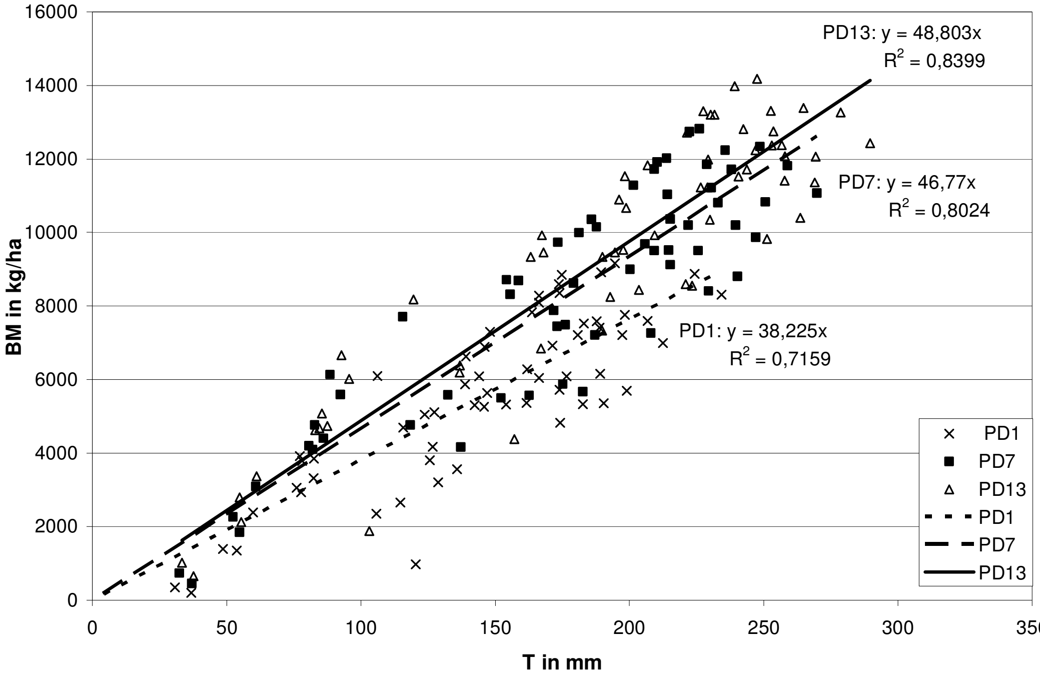

Figure 23 Simulation results of total above ground biomass as a function of transpiration for three different planting densities and five irrigation criteria

Figure 24 represents the course of *TE* as a function of planting density for twelve seasons. The simulation results in a slight increase of *TE* with increasing *PD* at low ranges throughout all seasons. *TE* seems to reach a constant level at higher PD, starting from about 2.2 × 10^6 pl ha^{-1}. This constancy of *TE* can be related to a certain canopy density and thus *LAI*. The results of this simulation suggest an averaged threshold of LAI = 2.62 ± 0.29, above which *TE* is about constant.

The order of magnitude from simulated *TE* (see Table 17) corresponds with the *TE* = 50.6 ± 12.2 kg $mm^{-1}.ha^{-1}$ for wheat suggested by the database.

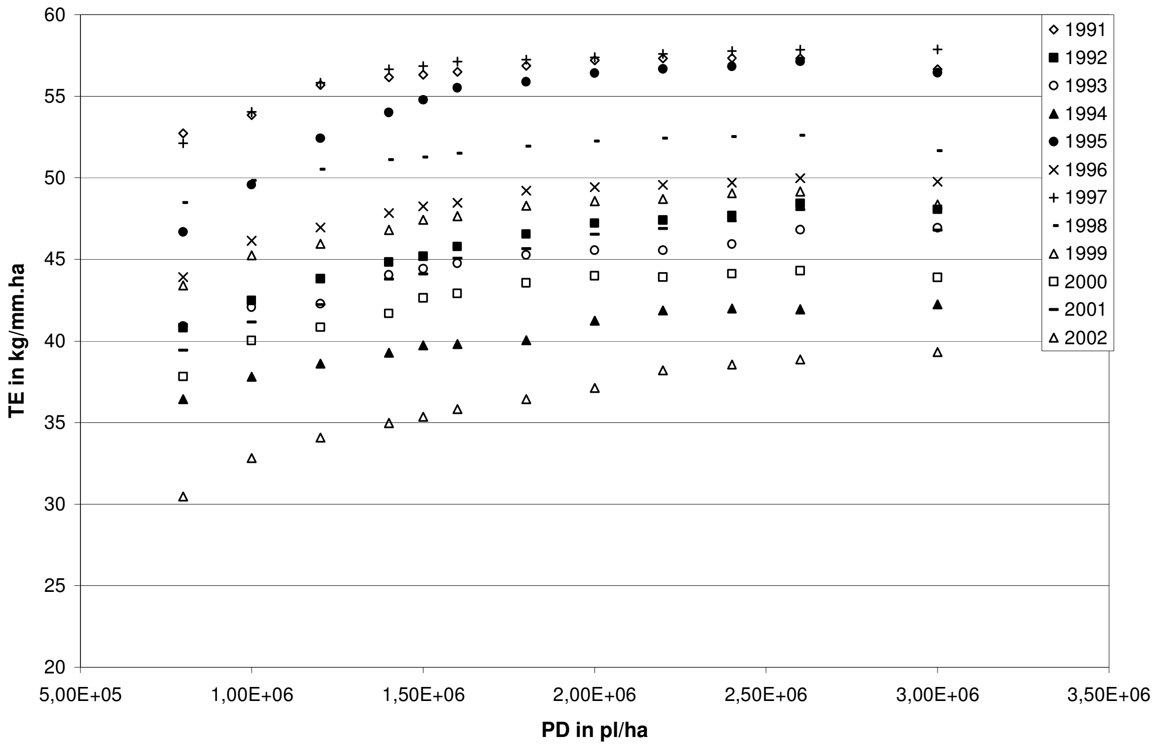

Figure 24 Simulation results of transpiration efficiency as a function of planting density for twelve planting densities and irrigation criteria I2, vertical scattering constitutes twelve different seasons, actual soil evaporation according to Boesten-Stroosnijder

