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Ecophysiological Experiments for Improving Landuse Patterns in the Drylands of Southeast Kenya by Means of Drought Resistant Leguminous Crops (Tepary Beans, Bambarra Groundnuts)

Ökophysiologische Experimente zur Verbesserung der Landnutzung im Trockengrenzbereich SE-Kenyas mit trockenadaptierten Leguminosen (Tepary-Bohnen, Bambarra-Erderbsen)

by Berthold Hornetz*

1 Introduction

Pressure induced by increased population of as much as about 4% per year (HAMMES and BAUER, 1985) has led to a dramatical diminution of arable land in the smallholder farming areas of Kenya, especially in the so called "high potential areas". RUTHENBERG (1980, p. 6) estimates that the per capita share of this ecologically favoured, highly productive land will be reduced from 0.78 ha in the year 1965 to 0.2–0.3 ha by the year 2000.

In former times, smallholders and also pastoralists from those regions affected by population pressure migrated into suitable areas without generally increasing the risks of harming food production (e.g. in Machakos: ZÖBISCH, 1986, p. 27 ff.). However, nowadays people either have to optimize their agricultural systems in these high potential areas by expensive investments or –as most of them– leave their homes and try to settle in uncultivated areas, predominantly marginal agricultural lands of the semi-arid and arid drylands (named "Agrosahel" in JÄTZOLD, 1979b).

It should be remembered that these areas have only short to very short agrohumid periods (= potential growing periods, AHP) of about 40/45 to 85/105 days (JÄTZOLD and

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SCHMIDT, 1982/3) with low intensity (water supply during the main part of the rainy season < 80% of the potential evaporation) and frequent dry spells.
As JÄTZOLD (1979a) showed with his description of the "Haraka Settlement Schemes" in Eastern Kenya, cultivation attempts in the extremely ecologically sensitive drylands were very often badly prepared. People were unconscious of the carrying capacity of their new fields, which resulted in desertification and finally food crisis and famine.

Though it can be observed that in the wetter parts of the drylands smallholders have started to cultivate drought resistant leguminous crops like pigeon peas *(Cajanus cajan)* and cowpeas *(Vigna unguiculata)*, there is a lack of ecologically adapted crops in the potential cropping areas. This is particularly the case in the drier parts of the agroecological zone 5 and in zone 6 (AEZ, acc. to: JÄTZOLD and SCHMIDT, 1982/3), which have until recently been dominated by extensive grazing systems (Zone 5 extends between the boundary of rainfed-agriculture of maize and that of millet; beyond is Zone 6, the Ranching Zone; see also: JÄTZOLD and KUTSCH, 1983). The reason for this being that on the one hand the pastoralists have little interest to cultivate albuminous food and fodder crops, while on the other the new settlers from the high potential areas generally possess crops with longer vegetation cycles and less ability to adapt to high temperature and water stress.

The multifunctional leguminous plants (e.g. GÄRTNER et al., 1982, p. 9) of tepary beans and bambarra groundnuts were stigmatized as "poor man's crops" (NATIONAL ACADEMY OF SCIENCES, 1979, p. 47) in the past due to the introduction of major food crops, such as maize and beans, into tropical agriculture. In spite of their image as "minor crops" both pulses produce nutritious foods (e.g. SMARTT, 1976; NABHAN et al., 1980; DUKE, 1981; GÄRTNER et al., 1982; BEGEMANN, 1988) and seem to be well adapted to hot and arid sites. Wild varieties of tepary beans can even be found at ecologically favoured sites in the semi-deserts and deserts (e.g. drainage lines) of SW-USA and NW-Mexico (NABHAN and FELGER, 1978), while wild varieties of bambarra groundnuts grow in the drier parts of the savannahs of Western and Central Africa (e.g. KARIKARI, 1971; BEGEMANN, 1988).

However, two things must be done before such scientifically neglected "minor crops" can be recommended as food and/or fodder crops to smallholders in dryland agriculture in order to stabilize food production and maintain soil fertility. First it is indispensable to test certain ecophysiological properties of the plants such as crop water requirements or response to high temperature and water stress (stress physiology). Second, it is necessary to apply this experimentally obtained information in spatially differentiated landuse patterns for planning purposes.

2 Material

2.1 Crops

Phaseolus acutifolius A. Gray, var. *latifolius* (tepary bean):

- originating from the semi-deserts and deserts of NW-Mexico and SW-USA;
- domesticated about 5000 years ago, predominantly by means of "floodwater-farming agriculture"; self pollinating; (SMITH, 1965; BRÜCHER, 1977, p. 190; NABHAN and FELGER, 1978, p. 8);
- growth chamber experiments at the University of Trier performed with seeds of a short-cycle variety (60 days) from the "Desert Botanical Garden" (Phoenix, Arizona/USA); age of the seeds: eight years; 1000-seeds weight: 127 g.

Voandzeia/Vigna subterranea (L.) Thouars (bambarra groundnut):

- originating apparently from the Sahelian and northern Sudanian zone (BEGEMANN, 1988, p. 30);
- domesticated varieties are differentiated in more than 50 native varieties in Africa (BRÜCHER, 1977, p. 209); smallholder farming in some regions of the savannahs of Africa and Madagascar; self and cross pollinating;
- growth chamber experiments at the University of Trier with seeds from the "International Institute of Tropical Agriculture" (IITA, Ibadan/Nigeria), "Southern Regional Plant Introduction Station" (Washington, D.C./USA), "National Food Research Institute" (Pretoria/RSA); ecophysiological experiments with an early maturing variety (90 days) from South Africa; 1000-seeds weight: 450 g.

2.2 Rhizobia

- host-specific rhizobia strains: *Rhizobium phaseoli* and tepary beans (strains R 510, 544, 578, 579, 585), *Rhizobium spp.* (cowpea-strains) for bambarra groundnuts (R 916, 924) (all strains had been provided by: RADICIN-Institut für landwirtschaftliche Bakteriologie, Iserlohn/FRG.);
- strains treated for inoculation and inoculated according to the methods of ROUGHLEY (1970).

2.3 Soil

Basic considerations:

- simulation of a marginal agricultural dryland site with strong degradation ("minimum scenario");
- minimum compensation of growth conditions as well as minimum conditions for nodulation;

Physical, chemical and biological properties of the soil:

- texture: 80.6% sand (< 2 mm), 4.0% silt, 15% clay (100% kaolinite);

- plant-available soil water: 6.7mm per 10cm of soil (pF 2.5–4.2);
- CEC (with AAS): *total* 3.300 (all in mval/100 g of soil), *K* 0.065. *Na* 0.073, *Mg* 0.172, *Ca* 1.070;
- pH value (measured in 0.01 M/l $CaCl_2$): 6.9;
- C/N ratio (N acc. to KJELDAHL, C acc. to WESTHÖFF): 10.55;
- analysis of humic substances: quotient of absorption 400/600nm (acc. to: KUTSCH and DANNEBERG, 1985) for fulvo acids 8.54 and humic acids 8.44;
- sterilization of the soil with hot steam (93°C, two hours).

Growth vessels:

- preliminary experiments in pots (clay, two liter, well aerated);
- main experiments in growth containers with a special irrigation equipment (HORNETZ, 1988).

