POTENTIAL PRIMARY PRODUCTION OF UNIRRIGATED LAND IN THE SAHEL

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SUMMARY

Primary production in arid and semi-arid regions is often limited by available soil nutrients. The removal of this limitation will increase yields of grasslands and agricultural fields up to a level imposed by amount and distribution of precipitation and the water storage capacity of the soil. This study shows that it is possible to compute this potential plant production to be between 0 and 4,000 kg above-ground dry matter per hectare per year with 270 mm of rain, and 5,000 to 9,000 kg per hectare per year with 540 mm of rain, depending upon soil type, soil depth and rainfall distribution.

INTRODUCTION

To grow, plants need nutrients, water and light. In contrast to a frequently expressed opinon, it is often not water shortage that keeps the productivity of the vegetation low in semi-arid regions, but a poor availability of nutrients, particularly of nitrogen. Rainfall only triggers the growing season. In huge areas of Australia legumes have been introduced successfully to improve the supply of nitrogen in grasslands. This has stimulated the growth of grasses and increased the productivity of cattle very substantially in the last decade, according to, among others the interesting book "Australian Grasslands", edited by R.M. Moore (1970). Based on such results, and on a preliminary inspection of soil chemical data (in the "Notice explicative", numbers 13, 14, 16 and 24 to the ORSTOM "Carte Pédagogique" of Chad and Senegal, published in 1964 and 1965; G.J. Staring, pers. comm.) it is expected that appropriate legumes and Rhizobium strains can be found to increase the soil nitrogen supply in Sahelian natural grasslands and in agricultural fields, and thus to raise their primary productivity. A higher nitrogen availability increases both quantity and nutritional values of the vegetation.

Yields may be increased by such measures up to a level imposed by precipitation. Plant transpiration and plant production are then closely related (de Wit, 1958). Since it is impossible to provide large areas with abundant water, the natural precipitation determines the maximum productivity of grasslands and rainfed agriculture. The relatively small areas in warm and dry climates that can be irrigated may yield 5 to 10 times as much dry matter as unirrigated areas (de Wit, this volume).

All animals require food and water. Water is taken from open sources if the food is too dry. Depending on the geographical location, current weather and animal species, both water and food can become scarce thus limiting subsistence and growth of animals. The water requirement per kg of dry food is from ten to a hundred times smaller than that of plants to produce the biomass. In principle, therefore, it seems easier to supply animals with sufficient water than plants, and that primary production in semi-arid regions sets a maximum to animal productivity. In the long run, an important question will thus be: what is the maximum productivity of vegetation on unirrigated land in semi-arid regions?

This question is attacked by Buringh, Van Heemst and Staring (1975) on a regional scale, and by Van Keulen (1975a) on a small field scale. The first study calculates the potential primary production of unirrigated land by multiplying the potential rate of growth of the vegetation by the smallest of two reduction factors, the first of which reflects topography and disturbing soil physical and soil chemical properties, and the second of which represents effects of water shortage. The potential growth rate of closed canopies on good soil with plenty of water and nutrients depends essentially on light intensity and temperature, and is remarkably similar for a wide range of agricultural and non-agricultural crops. Applying their method to Sahel conditions predicts maximum yields of 3,400 kg plant dry matter ha^{-1}

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at the 250 mm isohyet and 7,100 to 8,400 kg dry matter ha^{-1} with twice as much rain.

Van Keulen's approach combines knowledge of soil physics, agrometeorology, and plant physiology to keep track of the soil water balance and of plant growth during the growing season. This model is described below, and was used to compute vegetation growth at sites in the Sahel with weather conditions typical at the 250 mm and 550 mm isohyets, and with 7 soil types, including a shallow sandy soil, a deep loamy soil, and a heavy clay soil. Results of these computations are presented.