Table 17 presents results of *TE* for three different planting densities and two varying irrigation criteria. At dry conditions (no irrigation) the twelve season average *TE* seems to be higher than at well watered conditions (pF=3.6). Under rainfed conditions both biomass production and *T* drop considerable. Without irrigation the simulation suggests a larger decrease of *BM* compared to *T*. The difference in *TE* between well watered and rainfed is smaller at *PD1* (9.1%) and increases with a denser stand at *PD13* (17.3%).

TE average ± SD in kg mm/ha	*PD1*	*PD7*	*PD13*
pF=3.6	42.8 ± 6.0	48.1 ± 6.1	49.0 ± 5.4
no irr	46.7 ± 8.6	54.8 ± 8.9	57.5 ± 7.9
difference in %	9,1	13,9	17,3

Table 17. Simulation results: twelve season average values and standard deviation for transpiration efficiency for well watered and rainfed conditions, three planting densities, actual soil evaporation according to Boesten-Stroosnijder

d) Water use efficiency

To have a better overview of parameters influencing WUE, equation (9) is pictured below.

$$WUE = \frac{Y}{ET} = HI * TE * T / ET = \frac{Y}{BM} * \frac{BM}{T} * \frac{T}{ET}$$

Analyzing the simulation in terms of *WUE* results in a rise with increasing planting density. Figure 25 shows a steeper slope at low stand densities till about 1.5 × 10^6 pl ha^{-1} and a very low increase respectively constancy at higher *PD*. It seems that at greater *PD* the contrary effect of declining *HI* and decreasing E_a/ET_a respectively increasing T/ET_a cancels further changes in *WUE* respectively minimizes them. An optimum *Y(PD)* function would probably also lead to an optimum *WUE(PD)* curve. At least this was the expectation prior to the simulation.

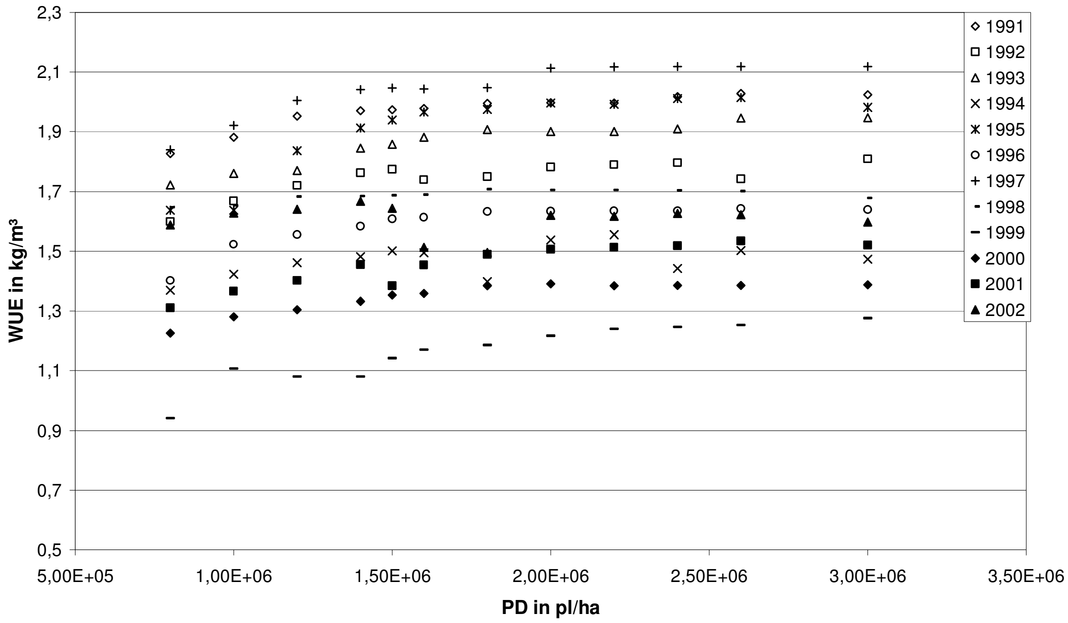

Figure 25 Simulation results of water use efficiency as a function of planting density for twelve planting densities and twelve seasons, irrigation criteria I2, actual soil evaporation according to Boesten-Stroosnijder

An increase from *PD1* to *PD7* at well watered conditions yields an *WUE* improvement of 10 % (see Table 18), whereas an increase from *PD1* to *PD13* results in an rise of 12 to 13 %. An increase from *PD7* to *PD13* further improves *WUE* by just 3 %. Therefore the simulation suggests a greater potential for *WUE* improvement in the lower *PD* range. The simulated *WUE* range corresponds with the range suggested by Zwart and Bastiaanssen (2004), which accounts for 0.6 – 1.7 kg m^{-3} for wheat.

	irrigation criterion	***PD in* pl/ha**		
		PD1	***PD7***	***PD13***
		800000	**1800000**	**3000000**
***WUE in* kg/m³**	***I1 (pF=3.0)***	1.5 ± 0.25	1.65 ± 0.27	1.69 ± 0.26
	I2 (pF=3.6)	1.51 ± 0.27	1.66 ± 0.28	1.7 ± 0.27
	I4 (pF=4.2)	1.16 ± 0.26	1.3 ± 0.28	1.23 ± 0.29
	I5 (no irr)	0.6 ± 0.32	0.55 ± 0.30	0.5 ± 0.29
imrovement or decrease compared to PD1 in %	***I1 (pF=3.0)***		10	12
	I2 (pF=3.6)		10	13
	I4 (pF=4.2)		12	6
	I5 (no irr)		-9	-17