2.4 Growth/climatic chamber at the University of Trier

Measures:

3.85–5.10 long, 1.55–2.70 wide, 3.00 high (about 37 m^3 volume, thermoisolation);

Growth conditions:

can be regulated according to the climatic and physiological demands of the plants (here: Voi/Kenya, first rainy season acc. to: KENYA METEOROLOGICAL DEPARTMENT, 1984; KAY, 1978; DUKE, 1981)
- illumination: up to 20000 lux (main peak at 550–650 nm, secondary peak at 380–400 nm);
- photoperiod: 12 hours;
- temperatures: 20–22°C (night), 30–33°C (day);
- relative humidity: 85–90% (night), 45–50% (day);
- ventilation: about 0.5 m/sec.

3 Methods

Research on the ecophysiology of tropical leguminous crops as well as its agroclimatic relevance in spatially differentiated cropping patterns of the drylands requires a number of examinations. These examinations, which concern plant- and ecophysiology (KREEB, 1977, p. 16) were adressed in preliminary and main experiments and will be detailed later on in this text in order to serve as a basis for all further testing. Numerical methods were then applied for the differentiation of landuse patterns, for water balance and simulation modelling as well as for recommendation and prediction purposes.

3.1 Experimental methods

Transpiration:

- gravimetric method according to STOCKER;
- plant-specific reduction coefficients (γ) according to the empirical formula of KUTSCH (1978, p. 46) depending on the evaporative demand of the atmosphere (ET_0), correlated with consumptive water use, hydrature (for the terminology see: WALTER, 1931; KREEB, 1958, 1974) and actual soil moisture;

Leaf water potential (ψ):

- in situ measurements with thermocouple hygrometers L-51A and dew point microvoltmeter HR-33T (WESCOR, Logan, Utah/USA);
- installation of probes according to: BAUGHN and TANNER (1981).

Actual soil moisture:

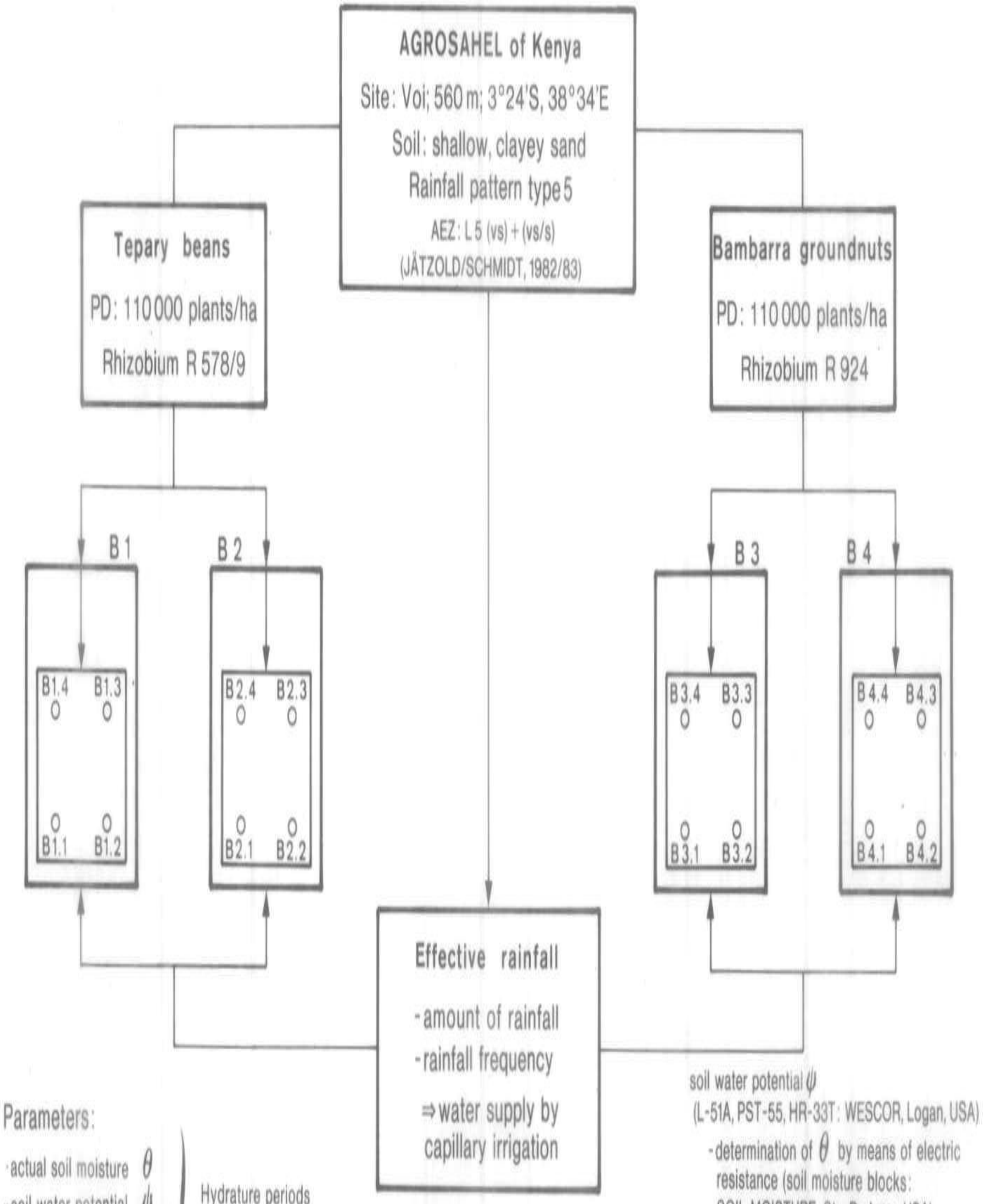
- gravimetrically;
- indirect measurements of soil water potential (ψ) with thermocouple hygrometers PST-55 and dew point microvoltmeter HR-33T (WESCOR, Logan, Utah/USA) and electric resistance (soil water suction) with LF 90 (WTW, Weilheim/FRG) and soil moisture blocks (SOILMOISTURE, Sta. Barbara, Calif./USA).

Irrigation control by leaf and soil hygrometers; irrigation intervals and amounts during main experiments were simulated according to typical rainfall distribution patterns in the drylands of Southeast Kenya (site: Voi; see Fig. 1).

3.2 Numerical methods

Evapotranspiration as the most important output parameter within water balance studies was calculated using the PENMAN formula, modified by McCULLOCH in 1965, on the basis of a mean albedo of 20% for the drylands of Southeastern Kenya (reference evapotranspiration, ET_0). The reference evapotranspiration in the growth chamber was computed by a new mathematical approach, combining an energy term (equivalent temperature) with an aerodynamic-hygric term, corrected by an empirical coefficient. This new formula was tested for several sites in Western Africa along a geographical profile from the Guinea coastal plains to the Sahara and was calibrated with the PENMAN standard.

