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AGRICULTURAL ADMINISTRATION UNIT

THE DESIGN AND MANAGEMENT OF PASTORAL DEVELOPMENT

THE PRODUCTIVITY OF SAHELIAN RANGELANDS - A SUMMARY REPORT

by

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International concern has been felt about the productivity
of the Sahelian Rangelands for a decade. From 1976-80 a major
research project , entitled "Production Primaire au Sahel"
(PPS) took place in Mali and its results have been published
in F W T Penning de Vries and M A Djitaye (Editors) La
Productivité des Palurages Sahelians, Centre for Agricultural
Publishing and Documentation Wageningen (ISBN 90 220 08061).
This substantial book, in French but with a 34 page integral
summary in English, substantially advances knowledge on this
subject. This present network paper was specially written
by one of the main report's editors for the benefit of network
members.

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INTRODUCTION TO THIS SUMMARY

0.01   What is the actual productivity of rangelands in the
        Sahel: in terms of quantity and quality? What is its
        variation from place to place and from year to year? Can
        productivity be increased? Is a further increase in the
        intensity of rangeland exploitation possible? Without
        overgrazing? What effect will that have on the soil?
        What kind of solutions to problems of exploitation and
        overgrazing is feasible, and what kind is not?

0.02   Such questions are discussed on the basis of our
        interpretation of data gathered by others and ourselves.
        Much emphasis is placed on the finding that soil
        fertility, in addition to precipitation, is a key factor
        in rangeland productivity, because it is the principal
        cause of the meagre production of forage, and its
        generally low quality.

0.03   Chapter 1 of the original report describes in general
        terms the problems of animal husbandry in the Sahel, one
        of them being low productivity of the natural rangelands.
        The systems approach, essential in our research of
        rangeland productivity, is presented in Chapter 2.
        Chapter 3 introduces the physical and plant ecological
        environment.

0.04   In Chapter 4 the potential of grassland production is
        discussed on the basis of the water balance of the soil,
        the botanical composition of the vegetation and
        physiological characteristics of plants. This potential
        level is not attained in the southern Sahel because of
        a shortage of plant nutrients. This is explained in
        Chapter 5. Chapter 6 compares many of the findings of
        the preceding chapters with field observations, and
        derives generalizations from them.

0.05   This information is used in Chapter 7 to formulate a
        methodology for surveying rangelands: to indicate quickly
        their potentialities, their actual conditions and how
        these may change after modification of the level of
        exploitation. Suggestions for improvement of the
        production and utilization of the forage are presented
        in Chapter 8. These options are discussed in the
        framework of improvement of the animal productivity in
        Chapter 9.

0.06   The structure of this summary is the same as that of the
        original French report, which contains a long summary
        in English, while its captions of tables and figures are
        bilingual. A textbook in French and English of a 4 week
        course on the same subject has been prepared by De
        Ridder, Stroosnijder and Cisse (Dept. Soil Science and
        Plant Nutrition, Agricultural University, De Dreyen 3,

Wageningen). The report results from the inter-
disciplinary P.P.S. project (Projet Production Primaire
au Sahel). The project was executed in Mali and in
Wageningen by a large group of researchers from the
Agricultural University and the Centre for
Agrobiological Research in Wageningen, The Netherlands,
and from the Institut d'Economie Rural in Bamako, Mali.

CHAPTER 1 ANIMAL PRODUCTION AND EXPLOITATION OF
          SAHELIAN RANGELANDS

1.01 The Sahel is one of the very large semi-arid zones of the
      world. About a quarter of the territory of the countries
      Chad, Mali, Mauritania, Niger, Senegal and Upper Volta
      can be characterized as Sahel. About a third of their
      total population lives in this zone. In these 6
      countries there are about 22 million head of cattle, 36
      million sheep and goats and 1.7 million camels. Almost
      all camels and 60-70% of the cattle are kept in the Sahel.

1.02 There are 3 principal forms of animal husbandry in the
      Sahel:

      - Nomadism: the herds and the nomads stay in the Sahara
      or the northern Sahel all year, continually moving in
      search of forage and drinking-water.

      - Transhumance: herds of cattle, sheep and goats are
      guided to fresh pastures in the northern Sahel in the
      rainy season, and return to the south in the dry season
      to avoid shortage of drinking-water. The annual
      production of cattle herds is about 12%, which
      corresponds to only 13 kg of meat per animal. Small
      ruminants produce annually 3-4 kg of meat per animal;
      annual herd productivity is about 25%. The transhumance
      system of husbandry is highly important for the Sahel
      countries.

      - Sedentary animal husbandry: most cultivators in the
      southern Sahel and in the savannah keep a few animals
      for milk, draught power and as an investment.

1.03 At least 4 types of problems for production of animals,
      cattle in particular, can be distinguished:

      - the degree of exploitation of herds is low;
      - the production per animal is low;
      - overgrazing occurs on many pastures;
      - little infrastructure is present to support animal
        production.

      Research has not concentrated on any one of these
      problems directly, but on a problem underlying at least

2 of them: the low production of forage on the
rangelands, in terms of quantity and quality.

1.04 It is generally thought that precipitation, more than any
other factor, determines plant growth in semi-arid
regions. There are many indications of an almost linear
relation between annual rainfall and annual productivity
of rangelands: an average productivity of above-ground
dry matter of 400-500 kg ha^{-1} is found in the northern
Sahel (annual precipitation less than 200 mm);in the
central part (200-400 mm per year) about 1000 kg ha^{-1},
and 1500 kg ha^{-1} in the south (400-600 mm per year).
But the latter value, in particular, is much lower than
expected on the basis of water balance research. The
observed relation between <u>rainfall and annual production</u>
is apparently an indirect one. This subject was
investigated here in detail.