Table 18. Simulation results for twelve season average water use efficiency, four irrigation criteria and three planting densities, actual soil evaporation according to Boesten-Stroosnijder

Figure 26 shows the twelve season average *WUE* for different planting densities and a varying irrigation criterion. For well watered conditions (pF = 3.0 and 3.6) the optimum in *WUE* is suggested to be in the high *PD* ranges. The simulation results in a steeper increase in the lower *PD* ranges and the curve is flattened in the higher *PD* ranges. Without irrigation *WUE* is proposed to constantly decrease with increasing *PD.* At water scarce conditions the optimum *PD* might therefore lie in the low *PD* ranges. Only in case of low irrigation (pF=4.2) *WUE (PD)* follows the expected optimum curve. The simulation suggests a maximum at about 1.8×10^{6} pl ha^{-1}.

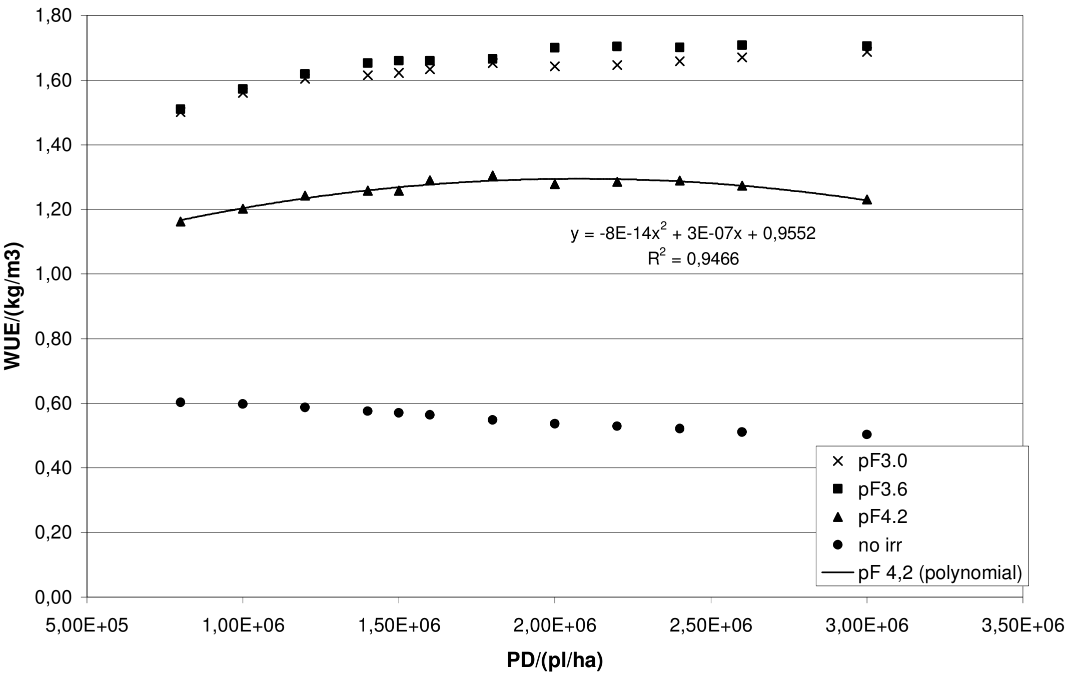

Figure 26 :Simulated twelve season average water use efficiency for four different irrigation criteria and twelve different planting densities

4.4 Analysis and Discussion: mulching

4.4.1 Introduction

First the physical functionality of mulch will be introduced. Effects on crop and water balance terms suggested in literature will be discussed further. Chapter 4.4.3 analyzes simulation runs, in which one irrigation criteria (I2) and two planting densities (*PD1* = low, *PD7* = medium) were used. The influence of an implemented mulch layer on crop and water balance terms will be shown.

4.4.2 Aspects from Literature concerning mulching and expected Changes of Crop and Water Balance Terms prior to the Simulations

Keeping in mind the basic concept of viewing *WUE* (Chapter 2.3), the possible effect of mulch on E_a and Y found in literature will be discussed in short. Interactions of the soil-water-atmosphere system will be explained.

a) Physical functionality of a mulch layer

Definition:

A mulch is "any material such as straw, sawdust, leaves, plastic film, loose soil, etc., that is spread or formed on the surface of the soil to protect the soil and/or plant roots from the effects of raindrops, soil crusting, freezing, evaporation, etc." (Soil Science Society of America 1997).

Stubbles and mulches reduce soil evaporation by providing a mechanical barrier to the drying forces of wind and they shield the soil surface from solar radiation. Mulches also buffer the connection between the water vapor in the soil and the air above (Burt et al. 2005).

The statement above indicates the functionality of a mulch layer with regard to soil evaporation. To put it in other words:

- Mulch cover lowers the energy load by reflection and absorption of the incoming net radiation and therefore has an influence on soil temperature.
- Mulch reduces the temperature and the vapor pressure deficit of the air above the soil
- Mulch reduces the turbulent motion of the air near the soil surface. Less vapor is transported from the evaporating surface to the air due to a lower wind speed.

Mulch smoothes out fluctuations in soil moisture and soil temperature. A mulch layer acts like an insulator. The dried up top layer insulates the water conducting bottom layer from the vapor absorbing atmosphere. Due to drying of the surface, E_a rate is reduced. There is already a "self mulching effect" of the soil, even without mulch. Mulching of organic or other materials strengthens this effect. That is a characteristic feature of conservation tillage practises that aim to leave a protective mulch cover at the soil surface, to achieve a less intense and shallower soil manipulation. Besides the effect on E_a, mulch also has a positive effect on the physical protection of the soil surface and therefore the aggregate stabilization. It contributes to better erosion stability, but this is not further discussed in the thesis.