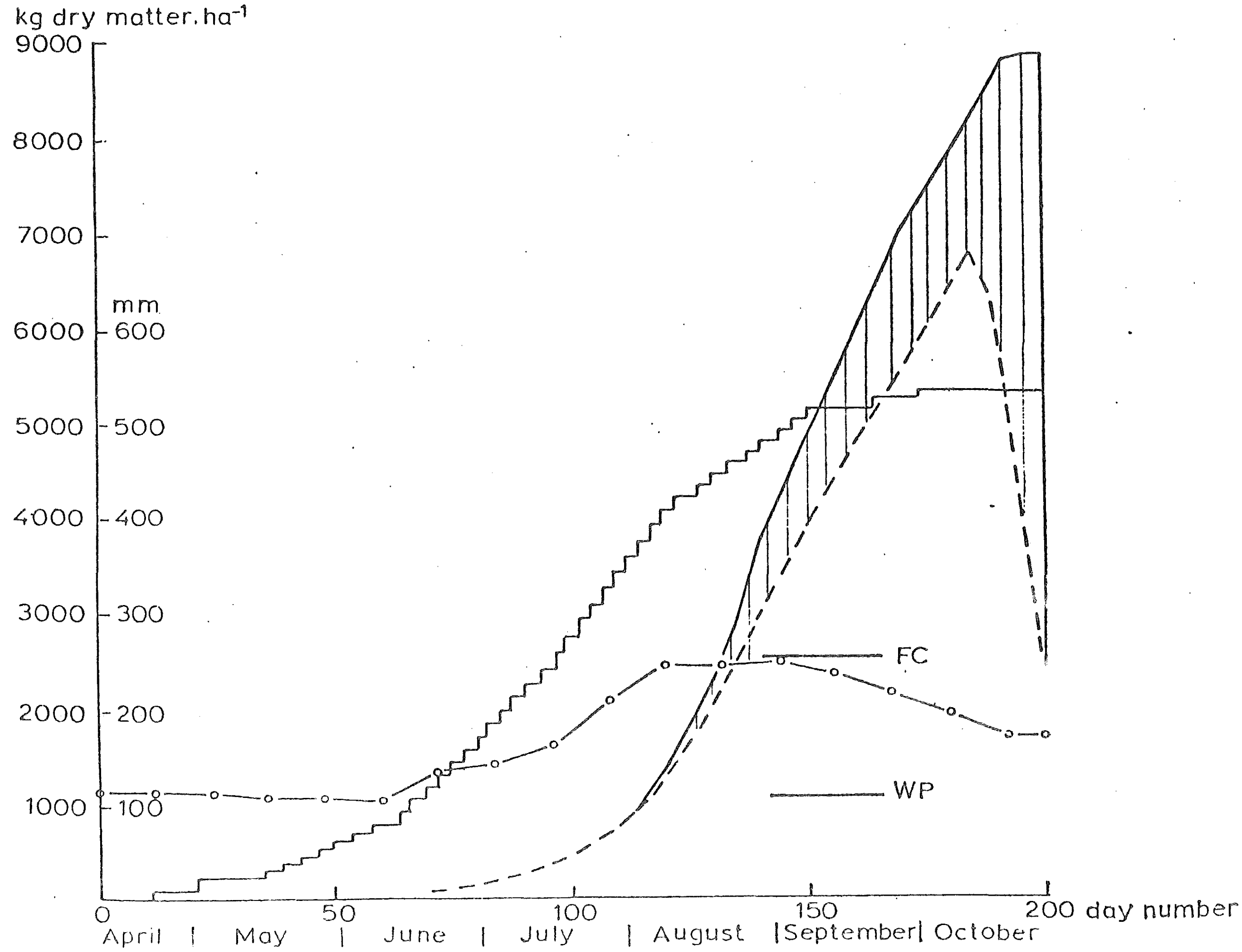
A simulation model of potential production on unirrigated fields

Van Keulen (1975a) divides the soil into 10 layers with identical properties, but with water contents and amounts of roots that may be different. The thickness of the layers increases from 2 cm at the top, to 6 to 30 cm at the bottom, such that the total depth of the profile is 50 to 180 cm. Water is added to the first layer by infiltration. The amount infiltrated equals the amount of rain minus run-off, or plus run-on. If more water is supplied to the upper layer than can be held in it, as determined by the field capacity of the soil, the excess drains into the second layer. When this layer still contains some water, or if the excess of the upper layer is large, it also becomes saturated, and the excess drains into the third layer. Persisting rains or large run-on may saturate the whole profile and eventually lead to drainage out of reach of roots.

Evaporation from the soil surface draws largely on water of the upper layers, and little on those below 25 cm. Potential soil evaporation is calculated according to the Penman formula, corrected for the radiation reflected from the soil surface and that absorbed and reflected by the canopy. The actual rate of soil evaporation equals the potential rate, reduced by the outcome of an empirical formula. Redistribution of water in the profile driven by water potential gradients is slow compared to water extraction by roots and evaporation, and is therefore treated in a very simple manner.