1.05 Elaborate descriptive studies of species composition
and productivity of Sahelian rangelands have been
published. However, the variability of the annual
precipitation and vegetation from year to year and from
place to place seriously limits the predictive value of
these studies. With the research carried out in the
P.P.S. project we aimed at <u>understanding and predicting</u>
the average actual production and its fluctuations on a
basis of knowledge about plant ecology, plant physiology,
soil physics and soil chemistry. The principal result
of our research is a scientific tool with which one can
establish the actual production and the productivity
potential more easily and accurately than was possible
before. It may be helpful for planning of development
projects and for preparing programmes of rangeland
research.

CHAPTER 2   RESEARCH METHODS

2.01 In applied agronomic research attempts are often made
to determine static and descriptive production functions.
But with the exception of very simplified cases, no useful
functions based on statistical data and practical
research have been produced that have a reasonable
generality. The use of dynamic simulation models
provides a promising alternative. But our knowledge of
basic processes is not yet far enough advanced to tackle
questions about productivity of vegetations exclusively
with models. That is why the <u>modelling approach and the
descriptive approach</u> still have to support and reinforce
each other.

2.02 Models are simple representations of systems, where we
define a system as a coherent part of the real world.
Models are necessarily simplifications of reality. With
dynamic models, one imitates aspects of the behaviour in

time of the real world. If formulations of processes in
the model are more or less analogous to those of the real
world, one speaks of simulation models. To focus P.P.S.
research to the most relevant questions, 4 systems of
processes related to plant growth were delineated by
distinguishing 4 levels of production. At each successive
level, production is limited by a new factor. These
levels are:

- Production level A: radiation limits plant production.
This situation is found in well-managed, irrigated crop
systems with ample use of fertilizer.

- Production level B: as for Level A, but the amount of
soil water limits production. The water balance of the
soil is an important part of any model at this production
level.

- Production level C: as for Level B, but the availability
of nitrogen from the soil also limits productivity.
Crucial variables are the amount of inorganic and organic
nitrogen in the soil, and important processes are those
affecting the nitrogen balance; transformations in the
soil, uptake by plants and fixation.

- Production level D: as for Level B, but the low
availability of other elements, particularly phosphorus,
reduces growth at some stage.

This order of production levels is followed in the report
and in this summary.

2.03   Three successive   phases of development of models may be
distinguished: preliminary, comprehensive and summary
models. Comprehensive models of the carbon balance
processes of the plant and of the soil water balance
have been used in the study to evaluate quantitatively
our knowledge of the processes involved. However, as
these models are very complex, summary models were
derived from them and presented in full in the original
report. Those models are particularly useful for
instruction, and to a certain extent also for prediction.
Preliminary models of the nitrogen and phosphorus balance
processes in the soil are discussed in the report.

CHAPTER 3   GEOGRAPHY OF THE SAHEL AND
OF THE EXPERIMENTAL FIELDS

3.01   The term 'Sahel' is employed for the zone receiving
between 100 and 600 mm of rainfall annually. It is a band
about 400-800 km wide and more than 5000 km long. Most of
the research of the P.P.S. project was executed at a
ranch 20-35 km east of Niono (14° 30' N, 5° 45' E), close
to the dead Delta of the river Niger. Many of the
ecological observations were made on a fixed north-south
transect, extending from the 100 mm yr^{-1} to the 1100 mm
yr^{-1} isohyet.

3.02   Of the meteorological   variables, precipitation shows by
far the widest variation from place to place and from
year to year. The rainy period is limited to 2 months in
the north and 4 months in the south, the rest of the year
being completely dry. The potential evapotranspiration
varies from 4 mm d^{-1} in the rainy season in the south to
6 mm d^{-1} in the dry season in north and south. Average
daily temperatures range from about 25 $^{\circ}$C to 30 $^{\circ}$C. A
considerable proportion of the annual precipitation falls
at very high intensities: 20-40% in showers exceeding
30 mm, during which the intensity often exceeds 50 mm h^{-1}.
The mean annual rainfall in Niono is 581 mm; its standard
deviation is 160 mm yr^{-1}. This large variation is typical
for the Sahel region.

3.03   Wet and dry years can be characterized as those extreme
years that occur only once per 10 years. Our 4 project
years in Niono were normal to dry. However, for plant
growth studies, the characterization of 'wet' and 'dry'
years makes little sense, because the composition and
final biomass of the vegetation depends only indirectly
on the total amount of rain as Table 1 shows.

Table 1.   The total amount of rain received in 4
successive years in Niono, the amount
of rain during the growing season and
the average amount of biomass of annual
pastures at the end of the growing season

year	total rain (mm yr^{-1})	rain in season (mm $season^{-1}$)	biomass (kg ha^{-1})
1976	587	372	2 500
1977	380	327	2 300
1978	453	371	2 000
1979	376	293	1 400

3.04   Three major groups of soils are distinguished: sandy
        soils, shallow detritic soils and fluviatile soils. These
        types occupy about 50, 30 and 20% respectively, of the
        total area of the Sahel. Sandy soils are deep,
        homogeneous and of eolic origin. Detritic soils have
        developed on laterite or sandstone. Most of them are
        loams, heterogeneous and have considerable runoff.
        Fluviatile soils are deep, clayey soils, or loamy-clayey
        subsoils covered with a sandy-loamy topsoil.

3.05   The only form of soil erosion is sheet erosion caused by
        runoff. It is considered to be of little importance.
        All soils in the Sahel are poor in carbon (organic
        matter), nitrogen, phosphorus and in other elements.
        The soils are generally slightly acid to neutral. Most
        sandy and loamy soils are covered with a crust, which
        causes 20-40% of the annual precipitation to run off.

3.06   As open grassland vegetation - steppe - is typical for
        the northern Sahel   annual grasses dominate, but some
        annual dicotyledons may be important. Perennial grasses
        are rare. Trees generally do not cover more than 5% of
        the area. Fire occurs infrequently. The spatial
        distribution of the vegetation can be quite heterogeneous,
        particularly on a loamy substrate. Relatively humid
        spots provide a longer growing season and consequently
        have a more southern vegetation than drier soils that
        carry a more northern vegetation type.