Measures to control evaporation have to be accompanied by measures encouraging infiltration in agriculture. The principle of roughness and openness of the topsoil that is valid for infiltration must also be considered for E_a. For infiltration holds that K_{sat} should be increased. In contrast to E_a, where K_{unsat} should be reduced in the higher tension ranges. (Ehlers and Goss 2004)

b) Materials

There are various possible materials that can be used as a surface mulch cover. Crop residue, plastic film, sand and gravel mulch etc. Sand and gravel are very labor intensive in application and maintenance (Xie et al. 2005). In some regions mulching is also a question of availability of materials, e.g. in West Africa it would be a desirable measure due to often sparse canopies and high evaporative demand. The problem is the feasibility because livestock eat most of the residue during the long dry season and residues are removed from fields for other purposes such as home construction. For reasons of availability of soil physical properties a sand mulch layer is chosen for the simulation.

c) Effect of a mulch layer on yield and actual soil evaporation

Opposed statements have been found regarding *Y*, while experimental data always suggests a reduction in E_a. *Y* variations apparently depend on:

- Delay of plant development due to low soil temperatures
- Amount of conserved water
- Occurrence of water stress
- Amount and distribution of rainfall
- Evaporative demand
- Occurrence of weeds respectively pest

Contradictory results are reported in literature concerning the feedback of *Y* in respect of mulching. Tolk et al.(1999) state that multi year studies showed a variable response to residue with each growing season, ranging from 0 % up to 70 % yield increases.
To give an example, consider the long term experiment in the North China Plain conducted by Zhang et al. (2005). In this region ET_0 greatly exceeds the annual precipitation of 450 to 600 mm, which indicates a high evaporative demand. Winter wheat and maize are combined in a single year rotation as a common practice. Biomass residues exclusive *Y* of winter wheat were used as mulch for maize. Over ten years of experimental observation of mulched (straw) versus non mulched treatment yield the conclusion that the average E_a rate for mulching was smaller than that of no mulching, especially in the earlier growth stages of maize when *LAI* was low.

Without mulching, seasonal soil evaporation accounted for about 30 % of total ET_a; with a mulch layer this value was reduced to 15 to 20 %. That indicates a reduction potential of 10-15 %. Comparison of *WUE* under mulched and non mulched conditions measured for the 10 year period showed that mulch significantly improved *WUE* by 8-10 %.

Yield was improved in some seasons by mulching, while during other seasons there was no significant difference between mulch and non mulch treatments. The mulch reduced actual soil evaporation by 40-50 mm in dry seasons, and the saved water was used by plants for *T* in dry periods, explaining why yield of maize was also improved by mulching in some seasons (Zhang et al. 2005). This example indicates a vapor shift potential for mulch.

Also in the North China Plain Chen et al. (2007) examined the effect of mulch on soil temperature, E_a, *WUE* and *Y* of winter wheat. The analysis lead to the conclusion that mulch reduced soil temperature increase during daytime and soil temperature decrease during night time. With the increase in mulch amount the effects were more obvious. When the crop cover reached its maximum size in May, the effect of mulch on soil temperature was reduced. Due to reduction of soil temperature crop development was delayed. The time of maturity from mulched crops was similar to the control, due to the rapid temperature increase in May and June which restricts the growing period of winter wheat in the North China Plain. Thus, the accumulation of biomass was slower under mulch than without mulch. Also the final grain yield of mulched winter wheat was affected. For the five experimental seasons (2000-2005) mulch reduced grain yield by 5 % to 7 %.

Although mulch reduced E_a, there was a reduction in yield and this resulted in a constant *WUE*, even a decrease in some years (Chen et al. 2007).

This example considering wheat in the same region but different growing period, shows that a delay of plant development in combination with timely, seasonal restriction can have a negative consequence on *Y* and therefore *WUE*. This delay is caused by a lower soil temperature, which inhibits crop development and possibly also deep rooting. This phenomena was also observed in other experiments, for instance by Yunusa et al. (1994), who did investigations on spring wheat. The reduction of deep rooting causes shallow rooting of wheat and corn, which leads to a reduced maximum depth of extraction of soil moisture. The reduced depth of extraction can happen within a magnitude of 0.2 - 0.4 m. This possibly causes a reduction in *T* and consequently in *Y*.

Management practices, climatic conditions and soil type may affect how well a crop responds to surface residue. This indicates that the success of mulching is dependent on various factors and cannot be evaluated as a generally positive measure concerning the improvement of *WUE* respectively in terms of a vapor shift.

4.4.3 Discussion of the Mulch Simulations

Two simulation runs are done for investigation of the 2 cm sand mulch layer:

a) *PD7* = 1.8×10^6 pl ha^{-1}= low, irrigation criterion I2 (pF=3.6), E_a.according to Boesten – Stroosnijder with β_2 = 0.54, time scale: 12 seasons from 1991 till 2002.

b) *PD1* = 0.8×10^5 pl ha^{-1}= low, irrigation criterion I2 (pF=3.6), E_a.according to Boesten – Stroosnijder with β_2 = 0.54, time scale: 12 seasons from 1991 till 2002.