Calculation of the vegetation transpiration is also based on the Penman formula, which is adjusted to the current leaf surface per hectare of soil surface, and in which the leaf resistance against transpiration is included. Water lost by the canopy is extracted evenly over the rooted zone from all layers in which the water content still exceeds the wilting point. The rooting depth increases by about 1 cm per day as long as the plants grow.

There is a ratio of 100 to 300 between the rate of transpiration (kgH_2O/ha^{-1}/day^{-1}) of a canopy and its gross (kgCO_2/ha^{-1}/day^{-1}) assimilation. The actual value of this ratio depends largely on the current weather and is computed continuously in the model. Canopy transpiration divided by this transpiration ratio yields the canopy assimilation. Some of the assimilates are utilized in biochemical maintenance processes, and the remainder is multiplied in the model by a conversion factor of 0.75 to reflect the growth processes and to give the vegetation dry weight increase. The distribution of this dry matter over roots and shoots is related to the developmental stage of the plants by an empirical formula. It is assumed that 0.5 percent of the living vegetation dies



per day throughout the growing season. This rate increases to 10 percent per day once soil water is exhausted. Plants die also when their physiological development is completed and seeds are ripe. The rate at which this stage is approached is a function of temperature. Seed germination starts when the upper soil layers are moist for about 5 consecutive days. The parameters and the relations to temperature, soil moisture and developmental stage, which in the model characterize the type of vegetation, apply to annuals, and more specifically to wheat and natural grasses. In terms of potential productivity and water use efficiency, there is remarkably little difference among such species.

The simulation model is based on a fair knowledge of the soil and plant processes, and is quite reliable. Meteorological inputs for the simulation program are daily readings of maximum and minimum temperature, radiation, relative or absolute humidity, wind speed and precipitation. The simulation model repeats the computation of the rates of all processes over one day from the current status of the system and the actual weather, and integrates these until the end of the growing season has been reached.

The model has been used to simulate vegetation growth in the Negev desert on deep, loamy soils. Precipitation in this area near Beersheva on the 250 mm isohyet falls between October and April. In 3 consecutive years well-fertilized fields were harvested at regular time intervals and their soil moisture content was recorded. Results of simulations of these experiments agree with the observations within the experimental error of 15 percent in almost all cases. Such results were obtained without entering the never-ending procedure of adapting model constants of parameters other than weather data, to improve model behaviour (Van Keulen, 1975b).

Sahelian soils and weather

Van Keulen's model applies to all warm arid and semi-arid regions. This section specifies the data needed to simulate conditions prevailing in the Sahel.

Of the plant properties, only the response of the rate of development to temperature is lowered, such that plants in the vegetation mature near the end of the period in which a moist soil allows growth.