3.07   The Sahelian zone is traversed by large rivers, such as
        the Niger and the Senegal. They flood annually huge
        surfaces. There the annual production can exceed the
        production of the rainfed rangelands considerably. Its
        vegetation consists primarily of perennial grasses. In
        the southern Sahel the savannah replaces the steppe: a
        vegetation with high perennial grasses, generally burnt
        every year, and with a considerable tree cover.
        Agriculture is common.

3.08   On the transect across the Sahel sandy soils dominate
        in the northern part, and clayey and loamy soils in the
        southern part. The ranch at Niono is located in the
        transition zone of steppe to savannah. On the sandy
        dunes, the grass species Schoenefeldia gracilis,
        Diheteropogon hagerupii and Cenchrus biflorus dominate.
        The annual biomass production is 2000-3000 kg ha^{-1}. The
        tree cover is about 10%. On the loamy soils tree cover
        is about 25% on average, but irregularly distributed.
        The herbaceous vegetation consists of the dicotyledons
        Borreria spp., Blepharis linariifolia and the grasses
        Elionurus elegans, Schoenefeldia gracilis and
        Diheteropogon hagerupii, with small spots with the
        perennial Andropogon gayanus. Its productivity varies
        from 1000 to 2500 kg ha^{-1}. On the clayey soils, the tree
        cover is regularly distributed and is about 30%. The

herbaceous layer is dominated by the grasses <u>Loudetia</u>
<u>togoensis</u>, <u>Diheteropogon</u> <u>hagerupii</u>, <u>Pennisetum</u>
<u>pedicellatum</u>. Its productivity is 2000-3000 kg ha^{-1}.

CHAPTER 4   THE PRODUCTION POTENTIAL OF
            SAHELIAN RANGELANDS

The Physiological Potential of Grasslands and Crops

4.01   The productivity of the grasslands north of the 200 mm
       yr^{-1} isohyet is always limited by the availability of
       water. This chapter gives the information required to
       characterize the productivity of these rangelands.
       South of the 400 mm yr^{-1} isohyet on soils with good
       infiltration; productivity of the vegetation is
       restricted by the low fertility of the soils.
       Fertilization will stimulate biomass production up to
       the level commensurate with water availability; this
       maximum level (Production level B) is considered in this
       chapter. But Production level A is to be considered
       first.

4.02   The <u>growth rate</u> of a closed canopy in the vegetative
       phase in conditions of Production level A is quite high:
       from 200 up to 350 kg ha^{-1} d^{-1}. Once a full soil cover
       is established, the weather is the only variable that
       determines the growth rate. The yield of vegetation or
       the crop is then linked directly to the duration of the
       growth period. Such rates of growth are 3-5 times higher
       than those under 'normal', sub-optimal Sahel conditions,
       where also the period of rapid growth lasts only briefly.

4.03   A simple <u>summary model</u> to calculate the rate of growth
       (GR) of a <u>vegetation is</u>: GR = (GP-ME) x CE. It states
       that canopy 'net' rate of photosynthesis multiplied
       with a conversion efficiency (CE) equals the growth rate.
       'Net' photosynthesis equals gross photosynthesis (GP)
       minus the energy required for maintenance of the tissues
       (ME). The biomass formed is distributed over plant
       organs in a proportion that changes with the stage of
       phenological development of the plants.

4.04   Canopy photosynthesis is the sum of the contributions
       of the individual leaves. Leaf photosynthesis depends
       on the intensity of incident irradiation and on leaf
       characteristics. One important distinction between
       groups of species is based on the mechanism of
       photosynthesis: so-called C_3 species have about 50%
       lower maximum rates of leaf photosynthesis than so-called
       C_4 species. The rate of CO_2 assimilation of a closed
       canopy of C_4 species in the Sahel is therefore higher
       than that of C_3 species (about 850 and 600 kg ha^{-1} d^{-1},

respectively). Some of the glucose formed in the photo-synthesis process is used for maintenance of the biomass present: about 1-2% per day of the weight of the biomass. The remainder is converted into 'structural biomass', consisting of protein, cellulose, etc. On average about 0.7 kg of vegetative tissue is formed from 1 kg of glucose (=CE).

4.05 Much knowledge of the processes of canopy photosynthesis, respiration, conversion processes and partitioning of assimilates, as well of transpiration, is integrated in the comprehensive simulation model BACROS. The degree of agreement between experimentally obtained data of field crops of rice and maize and the simulated data confirms that the model simulates these basic processes well, and that it can be a reference point for the models used in the following sections.

The Botanical Potential of Rangelands

4.06 To determine the availability of forage of rangelands, the species composition has to be considered, as it co-determines forage quantity and quality. Characteristics of species that are important in these respects are described.

4.07 Speed and homogeneity of germination determine the relative abundance of a species. The duration of the germination process depends on specific characteristics of the seeds and on the humidity of the upper soil layers. The precipitation distribution in time is therefore an important determinant of the germination pattern in a particular year. In the southern Sahel, up to 100 kg ha^{-1} of seed germinates annually; the amount is 10 or more times smaller in the northern part.

4.08 Many seedlings and germinated seeds die shortly after germination because of too long dry periods between rains. About 1500-15 000 seedlings per square metre is a normal result of germination; or average, about 10% survive. Rapid and homogeneous germination may seem too risky to be a good strategy for survival in the Sahel. However, one often finds that species with such properties dominate the vegetation: Cenchrus biflorus, Diheteropogon hagerupii and Schoenefeldia gracilis. If establishment succeeds, there is a large premium on being the first, while the heterogeneity of soil surface, seed depth and seed hardiness ensures that sufficient viable seeds always remain for new waves of germination, if necessary. Slowly germinating species are quite sure to succeed by avoiding drought periods, but they only dominate the biomass when the vegetation has been disturbed considerably.