E_a was expected to decline prior to the runs, while *Y* should stay constant or slightly increase. Depending on the magnitude of these two terms *WUE* is mostly expected to improve. *TE is* assumed to stay constant.
Due to the chosen irrigation criterion the model suggests a difference in the added amount of irrigation water. Investigations showed that the lower *PD* is chosen, the lower gets the difference in the amount of irrigation water between mulch and no mulch. In order to minimize the negative effect of the irrigation criterion, a second run with the lower planting density *PD1* is carried out. The difference in irrigation amount is reduced to 5 % between mulch and no mulch. Table 19 presents twelve season average values plus standard deviation for relevant crop and water balance terms for both *PD7* and *PD1*. On average *Y* decreases slightly in both cases, although there are three seasons when it even increased. For the medium planting density *PD7* the *Y* decrease is lower than for *PD1,* which constitutes the low stand density.
Both runs suggest a decline of all green water fluxes due to an implementation of a mulch layer, but to a different extent. E_a decreases most and accounts for about a quarter less with a mulch layer than without. Due to the application of mulch ET_a on average decreases by 7 to 8 % which is both caused by the lowering E_a and the decreasing amount of irrigation and rainfall water. Due to the variation of the amount of irrigation water it is difficult to clearly allocate the decrease of ET_a. *T* nearly stays constant and shows a very slight decrease with about 1 to 1.5 %. Consequently also the relation T/ET_a improves by about 5 % for both runs. Compared to percentage ranges of 10 to 15 % for the improvement potential of mulch found in literature, the calculated improvement potential appears to be low. The simulation suggests only one season with a peak improvement of 14 %. It is not valid to speak of a “real” vapor shift because due to mulching both *T* and E_a decrease. Despite T/ET_a improves the simulation does not suggest a shift from unproductive to productive flow. When considering Figure 3 of the basic concept, the simulations would cause both *ET* and *E*

course to shift downwards, while *Y* would also slightly decrease. All green water fluxes demonstrate seasonal average values for the whole growing period. Early season soil evaporation just accounts for 16 ± 6 mm on a twelve year average and therefore offers little reduction potential for mulching.

During both simulations TE stays uninfluenced by the mulch layer. Values are nearly constant and can be seen in Table 19. Mean *WUE* improves by about 6 to 7 % when a mulch layer is applied. Despite *Y* and therefore harvest index is assumed to decrease, the simulation suggests *WUE* to improve due to the stronger influence of the T/ET_a increase.

		PD7		***PD1***	
		average	**sd**	**average**	**sd**
***Y* in kg/ha**	**nomu**	4887	688	3977	669
	mu	4842	702	3873	667
	Δ in %	-0,9		-2,6	
E_a in mm	**nomu**	68	9	71	16
	mu	49	10	52	11
	Δ in %	-26,7		-25,5	
ET_a in mm	**nomu**	295	18	265	25
	mu	274	14	243	22
	Δ in %	-7,0		-8,2	
***T* in mm**	**nomu**	227	9	194	9
	mu	226	4	191	11
	Δ in %	-0,9		-1,5	
T/ET_a	**nomu**	0,77		0,73	
	mu	0,82		0,79	
	Δ in %	5,1		5,4	
***TE* in kg/mm ha**	**nomu**	48	6	43	6
	mu	48	6	42	6
	Δ in %	-0,2		-0,9	
***WUE* in kg/m³**	**nomu**	1,66	0,28	1,51	0,27
	mu	1,77	0,28	1,59	0,25
	Δ in %	6,6		6,2	
Irr+rain in mm	**nomu**	298	33	253	43
	mu	263	33	240	37
	Δ in %	-11,0		-4,6	

Table 19. Crop and water balance terms changing due mulch for low and medium planting density, irrigation criterion I2, nomu = no mulch, mu = mulch

Table 20.

4.5 Conclusions

General conclusions concerning the modeling part

Viewing the simulation results for winter wheat in Sirsa with regard to the “vapor shift concept” led to the following conclusions. Generally can be said that a deterministic hydrological model can a proper tool to check the potential of water savings in a specific region. To create a hydrological simulation on a regional scale, the desired data amount is enormous. Knowledge of plant growth characteristics, soil physical properties, meteorology and irrigation amounts lead to a considerable experimental setup. On a regional scale demanded data might become too heterogeneous and complex, which makes it possibly expensive to simulate with SWAP. Although the study in Sirsa by Dam and Malik (2003) showed that it is a feasible possibility. Depending on the data availability it might be reasonable to take in account the use of simpler models like e.g. the Water Productivity Simple Dynamic Model (WPSDM) by the Food FAO. The regional scale seems to be the threshold above which it is difficult to apply SWAP-WOFOST due to increasing heterogeneity of soil-, water- and plant characteristics. It strongly depends on the scale of the examination respectively the chosen agricultural measure, if SWAP is the proper tool for further investigations concerning the vapor shift potential of agricultural management options.

Conclusions concerning early season soil evaporation and leaf area index

To minimize early season soil evaporation seems to be a negligible measure for conditions in Sirsa. Early season soil evaporation just accounts for about 10 % of the value suggested by Falkenmark et al. (2004) and the question remains if this order of magnitude is similar for winter cereals in other double cropping systems in different climatic regions. Possibly in general the reduction potential for early season soil evaporation for winter cereals is negligible. Results indicate that the vapor shift concept has to be elaborated more differentiated in terms of crop seasonality. The concept does not say anything about double cropping systems with two cropping seasons in one year or the distinction between summer and winter crops. Due to the wet monsoon months from July until September and a higher evaporative demand summer cereals possibly contains a greater potential to save early season soil evaporation for the investigated region.
Assuming leaf area index as the crucial parameter in calculating actual soil evaporation, the suggested seasonal leaf area index courses clearly indicate its

potential with regard to differing planting density. A higher planting density leads to an increased leaf area index, which causes an earlier canopy closure and therefore soil evaporation both in absolute and in relative terms (E_a/ET_a) to decrease. The seasonal course of leaf area index appears to be the crucial data required to determine early season soil evaporation. For reasons of better comparability, standardization with regard to the definition of early season soil evaporation would be desirable. Two possible standard definitions are given in Chapter 4.3.3 b.