The optimization of agricultural systems as a predominant subject of tropical and subtropical landuse planning requires relevant methodological instruments like "scenario-concept" (HORNETZ, 1985) and simulation computation (e.g. HANKS and HILL, 1980; PENNING DE VRIES and VAN LAAR, 1982; KUTSCH and SCHUH, 1983). These two approaches belong to systems analysis (see e.g. VAN KEULEN and WOLF,



Parameters:

- actual soil moisture θ
- soil water potential ψ
- leaf water potential ψ
- crop water requirements, consumptive water use
- plant morphology

Hydrature periods

- drought resistance
- yield potentials

Methods:

a) observative: alteration in plant morphology

b) experimental:

- hygrometric measurements of leaf and soil water potential ψ (L-51A, PST-55, HR-33T: WESCOR, Logan, USA)
- determination of θ by means of electric resistance (soil moisture blocks: SOIL MOISTURE, Sta. Barbara, USA)
- transpiration measurements

c) numerical: computer simulation of

- agrohumid periods (AHP)
- hydrature-dependent yield potentials

Fig. 1: Experimentation in growth containers (methods, aims of research)

1986) and permit simulation modelling of real cropping patterns under defined aspects. These aspects include the water supply of a crop stand and its optimization by means of EDP-computation of agroecological and -economical data.

Data on plant physiology, climatology, pedology and landuse practices are obtained either empirically or by experimentation and are later prepared in scenarios. The computations of these scenarios and the information arising from them surpass traditional field experiments for two reasons. First, the low cost of equipment and scientific and non-scientific labourers makes the scenarios economical. Second, results are arrived at rapidly and prove spatially transformable.
The simulation model WATBAL (KUTSCH and SCHUH, 1983) with its three submodels (modules) for

1. testing/calculating the ecological conditions for potential growing periods (= agrohumid periods, AHP);
2. calculating crop water requirements, expressed as physiological coefficients, Kc, (DOORENBOS and PRUITT, 1977; DOORENBOS and KASSAM, 1979; KUTSCH and SCHUH, 1980; applied for crop stands of potatoes by: KERSCHER, 1982), as well as the mean optimum growth of the roots within the main rooting zone of the soil;
3. computing crop and soil water balances within the main rooting zone and the actual water supply, expressed as fraction of the corresponding Kc-value

was refined, considering the following parameters of stress physiology with yield relevance:

- threshold values of hydrature depending on certain amounts of actual soil moisture;
- adaptation of transpiration rates and consumptive water use to the decreasing soil water reserves;
- drought resisting mechanisms (morphological and physiological responses) and the retardation of the permanent wilting point, increasing the amount of plant-available soil water (HORNETZ, 1988).

4 Results and discussion

4.1 Crop water requirements and consumptive water use of tepary beans and bambarra groundnuts

Crop water requirements (CWR) and consumptive water use (C.U.) of tepary beans were measured in preliminary experiments under almost optimum climatic and hygric (optimum hydrature period, optimum nutritive supply: mineral nutrition, host-specific rhizobia) conditions with optimum plant population density (Fig. 2). The values of the curve are correlated by a coefficient of r = 0.99 (correlation coefficient acc. to: PEARSON) with the mathematical approach introduced by KUTSCH and SCHUH (1980). The physiological demands showed distinct differences between the phenological parts of the vegetation cycle. This observation coincided with the results of DOORENBOS and PRUITT (1977) and DOORENBOS and KASSAM (1979) for some "major pulses" like soybean and common beans.

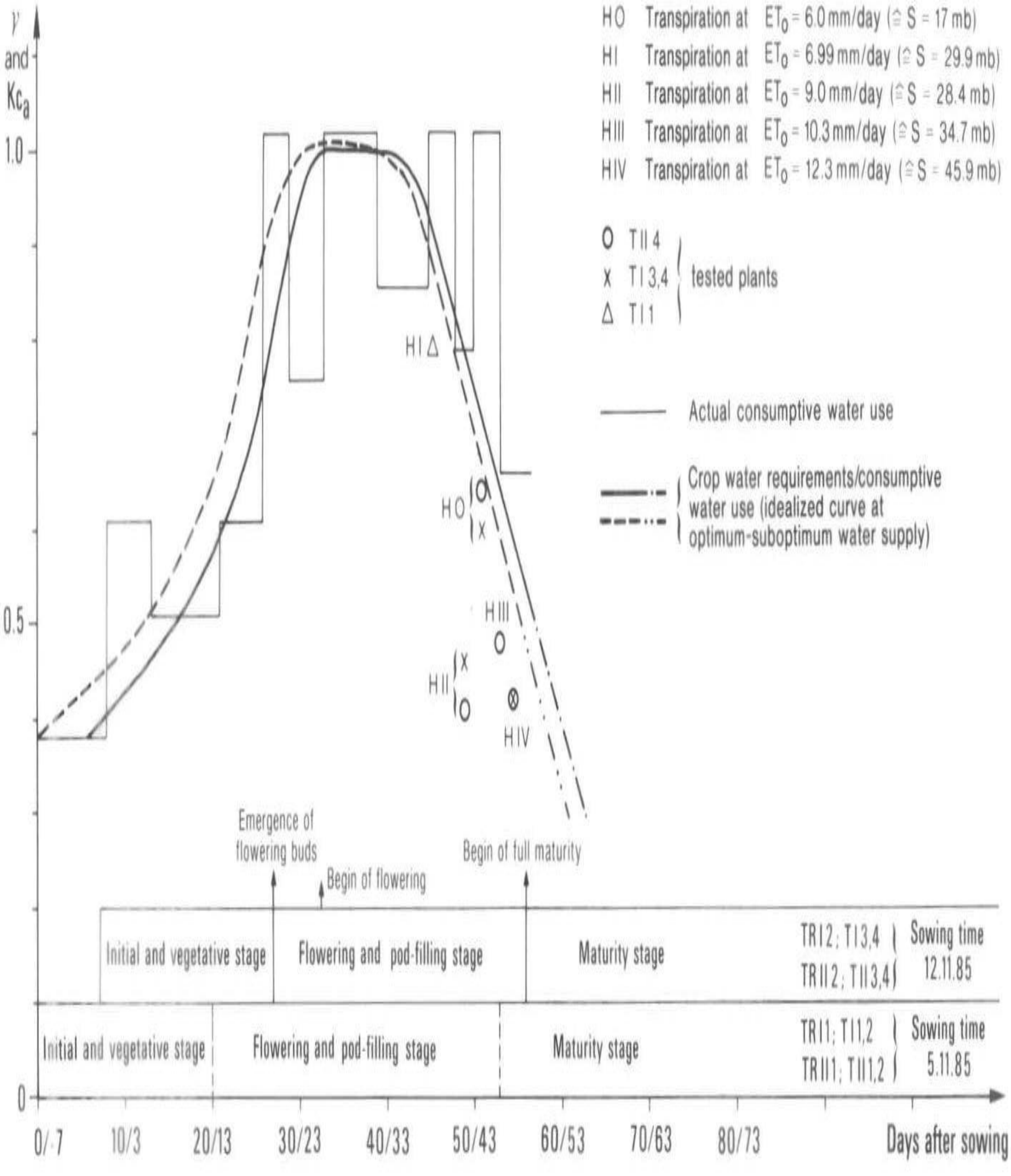
Tepary beans are able to adapt their transpiration activities to extreme atmospherical conditions (= evaporative stress), as was demonstrated by an experiment in the late pod-filling stage under optimum water supply with increasing saturation deficits (S) ("Harmattan-Experiments": Fig. 2).

Kutsch (1978, p. 127) observed in Morocco that subtropical wheat and barley varieties start to reduce their transpiration rates by stomatal closure at a daily evaporation of about 6.5 mm. The transition from stomatal to cuticular transpiration seems to appear at a saturation deficit of more than 40 mb, as Papadakis (1965; cited in: Kutsch, 1978, p. 26) found out. At this threshold value, mesophytic plants are no longer able to take up enough soil water and transport it to their leaves for stomatal transpiration (which equals the end of photosynthesis due to external stress).