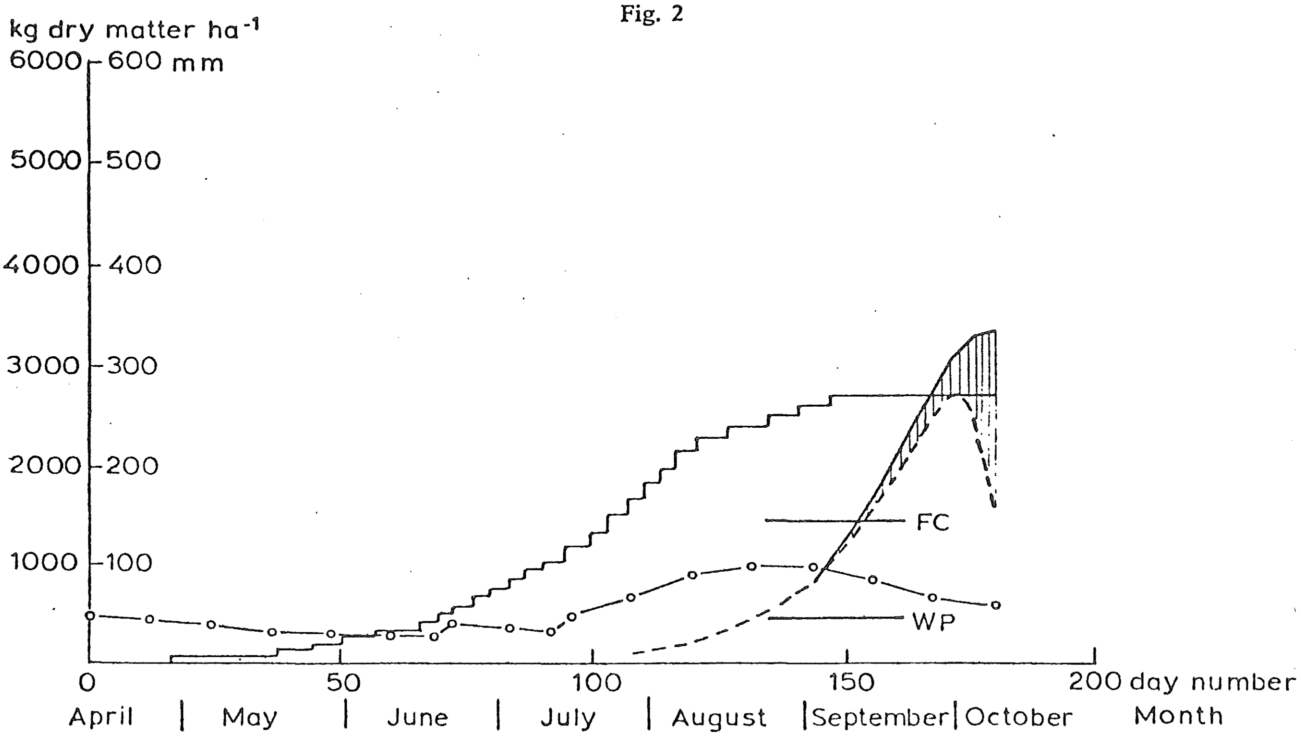
Sahelian soils are generally very sandy, although some contain much clay. In the model, soils are characterized by their water content at field capacity (which corresponds to a water potential of -0,3 bar) at the permanent wilting point (-15 bar) and when air dry (about -1,000 bar). Numerical values for these water contents in different soils, and for frequently occurring soil depths were collected from various reports and are shown in table 1; the soil types 1, 2, 3 and 4 are estimated to cover about 15 percent, 25 percent, 20 percent and 15 percent of the Sahel, respectively (G.J. Staring, pers. comm.).

Long-term monthly averages of weather data were taken from the World Survey of Climatology (Griffits, 1972) for Gao at the 250 mm isohyet and for Mopti at the 550 mm isohyet, both in Mali. All factors but precipitation change slowly throughout the year, so that their daily values can be derived by interpolation. The summer months in Gao are somewhat warmer and drier than in Mopti. Inspection of the total precipitation in May, June, July, August, September and October in Gao (8, 23, 71, 127, 38 and 0 mm respectively) and in Mopti (23, 56, 147, 198, 94 and 18 respectively) and the number of days with more than 1 mm of precipitation (1, 4, 8, 8, 4, and 0 in Gao; 2, 7, 11, 12, 8 and 2 in Mopti) indicates an average precipitation per rainy day of 10 to 15 mm in the wettest months and 6 to 8 mm in the preceding and following months. This preliminary study assumes a regular distribution of average showers within each month. It is realized, however, that an irregular rainfall distribution can be of critical importance for plant survival and plant growth, for run-off and deep drainage. The results presented demonstrate, therefore, the capabilities of calculation of potential production when the course of the weather is known or predicted, rather than giving exact predictions for production.

Potential primary production of unirrigated land in the Sahel

Figures 1 and 2 present typical results of simulations of water use and dry matter production during

Fig. 2



the growing season, using soil properties and weather data as inputs. For a luvisol of 180 cm depth with 540 mm rain, a top yield of 8,900 kg of above-ground dry matter ha^{-1} is computed (fig. 1); on cambisols near Gao, highests yields are calculated to be 3,300 kg dry matter ha^{-1}. Figure 1 shows that, with the rainfall distribution assumed for Mopti, only after some 100 mm of rain is the soil moist enough to permit germination. The initial phase of exponential growth lasts about 40 days and ends when the canopy intercepts almost all direct radiation. It is followed by a phase of a slowly decreasing growth rate of 120 kg ha^{-1}/day^{-1} in the beginning to 85 kg ha^{-1}/day^{-1} at the end of the season. By the first weeks of October the vegetation is ripe and dies rapidly.