Conclusions concerning increased canopy cover

Simulation output concerning vapor shift is difficult to relate to increased canopy cover. An irrigation criterion had to be used to create a reasonable yield range. A more sufficient irrigation is logically mostly related to a denser canopy cover. The course of soil evaporation as a function of yield is contrary to the suggested theoretical approach of the vapor shift concept and soil evaporation increases with increasing yield. It would be of interest how actual soil evaporation develops as a function of yield for different climatic and agricultural environments. Still the question remains if it is valid to assume the suggested theoretical course of the green water flows over yield (Figure 3) for generalizations.

Whatever the actual slope of soil evaporation vs. yield might look like, a tendency of the course to shift downwards with increasing planting density is observed. In other words, the simulation suggests absolute values of actual soil evaporation to decrease with a denser canopy. Plant transpiration increases to a bigger extent than actual soil evaporation decreases. Additional water for transpiration originates from an increasing amount of irrigation water. Shifting evaporation towards transpiration without a variation in actual evapotranspiration or water supply can be considered as a real vapor shift. Therefore results show the reduction of actual soil evaporation as an actual vapor shift. Doing so, the simulation suggests a low vapor shift potential for the measure of increasing planting density, ranging from 0 till about 9 mm per season (for comparison: Falkenmark et al. (2004) estimate a vapor shift potential of 36 mm for increased canopy cover) depending on the irrigation criterion and the variation in planting density. On a 12 year average the simulation suggests relative transpiration (T/ET_a) respectively relative evaporation (E_a/ET_a) to improve by 7 % due to increased planting density. This improvement also causes crop water productivity on average to increase; the simulation suggests yield and total consumptive water demand to increase with increasing planting density.

Conclusions concerning the improvement of crop water productivity by increasing yield levels

Results of the numerical simulation also confirm the improvement of relative evaporation (E_a/ET_a) respectively relative transpiration (T/ET_a) with increasing yield, which is considered to be an option improving crop water productivity. The model output coincides well with the results of the database and a variation of crop climate specific parameters showed that it is possible to adapt the crop water productivity yield function (*CWP(Y)*) to certain environmental conditions.

It might be reasonable to fit to specific regions and cultivars, in order to be able to estimate improvement potentials, both for yield and crop water productivity. A crop water productivity yield function could be a supporting management tool for integrated water management decisions. Knowing demographic development is the precondition to estimate future water demand. Considering the agricultural area and the potential water availability of a region leads to the question of how much crop can be sustainably produced for a population with the available resources. Thereby crop water productivity yield function could be a support for estimating yield amounts and their effectiveness in terms of water productivity. Doing water demand and availability predictions are crucial as they indicate possible crisis or even system collapses. SWAP could act as a support in finding a balanced compromise between the total water availability and the yield demand, which constitute two antithetic interacting magnitudes.

Viewing crop and water balance terms with the more differentiated approach - changing planting density

The simulation results show that interactions among crop and water balance terms are complex. Interactions in the field are even more complex. Thus it is a question of balancing and managing available water resources with desired yield output. To achieve maximum yield might be crucial, but the main aspect must always be agricultural sustainability. Besides water availability, other possible constraints concerning crop growth (for instance nutrient availability) must be considered. During investigation it turned out that the problem definition is multidimensional. It is not just a question of minimizing actual soil evaporation in favor of transpiration, it is also a question of possible other feedbacks, that are caused by an agricultural measure. The differentiated approach of viewing crop water productivity in combination with multivariate statistical methods might be an appropriate “tool” to cope with this multi dimensionality. Multivariate statistics are only useful for results from field measurements (personal communication with Franz Konecny) and could not be used for simulation results.

Considering crop water balance terms with the more differentiated approach, show transpiration efficiency to increase with increasing planting density. Transpiration efficiency is also suggested to experience a decrease with lower supply of irrigation water. Viewing yield respectively harvest index show both parameters to decrease at rainfed conditions. Under well watered conditions harvest index also decreases despite yield experiencing a considerable increase.

The expected optimum relation for water use efficiency over yield is indicated for the low irrigation criterion (pF=4.2). Simulation results with well watered conditions indicate a continuous increase of water use efficiency with increasing planting density. Interplant competition for water, light and nutrients should in reality also cause an optimum water use efficiency course at well watered conditions. Twelve season average values of water use efficiency at water scarcity are suggesting an optimum planting density the low yield range (see Figure 26).
It can be concluded that in terms of yield respectively harvest index it is not recommendable to increase planting density if water is scarce and no supplemental irrigation is available. On the other hand, at well watered conditions planting should be chosen as high as possible to achieve a maximum yield.

Crop and water balance terms – mulching

Concerning the mulch simulation it must be mentioned that despite a sand layer not being a common practice, the assumption indicating tendencies of water balance terms can be made.
The simulation results show both for low and medium planting density an improvement of water use efficiency of about 6 % due to a mulch layer. This is caused by a decrease in actual soil evaporation. Transpiration stays constant and evapotranstranspiration decreases to the same extent as soil evaporation. Thus it is questionable if it is useful to speak of a vapor shift. Nevertheless the model simulation suggests a reduction of consumptive total water demand.
The next chapter summarizes both constraints concerning the model itself and parameterization. Finally, it can be stated that further investigation of varying planting density and mulch both need improvement of the model and additional empirical research for parameterization.

4.6 Constraints and Recommendations concerning the Model Simulation

Ongoing parameterization and discussion revealed several constraints of the simulation. It turned out that there are several effects and difficulties which simply cannot be accounted for at the current development stage of SWAP. Moreover lacks of data for parameterization will be summarized.