4.09   The end of the growth period of annuals is often not
       determined by water and nutrients, but is strongly
       influenced by day length. Photoperiodism provides some
       assurance for completion of the reproductive phase. Two
       types of responses to day length were found and
       quantified.

4.10   The uncertainty of the availability of water during the
       reproductive phase causes the annual production of seed
       to be highly variable. The seeds make up 5-15% of the
       total weight of the biomass at maturity. Because the
       weight of individual seeds is relatively constant, the
       bigger the plant, the larger the number of grains it
       produces. In the order of 10% of the seeds produced in
       a certain year survive and produce seedlings in the next,
       but this fraction is highly variable. Factors that
       contribute to loss of viable seed are: grazing before
       seedfall, predation by ants, termites and birds, fungi,
       erosion, fire and pre-emergence mortality due to drought.
       In spite of such losses, the number of seedlings at the
       beginning of the growing season is usually not a
       limiting factor for biomass production, except for years
       with unfavourable distribution of early rains, and even
       more so in the north than in the south.

4.11   A 'nodal component analysis' of all our observations of
       vegetation compositions provides a characterization of
       the extent to which species appear in combinations in
       the field. It was used to develop a generalized scheme
       of changes in the vegetation composition that may be
       expected from changes in precipitation, exploitation
       intensity, fire, etc.

       The Soil Water Balance

       Production level B

4.12   The water balance of a soil describes the sum of the
       processes that contribute to its humidification and its
       drying: precipitation, runoff, evaporation from the
       surface and transpiration by plants. Deep drainage is
       only locally important, and it will not be discussed.
       Proper knowledge of the soil water balance is required
       to understand the development of the specific species
       composition of the natural vegetation and its growth
       rate during the rainy season.

4.13   Infiltration of water into the soil is a key process.
       The rate of infiltration into fairly homogeneous soils
       is usually high initially and tapers off soon. This
       pattern can be approximated by mathematical equations.
       Many soils are covered by a thin crust. The permeability
       of the dry crust is low, but increases after a few
       minutes of humidification. This phenomenon makes
       infiltration difficult to quantify from basic soil
       properties. Therefore measurements were made in the

field with a large rain simulator; single and double infiltration rings gave unsatisfactory results.

4.14 When the rate of precipitation exceeds the rate of infiltration, water ponds or runs off. The larger the shower is, the larger the fraction of it that does not infiltrate. Runoff is negligible on dunes of coarse sand, which consequently lack surface drinking-water for animals. On sandy loams and loamy sands, little runoff occurs on surfaces with a slope of less than 0.5%, but it is 20-50% of the annual precipitation when the slope exceeds 1%. On loamy plains runoff is locally equally important, as demonstrated by the presence of patches of perennials that need a long growing season. The small lakes, originating from runoff, provide a basis for exploitation of the zone. On lateritic formations, runoff is often very large and is a direct source for temporary lakes and local watertables near villages. Clayey or loamy plains that are completely flat often receive water from their surroundings. The infiltration capacity of soils on the ranch with and without vegetation was measured. Bare soils are less permeable. This implies that degraded areas carrying a sparse vegetation have more runoff than others, which can lead in turn to further degradation, reinforcing a negative spiral.

4.15 Evapotranspiration is the sum of evaporation from the soil surface and transpiration by the vegetation. The rate of evapotranspiration ranges from about 2.8 mm d^{-1} for natural rangeland, to about 5.1 mm d^{-1} for a rapidly growing vegetation on a fertilized soil.

4.16 Evaporation during a complete rainy season amounts to 80-90% of the evapotranspiration. Evaporation can occur very fast early in the rainy season: the air is dry, its temperature is high and the irradiation is intense: soil surface temperatures up to 60 $^{\circ}C$ (dry soils) were observed. Combination of model and measurements leads to a formula to quantify the rate of evaporation which is valid for most soils. Presence of vegetation reduces evaporation considerably.

4.17 Transpiration may be computed as the difference between the observed value of evapotranspiration and the computed value of evaporation. The rate of transpiration ranges from 1 mm d^{-1} (natural rangeland) to 4 mm d^{-1} (fertilized vegetation). The transpiration coefficient determined in this way is about 200 kg of water transpired per kilogram of dry matter formed.

4.18 On the basis of its effect on the water balance, the rainy season can be divided into 4 parts:

- Before frequent showers: until June or July. One or
more waves of germination, high rates of evaporation.
- Beginning of frequent showers: July. The earlier this
period falls, the longer the period of vegetation growth
can be.
- The growing season: August and possibly a part of
September. The growth rate of the unfertilized, natural
vegetation is in the order of 35-50 kg ha^{-1} d^{-1}.
- End of the growing season: The onset of the brief
reproductive phase of annual grasses is generally
determined by photoperiod. The more water falls in this
period, the more will remain in the soil, to be used
only by trees or lost slowly by evaporation.

The Potential Production of Rangelands

4.19   The term potential production is used in the sense of
'growth without nutrient shortage' (Production level B).
It concerns therefore natural rangelands in the northern
Sahel, and fertilized rangelands in the south.

4.20   The growth pattern of vegetations can be divided into an
exponential, a linear and a maturation phase. The
exponential phase of growth of vegetations lasts till
an aeric mass of about 1000 kg ha^{-1} is reached, when
mutual shading of plants becomes important. Under
optimal conditions, annuals may grow at a relative rate
of 0.5 g $g-1$ d^{-1}. When water limits growth temporarily,
the average relative growth rate during the exponential
phase was about 0.2 g g^{-1} d^{-1} (on natural pastures with
nutrient shortage, the relative growth rate is about 0.1
g g^{-1} d^{-1}). In the northern Sahel the aeric mass of
the biomass never exceeds 1000 kg ha^{-1}.