In the above mentioned experiment it was recorded that the reduction of stomatal activities at a rate of about 25–30% did not start before the daily evaporation was more than 9.0 mm ("Harmattan II": $S = 30$ mb). The reduced transpiration rate of $\gamma = 0.4$ was maintained even when the saturation deficit exceeded the critical threshold value till 45,9 mb ($ET_0 = 12.3$ mm).

Apparently the plants are able to withstand extreme atmospherical stress and continue the transportation of soil water to the leaves by means of a parahelionastic response. This phytodynamic stress pattern –also occurring in times of extreme illumination, high temperature and water stress– seems to be caused by the activation of turgorines (e.g. turgorin acid PPLMF 1: Schildknecht, 1984). In stress situations, these biochemical messenger substances are transported into the links of the leaves and the leafstalks.

The mean C.U. of bambarra groundnuts (Fig. 3) was about 5–10% higher than that of tepary beans during all phenological stages. Measurements of the transpiration coefficients γ showed that bambarra groundnuts have higher physiological demands. The values of the CWR/C.U. – curve are correlated by a coefficient of $r = 0.94$ with the mathematical approach of Kutsch and Schuh (1980).
Bambarras seem to posses a very stable and productive stomatal apparatus as different watering treatments such as abundant irrigation followed by desiccation indicated. For example, during the "flooding period" of about 33 days the transpiration rates were increased by as much as about 20 % (Fig. 3) without retardation and alteration of the phenological and morphological development (in a parallel experiment tepary beans showed signs of retardation in phenology as well as prematurity).
There is evidence that a reduction in the water supply to $KC_a = 0.9–1.1$ from the 33rd to the 49th day did not lead to a reduction of the stomatal activities because the plants were able to continue transpiring at the pre-stress-level ($\gamma = 1.32$) when the water supply was optimized again.



γ = Coefficient of transpiration (acc.to: KUTSCH, 1978)

Kc_a = Coefficient of consumptive water use $\left[Kc_a = \frac{\text{ET crop}}{\text{ET}_0 \text{ (growth chamber)}}\right]$

Fig. 2: Consumptive water use and crop water requirements of tepary beans with optimum water supply under "normal" and extreme atmospherical demands ("Harmattan-Experiments": H I – H IV)

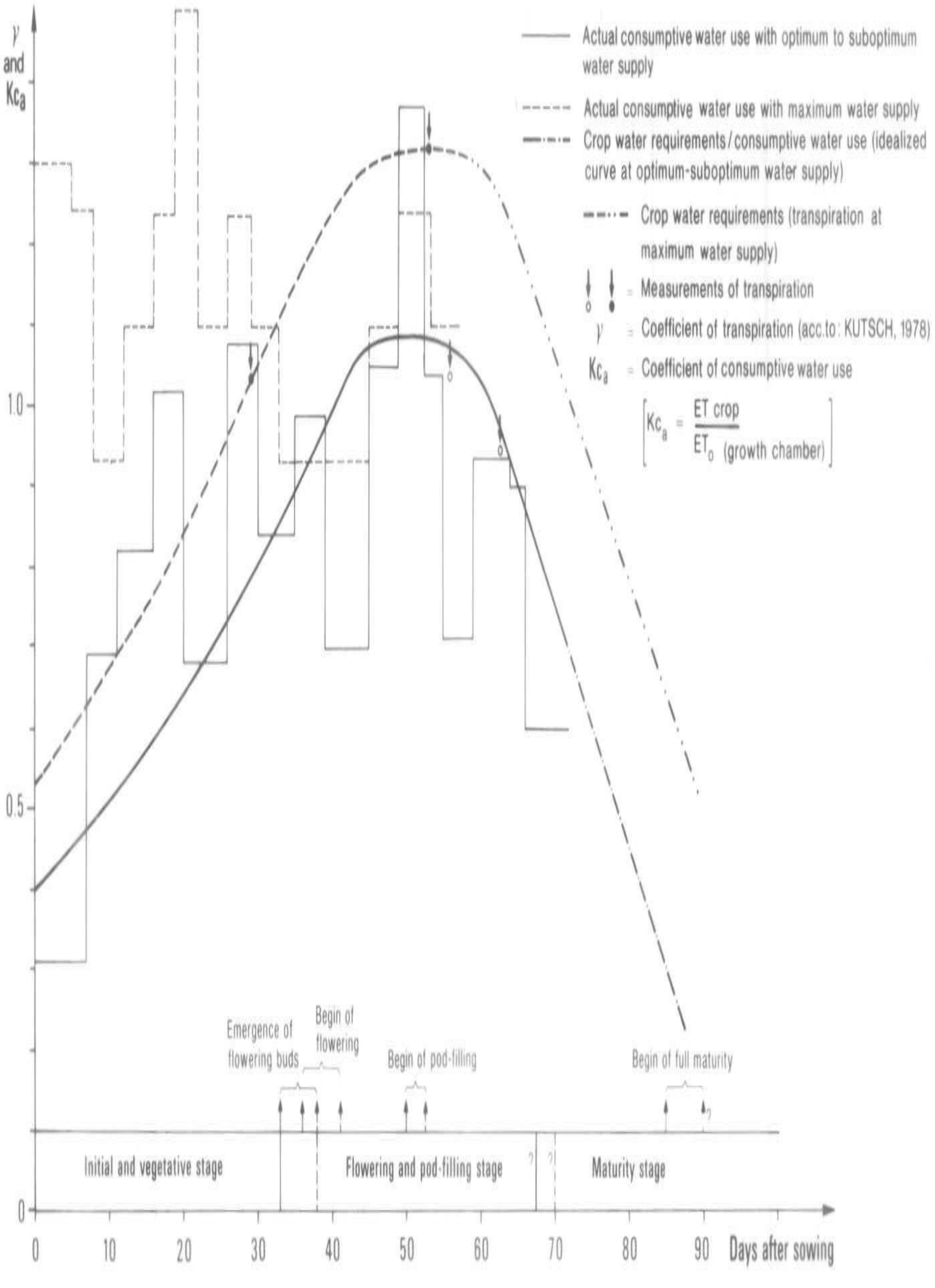


Fig. 3: Consumptive water use and crop water requirements of bambarra groundnuts under different watering treatments

4.2 Hydrature, responses to water stress

The responses of both "minor crops" to water stress were correlated with the hydrature periods observed by KREEB (1958), containing five main hydrature classes. This methodological approach was used since it permits the combination of ecophysiological observations with agroeconomical parameters. It is, for example, essential to differ the optimum hydrature period (hydrature period 1, „Optimumphase") from the postoptimum hydrature period (hydrature period 2, „Nachoptimumphase") because this decrease in hydrature is connected with the relative highest decrease in yield (KREEB, 1958, p. 32). The stopping hydrature period (hydrature period 4, „Endphase") possesses equal relevance due to the delay of transpiration and photosynthesis.

The classification was supplemented by transitional classes allowing the consideration of the overlapping of stress phenomena in different hydrature periods as well as retardation effects (see Tab. 1).