4.6.1 Constraints and Recommendations concerning the Model

- **Row spacing**

Creating a realistic simulation of varying planting density demands the consideration of two factors: One is seeding weight in kg ha^{-1} respectively seeding rate, which in SWAP could be manipulated by Initial Total crop Dry Weight (TDWI). Secondly, there is the so called row spacing which is the spatial alignment of the crop rows. The model is not able to account for this factor. The adjustment of planting density was restricted to the variation of TDWI in kg ha^{-1} without considering a variation of the distance in between the crop rows. The integration method of SWAP uses the daily course of radiation, planting density distribution (leaf area distribution) over height and light interception functions to simulate crop growth. Planting density is always considered to be evenly distributed without including effects resulting from varying row spacing, for instance the clothesline effect (Chapter 2.2.3). SWAP needs further development and programming changes in the source code are necessary for pursuing research with regard to row spacing.

- **Interplant competition for water, light and nutrients at high stand densities**

There is interplant competition for water, light and nutrients at high stand densities with an effect on canopy height, canopy density (leaf area index) and root development. If there are limited resources (water, light, nutrients) and a certain threshold planting density is exceeded, a decrease in plant height and canopy density will be experienced. Also root development could be influenced negatively by a crop stand that is too dense. Furthermore yield, harvest index and therefore water use efficiency would probably decrease. The model can account for water and light competition using a reduced assimilation rate. SWAP can not account for the influence of fertilizer and inter plant competition for nutrients.

- **Static plant growth characteristics concerning planting density**

In SWAP the development of rooting depth and crop height is not influenced both by planting density and irrigation criteria. Crop height is a function of development stage

and rooting depth is defined by an initial value, a value for maximum daily increase and a maximum rooting depth. Regardless of drought or overpopulation, rooting depth and plant height always develop similarly. The importance of plant height during the simulation is an open question.
Same static behavior also accounts for partitioning of leaves, stems and storage organs to the total above ground dry matter. Fixed values are prescribed and bound to the development stage. These static assumptions concerning plant physiology do not account for the dynamic interactions due to sudden changing environmental conditions in the field.

- **Stress during different development stages of the crop**

It was not the objective of the thesis to investigate the influence of water scarcity in combination with stand density during certain development stages of the crop. But during investigation it turned out that it would be of great concern. For instance it is of interest to examine soil water depletion of a high planting density during early season and its influence on the growth dynamics and post anthesis water use. To both investigate water stress on crops for different growth stages by field measurements and by model simulation is a topic for future research.

- **Static plant growth characteristics concerning mulching**

The same problem as mentioned above also accounts for the mulch simulations. The implementation of an additional layer neither changes root development nor plant height. The model does not account for plant physiological interactions as e.g. additional investment of a plant in root growth during drought. Currently in SWAP it is not possible to prevent root growth into of the mulch layer.

- **One dimensional character of the model**

The influence of mulching and varying planting density on horizontal root development is of great interest. Roots could deplete water from zones, where it otherwise would be exposed to soil evaporation. The one dimensional character of the model does not allow accounting for the effect of a horizontal water flow that possibly occurs in the root zone during a vapor shift. Possibly a two dimensional model would be beneficial for investigations concerning the water flow dynamics of a vapor shift in the root zone.

4.6.2 Constraints and Recommendations concerning the Parameterization

- **Chosen irrigation criteria**

The chosen irrigation criteria strongly influences water supply and therefore the green water flows. The more water that is evaporated respectively transpired, the earlier the soil is depleted and the more is irrigated. This effect made it somehow difficult to compare the water flows between planting densities. In terms of a vapor shift investigation with respect to a varying stand density a fixed irrigation criterion would possibly yield a better comparability of the results. This also accounts for the mulch simulations. The implementation of the 2 cm sand layer leads to a decrease in the amount of irrigation water.

- **Parameterization of mulch**

A sand mulch layer is chosen due to a lack of information concerning soil physical input data for an organic mulch layer consisting of plant residues. This alternative solution is very labor intensive and not the common practice in agriculture. It would be desirable to get knowledge of soil physical properties of layers consisting of organic material from empirical research.

- **Empirical coefficients for calculation of actual soil evaporation**

Data availability for parameterization of the model was generally sufficient, but there was no possibility of comparing of green water flows from simulation runs with empirical measurements. Calculations for evaporation and transpiration by Dam and Malik (2003) are based on water contents, salinity concentrations and crop development.

There was a lack of information about empirical coefficients (Black respectively Boesten - Stroosnijder) for calculation of actual soil evaporation. The uncertainty concerning the estimate is shown in Chapter 4.2.2. More empirical data from field research is necessary to separate green water flows more exactly.

5 Summary and Outlook

Continuing global population growth puts increasing pressure on water resources. FAO future predictions concerning food production indicate that additional water resources have to be generated. Respectively, water must be used more effectively to help decrease the number of currently 800 mio undernourished people. Agriculture is by far the largest water consumer besides household and industry water demand. Therefore it was worthwhile investigating crop water productivity improvement potential in cereal production within this thesis. Falkenmark et al. (2004) introduce a conceptual approach which suggests a 330 km^3 y^{-1} could be saved by shifting unproductive soil evaporation towards productive plant transpiration by 2050; a so called vapor shift. Reducing early season soil evaporation and increasing the canopy cover of a crop stand are the two suggested measures to reach this reduction of consumptive water resources. A vapor shift also implies an improvement in crop water productivity. Besides the two mentioned possibilities an increasing yield should also improve crop water productivity and Rockstrom (2003) introduces a biophysical crop water productivity–yield function. This function suggests the lower yield ranges to contain a great improvement potential of crop water productivity.