4.21   During the period of linear growth, the daily dry weight
increment is more or less constant: 200-250 kg ha^{-1} d^{-1}.
Depending upon the amount of water that has infiltrated
into the soil, this leads to an aeric mass of biomass of
6000-12 000 kg ha^{-1} in the southern Sahel.

4.22   Of particular interest is the corresponding rate of
transpiration. Most rangeland grown plants probably have
stomata that optimize their aperture. The transpiration
coefficient during the rainy season can then be derived
theoretically to be about 210 kg of water transpired per
kilogram of above ground dry matter formed in C_4 plants
and about 330 kg kg^{-1} in C_3 plants. (The stomatal
conductance is below its maximum value when the rate of
growth of the vegetation is reduced by nutrient shortage.
This indicates that the regulation mechanism of stomata
remains also functional under nutrient stress. This
confirms that pastures with low growth rates, i.e.
unfertilized pastures, utilize water at a lower rate than
fertilized pastures.) In models, the constancy of this
coefficient is used such that canopy photosynthesis times
the coefficient yields transpiration if plenty of soil
water is available, but that photosynthesis equals trans-
piration divided by this coefficient with water shortage.

4.23 Especially for grasses, flowering often marks the
      beginning of the final growth phase, which lasts for
      annual grasses 10-20 days. Some species flower
      prolifically till late in the growing season if
      conditions remain favourable.

4.24 <u>Roots</u> deserve special attention for the extent to which
      they explore the soil for water and for nutrients.
      Rooting patterns of annual grasses in experiments with
      and without fertilization are surprisingly similar: most
      of the roots are in the upper 20 cm, though some extend
      down to 1 m or more. Some roots go as deep as the soil
      is humid, so that roots can exhaust the total stock of
      soil water. The minimum rooting density required for
      efficient absorption of nitrate is roughly the same as
      that for water, so that nitrate can also be absorbed
      efficiently. For phosphorus, however, the normal
      rooting density in the upper layers is insufficient to
      exploit more than about 50% of the soil volume.

4.25 The comprehensive simulation model ARID CROP, which was
      developed before the P.P.S. project, was adapted for
      simulation of vegetation growth in the Sahel. To
      evaluate its performance, the model was used to simulate
      different experiments on the ranch where growth was
      observed. Agreement between simulation and observation
      is discussed in the original report and is fairly good.
      For instruction purposes, however, a simple model was
      derived from ARID CROP. Only a hand calculator is
      needed to use it. The model does provide realistic
      values of growth, evaporation, transpiration and runoff.

CHAPTER 5 THE PROCESSES DETERMINING THE ACTUAL
           PRODUCTIVITY OF SAHELIAN RANGELANDS

Introduction to Production Levels C and D

5.01 The actual productivity of rangelands is generally well
      below their potential level. It is therefore necessary
      to study the way in which shortage of <u>plant nutrients</u>
      reduces the productivity, the degree of shortage of
      the nutrients in the field and the reasons why there
      are shortages. One may then ask whether shortages can
      be relieved, and by what means.

5.02 Application of potassium, calcium, magnesium and sulphur
      on rangelands did not show any response. Limited
      experimentation with application of trace-elements, such
      as molybdenum, copper, cobalt and manganese, to
      leguminous plants did not show any response either. But
      application of nitrogen and/or phosphorus stimulated
      growth considerably.

The Actual Production and the Role of
Nitrogen and Phosphorus

5.03   The biomass at flowering and at maturity, and the total
amount of nitrogen (N) and of phosphorus (P) absorbed at
flowering were investigated. The response curve of the
production of a natural vegetation to fertilization with
N (in presence of sufficient P) is shown in Fig. 1. The
response curve of productivity to N absorbed (Ne), rather
than to N applied, goes through the origin and has an
upper limit that equals the potential productivity in
that situation. The initial slope of the curve is
generally equivalent to 1000 kg of dry matter per 5 kg
of N absorbed. Quadrant 3 of this figure shows the
linear relationship between the amount of N absorbed and
the amount of N applied. A similar set of response
curves can be drawn for productivity in case of
application of P (in presence of sufficient N). The
upper asymptote is identical to that of the former graph,
the initial slope is about equivalent to 1000 kg biomass
per 0.5 kg of P absorbed. The aspects 'soil' and
'vegetation' of these crucial relationships are analyzed
below.

5.04   Plant species are not characterized by specific
concentrations of N or of P. Such concentrations depend
almost completely on the fertility of the soil and plant
age. The average concentrations of N and of P in the
above ground dry matter of plants change in time. For
C_4 grasses, that grow with lower N and P concentrations
than legumes and other dicotyledons do, the minimum
concentration of N ranges from 1.5% in young plants to
about 0.5% in mature plants. At any stage, values up to
about 4 times as high are found in plants with ample
nutrient supply. Values for concentrations of P are
about 10 times lower. Absorption of N after flowering
is negligible: the biomass may increase by about 60%
between flowering and maturation, but the amount of N
absorbed remains constant. The total amount of N
absorbed by the vegetation during a growing season is in
the order of 10-20 kg ha^{-1}. Even less N is absorbed in
the northern part of the Sahel and in overexploited
areas, more can be absorbed in the south on relatively
favourable spots.

5.05   Results of experiments on different locations showed
that the recovery of fertilizer N over 2 years is 60-80%
on all soil types. Interestingly, there is also a
relationship between the richness of the natural soil
and the recovery of fertilizer N: the poorer the
unfertilized soil, the better fertilizer recovery the
first year after application.