It has been found that tepary beans are able to adapt to water stress morphologically and physiologically. The plants respond to the desiccation of soil by increasing the parahelionastic movements of their leaves. This phytodynamical phenomenon produces –according to BEGG (1980, p. 38; in: TURNER and KRAMER, 1980)– the same effect as the stomatal closure in times of water stress by adapting the transpiration rates to the changing growth conditions (mechanism of "water saving": LEVITT, 1972). It was measured that the transpiration rates during hydrature period 3 fell to about 20% of the optimum value.

On the other side it was observed that the plants stabilized their turgor pressure till hydrature period 4. At the same time, the leaf water potential ϕ dropped very slowly within the middle and upper leaf storeys (Tab. 1).

Both observations give evidence of osmotic adjustment. As TURNER and JONES (1980, p. 89ff.; in: TURNER and KRAMER, 1980) point out, the ability of osmotic adjustment in higher plants is shown by the fact that during periods of water stress turgor and water potential of the plant tissues are maintained at a level allowing favourable transpiration and assimilation. Tepary beans seem to possess this ability of drought resistance. The results of the biochemical analysis of COYNE and SERRANO (1963) show that the plants produce high amounts of soluble solids, e.g. glucose and sucrose, in times of good as well as poor water supply. These carbohydrates are stored in the vacuoles of the cells and act as osmotically effective substances during desiccation.

Due to limited phytodynamical possibilities for maintaining favourable hydrature and transpiration conditions in periods of water stress, such as parahelionasty, bambarra groundnuts apparently start to abandon parts of the stomatal tissues, which look like clear dots (hydrature period 3). The abiding photosynthetically active tissues remain stabilized and fully efficient, as measurements of the transpiration rates after the end of a strong water stress demonstrate. The transpiration coefficients of stress-affected

Tab. 1: Stress patterns and physiological response in the hydrature periods of tepary beans, main experiment January – April 1986

Hydrature per.	Leaf water potential φ (MPa) lower leaf storey	middle & upper leaf storeys	θ (% FC)	Response to water stress	Alternation of leaf colour, turgor pressure	Stress patterns on reproductive and apical tissues	Hydrature period according to: a) KREEB (1958) b) BAUMAN (1955)
H 1	> −0.4 (φ-soil: > −0.3)	> −0.4 (φ-soil: > −0.3)	> 60/55	parahelionasty ≈ one hour before illumination end	fully turgescent	—	a) Optimumphase b) Optimum H.P.
H 1-2	−0.4 – −1.60	−0,4 – −0,5	60/55 – 38/37	parahelionasty ≈ two hours before illumination end: declination of lower leaves by about 10–20°	fully turgescent	—	a) Nachoptimumphase b) Declining H.P.
H 2	−1.60 – −1.90	−0.5 – −0.55	38/37 – 33/32	parahelionasty ≈ three hours before illumination end: declination of lower leaves by about 45°	fading of the leaves in the lower unit, fully turg.	—	
H 2-3	−1.9 – −2.35	−0.55 – −0.65	33/32 – 28/27	parahelionasty ≈ four hours before illumination end: declination of lower leaves by about 90°	fading of all leaves, fully turgescent	desiccation of apical tissues and the young flowering buds	
H 3	−2.35 – −2.60	−0.65 – −0.75	28/27 – 23/22	parahelionasty ≈ five hours before illumination end: light declination of middle leaves	start of yellowing: lower leaves less turgescent	desiccation of young flowers: emergence of new flowering buds and leaves ("emerg. resp.")	a) Anstiegphase b) Rapid Declining Hydrature P.
H 3-4	−2.60 – −2.85	−0.75 – −0.85	23/22 – 20/19	paralionasty in early afternoon	continuation of yellowing: lower leaves less turgescent	flowering of the new buds	
H 4	−2.85	−0.85 – −1.05 (+)/ −1,28*	20/19 – 18/17	parahelionasty ≈ two – three hours before illumination start: vertical tendency of middle leaves (≈ 90°)	strong yellowed leaves: lower and middle leaves less turgescent	desiccation of youngest pods, older pods stabilizing	a) Endphase b) Stopping H.P.
H 5	records no longer possible	records no longer possible	< 18/17	wilting in all leaf storeys			a) Maximumph. b) Dying H.P.

* value possibly in H 4–5

(+) values above the upper resp. lower limits of the hydrature period leaves during the early maturity stage at optimum water supply ranged from $\gamma = 0.56$ to 0.83.

Besides this morphological adaptation to water stress the plants are also able to reinforce their cuticula as a protection against unfavourable transpiration ("water saving": LEVITT, 1972) and to trap soil water from deeper soil layers by means of deep rooting ("water spending"). The stabilizing effect of the cuticula seems to be possible only by the inducement of a preceeding water stress.

There is also evidence that the drought resistant plants are able to increase the osmotic adjustment by a preceeding water stress. A comparison between the measurements of leaf water potential of the first and the following stress periods during the first main experiment showed positive shiftings of about −0.2 MPa within all hydrature periods besides hydrature period 1. Though generally the osmotically effective soluble solids are removed after the cessation of a water stress under favourable soil moisture conditions, it is possible that within a sequence of several stress periods –like in the experiments– the intervals with optimum hydrature conditions are too short to remove those substances. This phenomenon was pointed out by TURNER and JONES (1980, p. 97; in: TURNER and KRAMER, 1980).

4.3 Spatial differentation of tepary and bambarra cultivation in the drylands of Southeast Kenya

The experimentally obtained results about CWR, hydrature, and response to water stress of the drought resistant teparies and bambarras were connected with data on climatology (rainfall, evaporation), pedology (rooting depth, water retention capacity, plant-available soil water) and landuse practices (e.g. population density of the plants) of several sites in the drylands of Southeast Kenya. Thus agroecological scenarios were arranged and systematically computed by means of the simulation programme WATBAL (HORNETZ, 1985).

4.3.1 Agrohumid periods
(for potential cultivation of drought resistant mesophytic pulses)

Based upon the physiological results as well as the studies of DOORENBOS and PRUITT (1977), KUTSCH (1978), DOORENBOS and KASSAM (1979) and JÄTZOLD (1979b), mesophytic scenarios with xeric adaptation were selected as representative of the dryland sites in the geographical transect between Mombasa and Nairobi (see Fig. 5).

The parameters for testing the agroecological conditions for potential cultivation of drought resistant pulses season to season were (see also Fig. 4; ILIM/ELIM, ISUM, ESUM, OLIM, STOCK and DISCON acc. to: KUTSCH and SCHUH, 1983):

- cumulative threshold values ISUM and ESUM according to the initial and end conditions of water supply as a minimum of the physiological demands (KUTSCH, 1978), 2.4 ($\hat{=}$ CWR = 0.4 ET_0 per decade);
- a cumulative threshold value ILIM as an internal controlling parameter for short periods of water stress lasting for 20–30 days during an AHP, 0.4 ($\hat{=}$ CWR = 0.2 ET_0 per decade);
- a storage of soil water surplus exceeding an optimum physiological demand (OLIM), 1.0 ($\hat{=}$ Kc = 1.0 ET_0 per decade);
- a mean water retention capacity of the soil within the main effective rooting zone for tepary beans and bambarra groundnuts (STOCK), 200 mm (fluvisols with a rooting depth of 80 cm);
- option minimum duration of an AHP (DUR) of 5 decades;
- option predominantly heavy rainfall conditions (DISCON);
- an effective rainfall (RE; x/100), 0.9 ($\hat{=}$ 90% of precipitation).