The aim of the thesis was an evaluation of the suggested potential of a vapor shift and an improvement in crop water productivity by Falkenmark (2004) and Rockstrom (2003). The evaluation was done in two steps and on two scales.
Firstly, a literature search was done. The search aimed to collect experiments that separated soil evaporation from plant transpiration on a seasonal scale. In order to build up a database it was also of interest to get additional information about relevant crop water balance terms. The global estimate was done with the results of the database and compared with the calculations of Falkenmark et al. (2004).
Secondly, the agro hydrological model SWAP was used for evaluating the vapor shift concept on a local scale. Available crop, soil and weather data for Sirsa in India was used to build up a model for investigating two promising agricultural measures: variation in planting density and mulching.

The global estimates using the built up database resulted in a 37 % lower overall vapor shift potential of 211 km^2 y^{-1}. Early season soil evaporation was 50 % and increased canopy cover 29 % lower. A possible reason is that the database mainly contained experiments in dry and Mediterranean climates while Falkenmark et al. (2004) used values for tropical agriculture. Literature indicated a wide range for relative evaporation (E_a/ET_a from about 0,2 to 0,7 %) which constitutes a great uncertainty within the estimate. The reduction potential of relative evaporation of about 20 % due to increased canopy cover was confirmed in Chapter 3.3.5. Transpirational water productivity was 25 % lower from the database than by Falkenmark et al. (2004). Within the estimate it was critical to assume a yield increase which logically also resulted in an increase of consumptive total water demand. Experimental results fitted to the form of the biophysical crop water productivity–yield relation. The function could be adapted cultivar and climate specific and offers to be a promising water management tool. Collected experimental green water flows showed a great scattering compared to the assumed linear course of the basic concept and a course for soil evaporation as a function of yield is hardly detectable.

The practical evaluation of the vapor shift concept on a local scale showed the more differentiated approach (Chapter 2.3 b) of viewing crop water productivity respectively water use efficiency to have a sufficient accuracy. The conceptual approach is useful in considering the variation of yield against total above ground biomass. The simulation suggested the saving potential for early season soil evaporation for winter wheat to just account for 10 % of the value suggested by Falkenmark et al. (2004). A low evaporative demand and low temperatures could possibly also mean a negligible saving potential concerning early season soil evaporation for other winter cereals. With regard to increased canopy cover the simulation suggested an improvement of relative transpiration (T/ET_a). The reason was the chosen irrigation criterion which increased total evapotranspiration with increased canopy cover. Contrary to the conceptual approach in Figure 3 soil evaporation is suggested to increase with increasing yield. Comparison of simulation results for crop water productivity as a function of yield with the database results and the theoretical function showed a good conformance. In terms of crop water productivity the SWAP simulation suggests increased canopy cover to be beneficial at well watered conditions but disadvantageous at rainfed conditions with low amounts of rainfall. An optimum of the expected crop water productivity yield relation was only shown for the irrigation criterion which starts from permanent wilting point.
Mulching simulations showed an improvement potential of crop water productivity of 6 %. With respect to a pure shift from soil evaporation to transpiration the chosen irrigation criterion with its varying water supply made the analysis of the simulations difficult.

The conceptual approach could be improved by giving a clearer definition of early season soil evaporation. The temporal scale of the concept should be defined more exactly and if it uses a yearly basis, the question of handling double cropping systems remains. Clearer definitions and equations standing behind the concept would be desirable. Increased canopy cover and increasing yield levels could hardly be separated and should be merged as one improvement option. Possibly, it could be more useful to concentrate on the improvement of crop water productivity and not on the trade off from soil evaporation to plant transpiration. The simulation with SWAP showed that it is difficult to detect the pure trade off between the green water flows.

The global estimates done with the vapor shift concept showed that a certain degree of differentiation is necessary. For instance, repeating the estimate for different climate regions would definitely improve its quality. Despite figures of population growth and yield improvement, they remain as uncertainty factors. As the figures anyway indicate a need for action it remains questionable, whether it is useful in putting more effort into improving the quality of the considered estimate. Possibly, it would be more reasonable to concentrate on improving crop water productivity on a local scale. In combination with field research the model SWAP could be a practical well developed tool for investigating the vapor shift potential of a certain agricultural management option. Besides mulching and increased planting density there are still other agricultural measures recommended by Falkenmark et al. (2004). Each of these measures must be checked empirically and by model simulation with regard to a more effective use of water in agriculture.

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Appendix

List of Symbols

Symbol	Description	Unit
β_1	Black coefficient	cm $d^{-0.5}$
β_2	Boesten-Stroosnijder coefficient	$cm^{0,5}$
BM	Aboveground dry biomass	kg
CWP	Crop water productivity containing the seasonal evapotranspiration per saleable yield	m^3 kg^{-1} or mm ha t^{-1}
DAS	Days after sowing	
E	Soil evaporation	mm
E_a	Actual soil evaporation	mm
E_a/ET_a	Relative actual evaporation	-
e*-e	Vapour pressure deficit of the air	kPa
E_p	Potential evaporation of a soil under a standing crop	mm
ET	Evapotranspiration	mm
ET_a	Actual evapotranspiration	mm
ET_{ref}	Reference crop evapotranspiration	mm
HI	Harvest index	-
k_c	Crop specific factor for calculating transpiration efficiency	kg kPa mm^{-1} ha^{-1}
LAI	Leaf Area Index	-
P	Precipitation	mm
PD	Planting Density or stand density	pl ha^{-1}
RH	Relative humidity	%
T	Plant Transpiration	mm
TE	Transpiration efficiency	kg mm^{-1} ha^{-1}
T_p	Potential plant transpiration	mm
WP_T	Transpirational water productivity	mm ha t^{-1}
T/ET_a	Relative transpiration	-
WUE	Water Use Efficiency	kg m^{-3} or kg ha^{-1} mm^{-1}
Y	Yield = marketable part of the total above ground biomass	kg ha^{-1}