5.06   An experiment in the northern Sahel (150 mm yr^{-1} isohyet)
showed no response of biomass or its N and P
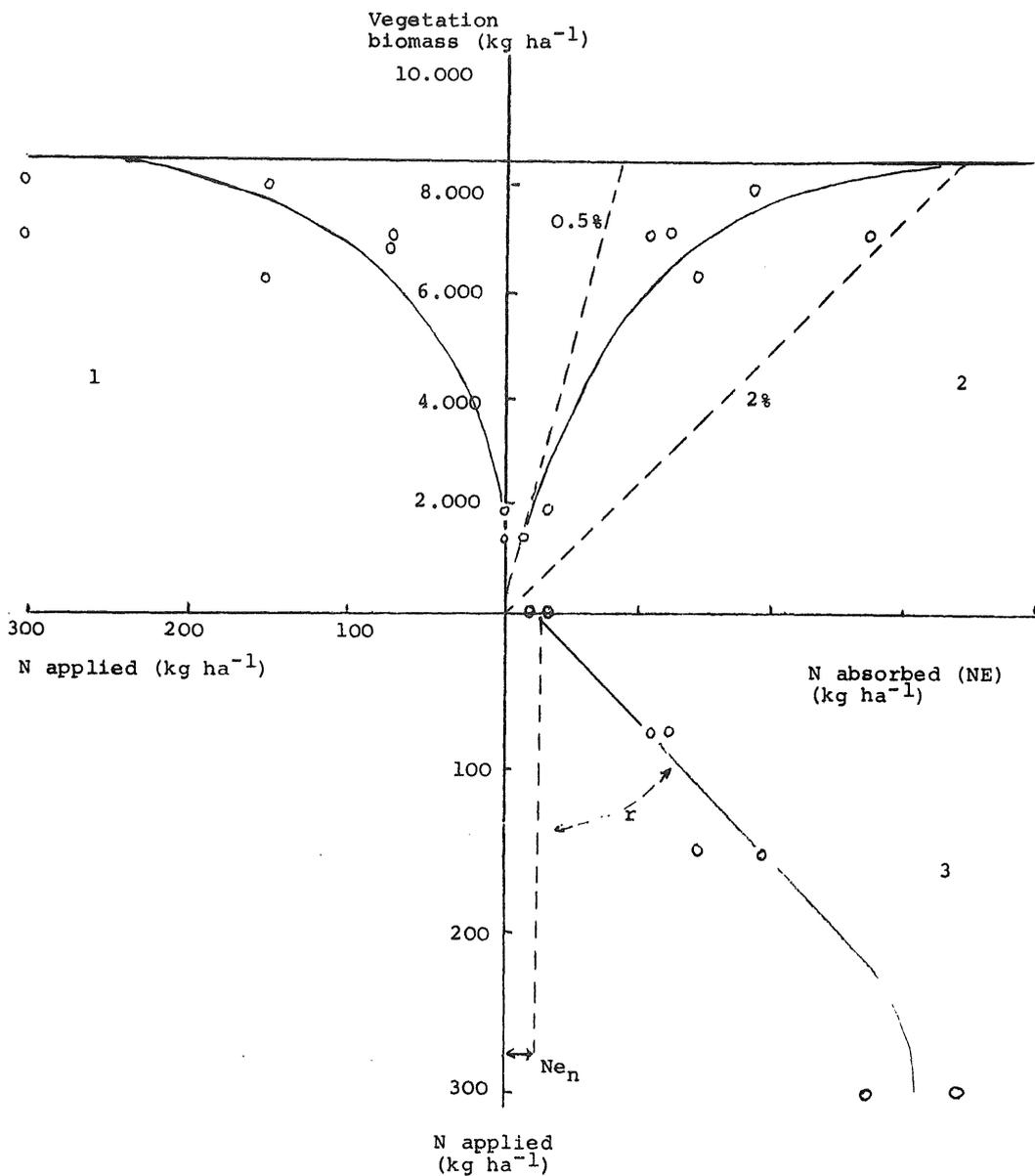concentration to fertilization. In fact, those

Fig 1. Some relations between the biomass formed, the amount of fertilizer applied and the amount of N absorbed (Ne) under the condition of high availability of P. The trial was on a clay soil on the ranch in 1977, with a vegetation of *Diheteropogon hagerupii*, harvest at flowering. The potential productivity there was 8500 kg ha^{-1} which is indicated by a horizontal line. The dots represent individual observations; the curves were fitted by hand. The minimum (0.5% N) and maximum (2%) levels at flowering are indicated as are the amount of N absorbed without fertilization (Ne$_n$) and the N recovery 'r).

concentrations of the unfertilized pasture were already
as high as those of fertilized pastures in the south.
This confirms that plant productivity in the north is not
limited by soil fertility, but by water.

5.07 The ratio of the weight of P to that of N in the same
plants is not below 0.04 g g^{-1}, and it does not exceed
0.15 g g^{-1}, because their concentrations are coupled to
a certain degree. As a consequence, N absorption is
reduced, and hence biomass production if too little P is
available. The P/N ratio has the strong and general
tendency to increase during the growing season. This
leads to 2 conclusions: productivity of biomass in the
final stage is almost always limited by the soil N
supply, and the P/N ratio of young grasses is an indicator
of the relative importance of shortage of P to N.

5.08 Rangeland biomass disappears after its maturation, even
without exploitation or fire. Its N concentration, and
hence its quality, diminishes also. The degree of
diminution of both is highly variable. An attempt has
been made to relate those losses to precipitation after
maturity.

The Processes of the Nitrogen Balance

5.09 A quantitative scheme of the processes of the N balance
of natural pastures has been developed. Of all N in
the soil, which amounts to 300-3 000 kg ha^{-1}, only the
N in an inorganic form (nitrate, ammonium) is available
to plants. The organic matter in the soil is substrate
for growth of micro-organisms. Their growth can lead
to mineralization and to immobilization; which of these
predominates depends in particular on the proportions of
carbon (C) and N in the substrate. Nitrification is
remarkably slow in the Sahel; it is not understood why.
Mineralization seems to be more important than
immobilization in the beginning of the rainy season,
but this reverses later on. This order leads to a
flush of inorganic N in the soil - a temporary excess
early in the season. Plants may not be ready to utilize
all of this excess immediately, because of a P shortage
or because they are still too small.