Table 2 compares potential yields on the main Sahel soil types, and shows that all soils deeper than 50 cm can yield with 540 mm of rain 7,000 to 9,000 kg dry matter ha^{-1}/year^{-1}, except the heavy clay soil (type 4). This soil needs most water and time to become sufficiently moist for germination. Consequently, it loses so much water by surface evaporation that little remains for the plants, which is reflected by the low potential yield. On the sandy soils, roughly as much water is lost by deep drainage as is transpired by the vegetation; but in all cases considered, still more water evaporates from the soil surface.

In Gao, the most productive soils are those with the lowest storage capacity (table 2), because the least water gets lost in the drying process of their upper layers between showers. On the other hand, a depth of at least 100 cm is required to prevent considerable drainage. Some 150 mm of rain is required before germination starts (fig. 2). Once established, the crop grows at a rate of about 90 kg ha^{-1}/day^{-1} until the soil is dry or the plants have completed their life cycle. In the examples presented, this occurs after 50 to 65 days. The longer the vegetation grows, the higher the total biomass produced (table 2).

One of the conclusions of these simulations is that at the 250 mm isohyet, even on the most productive soils, 70 or more percent of the precipitation is evaporated from the soil (table 2). The soils with a high field capacity lose essentially all water by evaporation, and no growth occurs. Drainage is seldom important. When the vegetation grows, its transpiration rate is as high or exceeds the soil evaporation rate, but due to the short growing season plants utilize only about one sixth of the total rainfall. Again it must be recalled that run-off and an irregular rainfall distribution will modify these proportions by adding more water to deeper layers, from which evaporation is very slow. It will depend on the soil storage capacity and its depth how much water will drain out of the root zone and how much is available to the vegetation. It is obvious, however, that on many soils a considerable loss of water by either surface evaporation or drainage is unavoidable. If plants have completed their life cycle before all available water is used, as in the example of Figure 1, the water is well protected against evaporation in deep layers during the dry months, and becomes again available to plants in the next season. In deep soils, carryover of water to the next growing season can be important to reduce the effect of water shortage in a following dry year.

Table 1

The water content of different soils at field capacity, at the permanent wilting point and when air dry *.

Soil type	Field capacity (g.cm^{-3})	Wilting points (g.cm^{-3})	Air dry (g.cm^{-3})	Depth (cm)
Cambisol (type 1)	0.08	0.025	0.015	100, 180
Luvisol (type 2)	0.14	0.06	0.04	50, 100, 180
Luvic-arenosol (type 3)	0.20	0.10	0.04	150
Fluvisol, gleysol, planosol, vertisol (type 4)	0.36	0.24	0.15	100

Table 2

Primary productivity and water use on 7 soils and in two weather regimes *

Precipitation	Soil		Total production (kg/ha^{-1})	Maximum live biomass (kg/ha^{-1})	Growing season duration (days)	Transpiration, soil evaporation, storage and deep drainage as a percentage of precipitation
	Type	Depth (cm)				
536 mm (Mopti)	1	180	8,600	6,600	112	31, 41, 4, 24
	1	100	7,700	6,000	108	28, 41, 0, 31
	2	180	8,900	6,800	112	33, 48, 10, 9
	2	100	8,700	6,700	112	32, 48, 0, 20
	2	50	7,100	5,300	96	25, 48, 0, 27
	3	150	8,500	6,600	112	32, 65, 3, 0
	4	100	5,200	3,800	88	19, 83, — 2, 0
267 mm (Gao)	1	180	3,300	2,700	64	18, 79, 3, 0
	1	100	3,300	2,700	64	18, 74, 3, 5
	2	180	2,800	2,200	56	16, 92, — 8, 0
	2	100	2,800	2,100	56	16, 88, — 4, 0
	2	50	2,300	1,800	52	13, 84, — 1, 4
	3	150	100	100	1	0, 112, — 12, 0
	4	100	0	0	0	0, 115. — 15, 0

Presented are the total amount of biomass produced above ground, the maximum amount of live biomass during the growing season, the duration of the growing season and the distribution of precipitation over canopy transpiration, soil surface evaporation, storage in the soil (the difference between the water contents in mid-April and mid-October), and drainage out of reach of the root system.

* Frequently occurring soil depths are given in the last column.

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