Fig. 4 shows that the agroecological conditions for potential cultivation of tepary beans for the site Voi are fulfilled for both rainy seasons in two out of three years inspite of high oscillations at the beginning of the first AHP.
However, most of the first AHP's do not deliver enough soil moisture to meet the minimum requirements of early maturing crops with a vegetation period of about 90 days. Better conditions can be found in the second AHP (mean duration of the first AHP at Voi 55 days, second AHP 77 days).

The computations with the first module of WATBAL for 12 sites within the study area led to a spatial and seasonal differentiation of potential cultivation of both crops along the geographical transect (Fig. 5). Short-cycle tepary beans can be cultivated at all sites of the study area if the soils are not waterlogged. Even in the drier parts of the Zone 6 (Ranching Zone; acc. to: JÄTZOLD and SCHMIDT, 1982/3) successful cropping is possible according to the results of the ecophysiological experiments. However, it is confined to the more humid of both rainy seasons with a probability of about 67%, e.g. as additional cropping. The Ranching Zone was up to now considered to be unsuitable for cultivation. The tested variety of bambarra groundnuts turned out to need at least 75 days of sufficient water supply during the AHP to meet the water requirements for obtaining minimum yields in two out of three years. Therefore, spatial distribution is limited to the second rainy season at the Machakos District sites and in Voi (there the second rainy season is the longer one) as well as to the first rains of Mariakani. This latter region is of course influenced by the coastal rainfall pattern (regarding distribution c.f. HORNETZ, 1988).

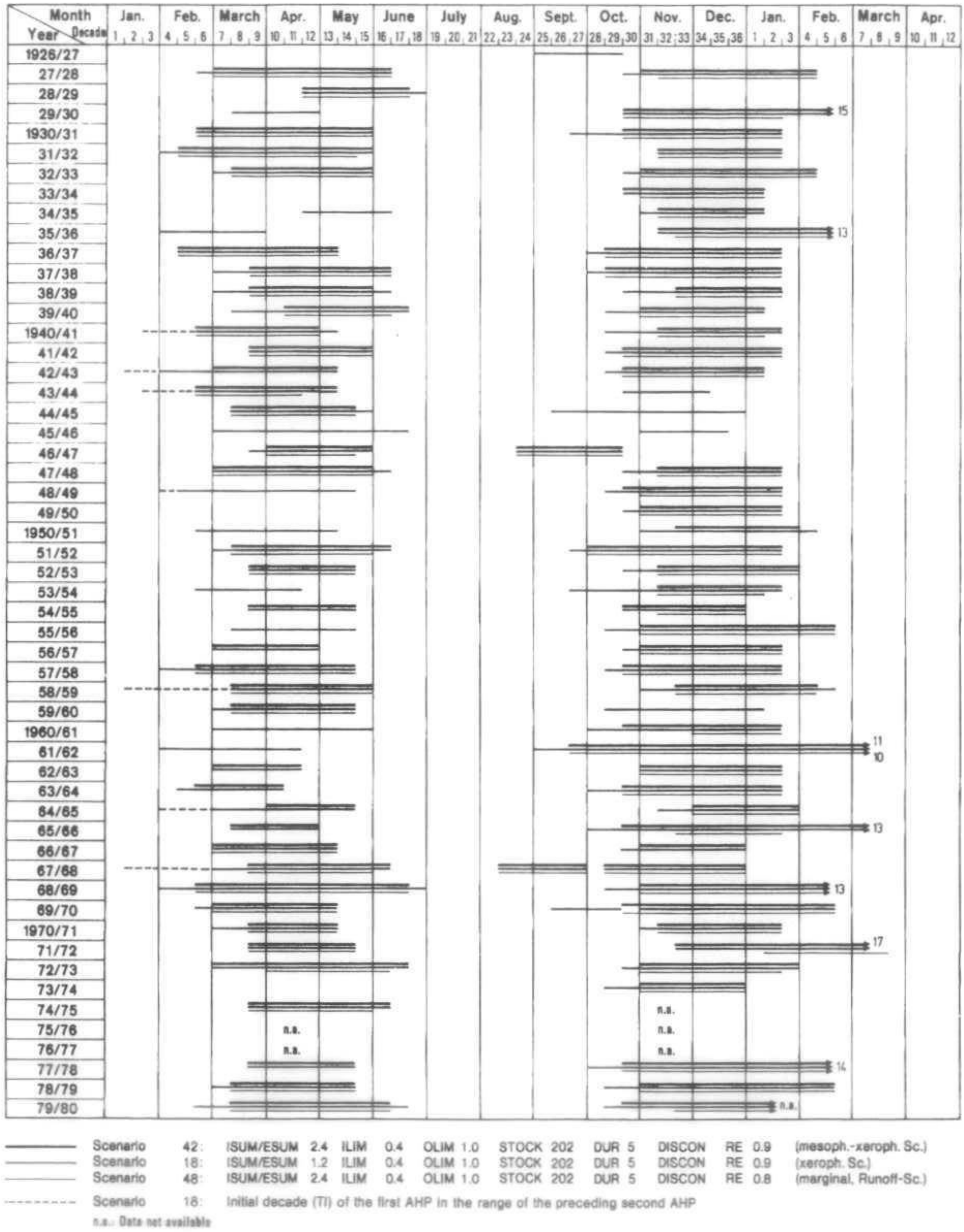
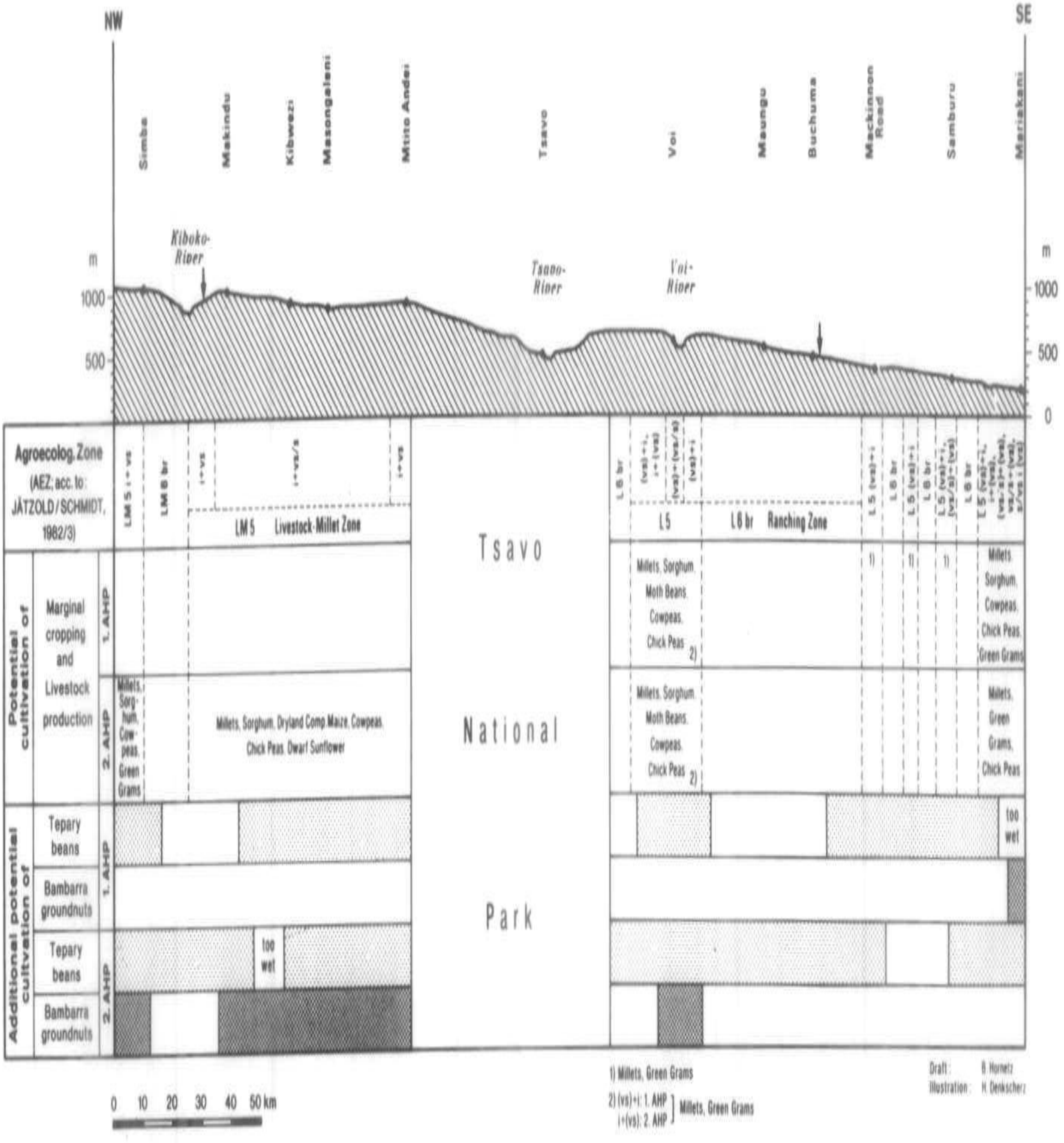