5.10 The intensity of micro-organism activity is generally
limited by shortage of C. This may be the cause of the
temporary excess of N early in the season. This is
relieved to a certain extent by decomposition of roots
and root exudation later on. About 1000 kg ha^{-1} of C
enters the soil each year as organic debris, and the same
amount leaves the soil as CO_2. This is a considerable
amount compared to the mass of C in the soil, which
ranges between 3000 and 15 000 kg ha^{-1}. An imbalance
of the C balance processes that lasts for several years
will therefore lead to a considerable loss of soil
organic matter.

Additions and Losses of N

5.11 In the order of 0.65 kg ha^{-1} of N is added to the soil
with each 100 mm of rain. Leguminous species fix about
75% of the N they contain. The remainder comes from
absorption; this percentage is lower if there is
plenty of N available. However, legumes make up only
about 5% of the biomass, so that their contribution of N
remains modest: in the order of 0.2-3 kg ha^{-1} per year.
Algae on the soil surface (incorporated in the crust) fix
aerial N. Their contribution is estimated to be about
0.2 kg per 100 mm of rain. Other micro-organisms in
the soil, decomposing organic material and dead plant
parts or using plant exudates, can also fix N. Their
combined rate of fixation is small: it is estimated to
be about 0.2 kg per 1000 kg of plant biomass produced.

5.12 All N incorporated in biomass that burns is lost. This
can be as much as 5-30 kg ha^{-1} in a single fire.
Exploitation also causes considerable losses of N: the
animal may deposit its faeces and urine outside the
grazing area, but even when faeces and urine are dropped
on the rangeland, in the order of 50% of the N in urine
volatilizes. Denitrification of NO_3^- can occur in
anaerobic conditions and in the presence of sufficient
organic matter. This process is probably unimportant
on natural rangelands as anaerobic conditions occur
only in isolated spots, and because the NO_3^-
concentration and the soil organic-matter content are
always very low.

Phosphorus in the Soil and its Accessibility to Plants

5.13 Application of P to natural rangelands was found to have
a positive effect on productivity in many cases and on
legumes in particular. We expect that this is a common
phenomenon on most of the Sahelian rangelands. Soils
generally have a low concentration of P: a few hundred
kilogram per hectare in the upper 20 cm of the soil.
It is partly in an inorganic form and partly
incorporated in organic material. Only dissolved P,
supplied at a low rate from organic and inorganic P and
a tiny fraction of the total, can be absorbed.

5.14 The balance of P in soils is less complex than that of
N: there are no processes analogous to N_2 fixation,
denitrification, loss by fire or supply by
precipitation. On the other hand, the dynamics of the
cycling of P in inorganic and organic forms is much
less understood. In an equilibrium situation, the same
series of processes with the same intensity repeat
themselves each year. In such a situation, 4-20% of
the total P is in an inorganic form, a fraction which is
directly proportional to the productivity. A real
equilibrium does not exist at any level of exploitation:

there is always some export of P, leading to a very slow
decrease of the soil P content. This reduction is
estimated to be about 0.1 kg ha^{-1} yr^{-1} on the Niono
ranch. This may seem slow, but it will exhaust the pool
of most available P within a few decades.

5.15 Depending upon conditions, vegetations generally absorb
P at an annual rate of 0.3-2 kg ha^{-1}. Various methods
exist to estimate the capacity of the soil to dissolve P
and make it available to roots. However, the most
accurate and direct method to measure availability of P
from the soil remains the harvesting of the vegetation
and the determination of the absorbed P. For absorption
by roots, their total length and the absorption per cm
are important. The latter depends directly on the rate
at which P dissolves and diffuses over a very small
distance (fraction of a mm) to the root surface. The
degree of exploitation of the soil volume by the root
system is probably about 50%. The extent to which
mycorhiza increase the volume searched by roots could
be considerable.

5.16 The fertilizer triple super phosphate (TSP) and the
Malian natural rock phosphate from Tilemsi (PNT) have
been applied at different rates. Recovery of TSP-P in
the first season after application by the rangeland
vegetation was up to 0.5 g g^{-1} at low doses, and
decreasing at high doses. The maximum efficiency of
PNT-P was only about 0.03 g g^{-1} in the first year after
application. Its low recovery can be compensated for
by high doses, which will remain effective for many
years.

The Actual Productivity in an Equilibrium Situation

5.17 The growth of vegetations is usually limited at the end
of the growing season by the availability of N. A first
discussion of productivity in the equilibrium situation
should therefore concentrate on the equilibrium of the N
balance. In an equilibrium, the amount of N that enters
the system equals the amount that leaves it. This
situation may be hypothetical for any individual year,
but it merits attentions as it leads to very useful
insights. The annual influx of N equals the amount
related to rainfall plus an amount fixed by legumes and
micro-organisms. The latter fractions are proportional
to the legume biomass and the total biomass,
respectively. Even without any exploitation, there is
loss of N, particularly due to volatilization. With
exploitation, the fraction of the N in the biomass lost
annually is much larger. The fraction of the N
contained in the biomass at flowering (N_b) that is lost
annually by all processes combined is called f; f N_b
(in kg ha^{-1} yr^{-1}) equals the amount lost. N_b appears in
both the equation for input of N and for loss of N, so

that they can be combined and N_b made explicit:
$N_b = 0.0085 \times Pl / (1.025 \times f - (0.02 \times L + 0.038))$
in which Pl is the precipitation (in mm yr^{-1}) and L the
percentage that legumes make up of the biomass. The
report gives sets of values of N_b, f and their product
at the 500 mm yr^{-1} isohyet.