Fig. 4: Ecological conditions for potential growing periods of drought resistant, short-cycle crops at Voi/Southeast Kenya (1926–1979)



Trial sites for tepary beans and *Rhizobium phaseoli* since 1988:

1. National Range Research Station Kiboko
2. Range Resarch Station Buchuma

Fig. 5: Potential cultivation of tepary beans and bambarra groundnuts in the semi-arid and arid drylands of Southeast Kenya

4.3.2 Calculation of hydrature-dependent levels of yield potentials for tepary beans and bambarra groundnuts at Voi

The further refinement of crop water balances on a daily basis for determining hydrature-dependent levels of yield potentials by means of the EDP-submodels 2 and 3 (see chapter 3.2) requires additional agroecological parameters:

module 2

- coefficients of CWR (Kc) for initial and vegetative, flowering and pod-filling as well as maturity stage;
- duration of the phenological stages;
- plant-specific and time-dependent optimum development of the main rooting complex.

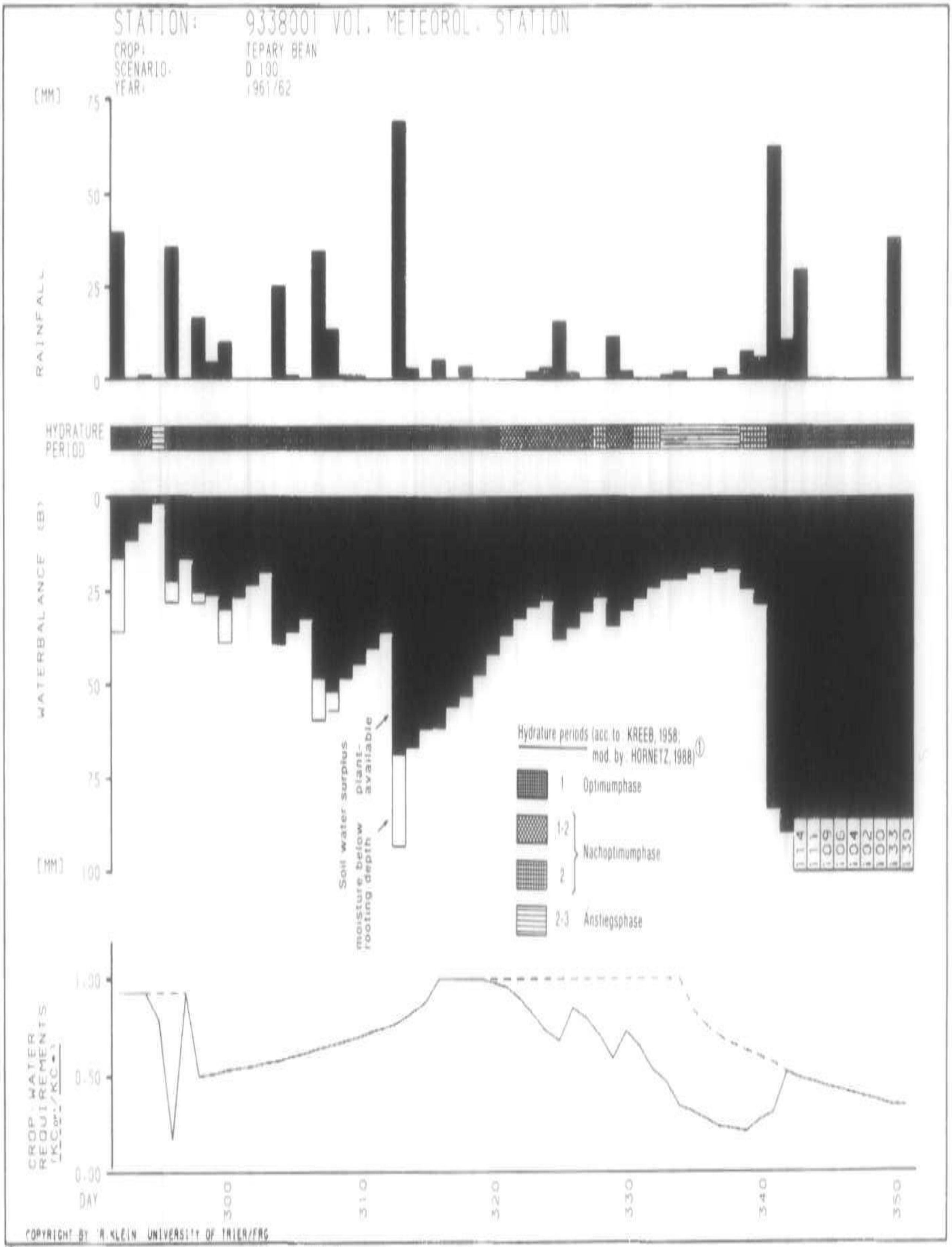
module 3

- separation of the moderately deep to deep fluvisols at the Voi River into several layers with specific water retention capacity and plant-available water respectively; the roots of the crops with a mean rooting depth of about 80 cm (according to the observations made in the experiments) trap the soil water from these layers when penetrating the stratum;
- increased amount of plant-available soil moisture by about 20–22% due to the "water spending" mechanisms of both plants during periods of water stress;
- duration of the optimum hydrature periods (hydrature period 1); according to defined threshold values of available soil moisture (ß');
- threshold of plant-available soil moisture at which certain hydrature periods for the crops generally occur respectively.

"Scenario-concept" and simulation computation allow the daily performance of crop/soil water balances containing the actual evapotranspiration rates as ecophysiologically adapted Kc-values (Kc*) and the hydrature periods (see Fig. 6). By means of these hydrature-dependent results the climatological sequences can be classified into typical rainfall patterns (HORNETZ, 1988) on a daily data basis.

It turned out that these rainfall types are suited to deliver qualitative and quantitative information for determining yield potentials. This is exemplified by optimum type 1 in figure 6. The distribution of rainfall events during the AHP of the second rains (Oct./Nov. till Dec.) of 1961 leads to a relative homogenous water supply for short-cycle crops like teparies without yield-reducing periods of waterlogging. The CWRS during the most sensitive phase of early flowering and pod-filling are fully compensated. The phenological development cannot be retarded even by short dry spells during the vegetative and maturity stages. This results in high yield expectations.

This rainfall pattern occurs with a probability of about 10% in the first and 25% in the second rainy season for tepary beans (Tab. 2). Generally, it can be determined when precipitation activities are stabilized due to the convective dynamics of the destabilized atmosphere. This normally happens after the occurrence of less effective "pre-rains".



① For the definition of hydrature periods of tepary beans see table 1

Fig. 6: Hydrature-dependent rainfall pattern/type 1 (optimum) at Voi, second rains 1961, fluvisols

By statistical analysis of the rainfall patterns from 1926–1979 it was further found (Tab. 2) that lower yields can be expected for the less suitable rainfall patterns 2 and 3, especially 4 and 5 because of yield-reducing dry spells during the vegetative and reproductive periods of plant growth. Total crop failure (pattern 6) due to short or less intensive rainy season equaled 30% during the first and 17% during the second AHP (Tab. 2).

By similar statistical analysis early maturing bambarra groundnuts (90 days) turned out to be successfully cultivated only in the second AHP, total crop failure equaled 28%. However, in 24% of all events this AHP was so short that only marginal to minimum yields can be expected. This concludes that in about three out of ten years rainfall seems to be sufficient to produce at least suboptimum yields.

Tab. 2: Probabilities of certain hydrature-dependent rainfall patterns/types during the AHP's (in % of all events) for short-cycle tepary beans (60 days) and early maturing bambarra groundnuts (90 days) at Voi (1926–1979) acc. to: HORNETZ (1988)

Rainfall pattern	1. AHP		2. AHP	
	Tepary beans	Bambarra groundnuts	Tepary beans	Bambarra groundnuts
Type 1 (optimum)	10	0	25	6
Type 2 (subopt.)	13	10	29	20
Type 3 (average)	15	4	10	16
Type 4 (marginal)	13	8	13	6
Type 5 (minimum)	19	15	6	24
Type 6 a, b (failure)	30	63	17	28

5 Summary

This study deals with potential cultivation of the "minor pulses" of tepary beans *(Phaseolus acutifolius)* and bambarra groundnuts *(Voandzeia/Vigna subterranea)* with special reference to their ecophysiological demands.

The aim of this research is to supplement actual landuse patterns in those areas recently dominated by integrated systems of crop cultivation and livestock production with ecologically adapted leguminous crops of high nutritional values. This would subsequently reduce the risks of crop failure, food crisis, and soil degradation (mainly by means of nitrogen fixation).

Newly constructed growth containers gave possibilities to simulate different durations and intensities of water stress under controlled environmental conditions in climatic chamber experiments.

It was observed and recorded that teparies and bambarras possess different mechanisms of morphological and physiological adaptation to high temperature and water stress. This apparently includes the ability of osmotic adjustment. The patterns of adaptation to water stress are combined with defined hydrature periods closely connected with the reduction of soil moisture.

The results of the ecophysiological experiments were transformed into a numerical model. This methodological approach was combined with agroecological simulation computation and "scenario-concept", thus allowing to test the possibility of cultivation of defined crops in certain dryland sites and areas of Southeast Kenya.

The computations resulted in a spatial differentiation of potential cultivation patterns of tepary beans and bambarra groundnuts. Short-cycle teparies can be cultivated in all areas of the analyzed geographical transect. Successful cropping with a probability of about 67% is even confined to the more humid rainy seasons in the drier parts of the agroecological zone 6 (Ranching Zone acc. to: JÄTZOLD and SCHMIDT, 1982/3; e.g. as additional cropping; see also: Fig. 5 and Tab. 2).

The tested variety of bambarra groundnuts turned out to need at least 75 days of sufficient water supply during the agrohumid period (AHP) to receive the water requirements for obtaining minimum yields in two out of three years. Therefore, the spatial distribution is limited to the second rainy season of the sites in the Machakos District and in Voi as well as to the first rains of Mariakani.

Zusammenfassung

Zwei als „minor pulses" einzustufende Leguminosen, Tepary-Bohnen *(Phaseolus acutifolius)* und Bambarra-Erderbsen *(Voandzeia/Vigna subterranea)* wurden für ein potentielles Anbaugebiet im Agrosahel SE-Kenias unter besonderer Berücksichtigung ihrer ökophysiologischen Ansprüche getestet.
Das Ziel der Untersuchungen bestand in dem Versuch, die aktuellen Landnutzungssysteme im Trockengrenzbereich, die meistens Betriebsformen der Viehhaltung und des Anbaues integrieren, durch ökologisch angepaßte und ernährungsphysiologisch hochwertige Leguminosen zu ergänzen und damit das Produktionsrisiko sowie die Gefahr von Hungerkatastrophen bei gleichzeitiger Stabilisierung der Bodenfruchtbarkeit (v.a. durch symbiontische N_2-Fixierung) zu minimieren.

In Klimakammerexperimenten konnte mit Hilfe neu konzipierter Bestandscontainer messend erfaßt werden, daß Tepary-Bohnen und Bambarra-Erderbsen über ein differenziertes Repertoire an morphologischen und physiologischen Anpassungsmöglichkeiten gegenüber extremen klimatischen Bedingungen wie Überhitzung und Austrocknung verfügen.

Die experimentellen Ergebnisse wurden anschließend in ein numerisches Modell eingebracht, das mit Hilfe von Szenarientheorie und agrarökologischen Simulationsrechnungen die Austestung der Anbaufähigkeit bestimmter Standorte bzw. Regionen im Trockengrenzbereich SE-Kenias ermöglichte.

Es ergibt sich eine räumliche Differenzierung des potentiellen Anbaues von Tepary-Bohnen und Bambarra-Erderbsen:

Die kurzzyklischen Teparies können im gesamten Untersuchungsgebiet angebaut werden, wobei sogar an trockneren Standorten der agroökologischen Zone 6 (Ranching Zone: nach JÄTZOLD und SCHMIDT, 1982/3), über die bisherige Regenfeldbaugrenze hinaus noch eine der beiden Regenzeiten potentiell anbaufähig ist (z.B. in der Form eines "additional cropping"; siehe Fig. 5 und Tab. 2).
Obwohl in der vorliegenden Untersuchung die nach dem bisherigen Kenntnisstand kurzzyklischste Varietät von Bambarra-Erderbsen verwendet wurde, scheint nur noch bei einer Länge der agrohumiden Periode (AHP) von mehr als 75 Tagen eine ausreichende Wasserversorgung zur Produktion des Minimalertrages in zwei von drei Jahren erreicht zu werden. Dies beschränkt ihre Einsatzmöglichkeiten auf die 2. AHP der nördlichen Standorte im Distrikt Machakos und von Voi sowie auf die 1. AHP des küstennahen Mariakani.

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