CHAPTER 6   ACTUAL PRODUCTION OF RANGELANDS IN RELATION
            TO ENVIRONMENTAL FACTORS AND HUMAN INFLUENCES

Production of Perennial Grasses and Trees

6.01   Production of perennial grasses usually exceeds that of
       annual species considerably. But this difference in
       production is not nearly as important as it seems,
       because cattle make most use of the small amount of
       regrowth of perennials during the dry season. The large
       biomass at the end of the growing season is too low in
       quality: only about 1000 kg ha^{-1} of it can be exploited
       without overgrazing, and the quality of this amount is
       just sufficient for maintenance of the animals.

6.02   Another reason for overestimating the importance of
       perennials is that their annual uptake of N seems to
       exceed that of annuals. However, a fraction of the N in
       the above ground biomass stems from a stock of N in the
       root system, which is transferred to the leaves early in
       the season and transferred back at the end. Perennial
       grasses are sensitive to overexploitation because of
       exhaustion of this stock of N and because of elimination
       of growing points.

6.03   Trees and perennial grasses survive the dry season by
       dependence on the little water in the soil that the
       annual plants have left. This makes perennials
       particularly sensitive to relatively dry years, when
       annuals leave little or no water. Like perennial grasses,
       trees can use water from a large depth on the few places
       where this occurs. In general, however, trees compete
       with grasses for most of their water and nutrients. This
       is the basis of the inverse relation of tree leaf
       production (as a measure of tree growth) to grass
       production.

Leguminous Species

6.04   Legumes make up about 5% of the biomass over the whole
       Sahel, but they tend to be more common on places with
       much runoff. Legumes are probably not much more
       important because they are weak competitors with grasses.
       Vegetation consisting almost exclusively of the legume
       Zornia glochidiata is common on soils with a high runoff.
       Such soils are enriched with N. As a result, their

vegetation does not respond to fertilization with N, but
strongly to fertilization with P.

Precipitation and Forage Production of Rangelands

6.05 The amount of N in the biomass in an equilibrium situation
can be calculated with the equation given above when the
fraction of legumes, the annual precipitation and the
fraction of N lost are specified. The agreement between
the values calculated for the north-south transect and
the schematized, observed values is good. The way in
which the composition of the vegetation is related to the
availability of water is depicted by key species; the
direction of change of the composition as a result of
the 1969-1973 drought is indicated. The effect of the
vegetation composition, through the length of its growing
season, on biomass production is also shown in the
original report. The effect of yearly variations in
rainfall is probably fairly small in the northern Sahel
(when expressed in kg ha^{-1}): it is considerable
between the 200 and 500 mm yr^{-1} isohyets, and it is
relatively small again at higher levels of precipitation.

6.06 The concentration of N in plants is higher the lower the
level of precipitation is: the concentration of N at
the end of the growing season is higher in the northern
part of the Sahel and low in the south, although local
variations are large. Fig. 2 is a schema of the relation
of production and biomass N concentration to rainfall;
Fig. 3 is a schema of the relation of productivity and
N concentration.

Substrate and Vegetation

6.07 The term 'substrate' is used as the sum of geomorphological
aspects and physical and chemical soil characteristics.
The most important of these are the compaction of the
surface layer, which leads to formation of a crust,
affecting the soil water balance, the seed balance, and
soil fertility. The landscape is of prime importance
in determining whether there is runoff, influx of water
or neither of them. Plant characteristics to be
especially considered are the relative rate and
homogeneity of germination, the resistance to drought
of seedlings and the productivity of the species in
terms of biomass and seeds.

6.08 The relation between <u>substrate and vegetation composition</u>
in any year is not very strong. The vegetation of a
region should thus not be characterized on the basis of
observations of a single year. However, the average
frequences of species on particular substrates differ
clearly. A better picture evolves when species are
grouped on the basis of physiological characteristics.
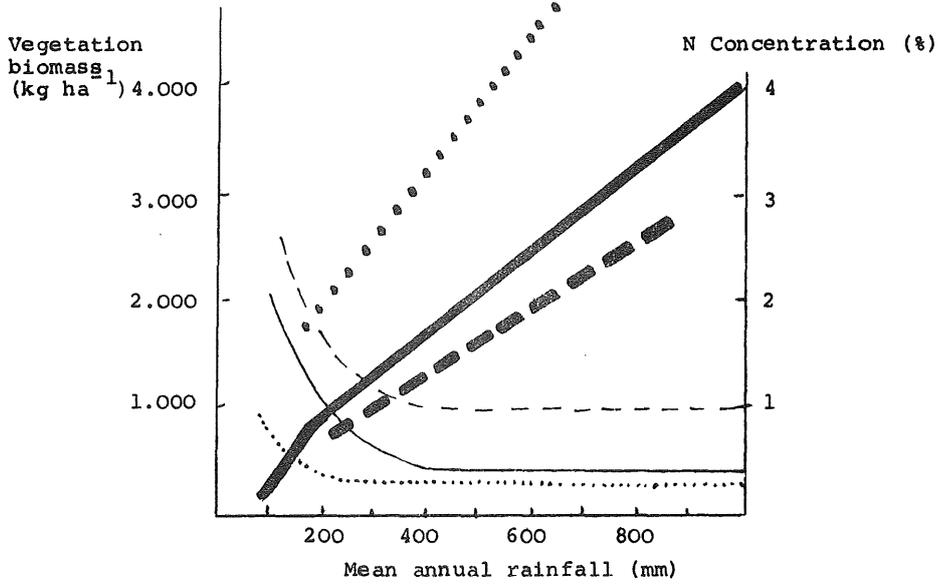In the landscape it is important to distinguish:

Vegetation
biomass
(kg ha^{-1}) 4.000   N Concentration (%)

Mean annual rainfall (mm)

Fig 2.   The mean biomass and its N concentration in relation
         to the mean rainfall, for 3 species groups:
         (.......) perennial grasses,
         (————) C$_4$ annuals
         (-------)   C$_3$ annuals;

         fat lines: biomass, thin lines: N concentration

biomass
(kg ha^{-1})

5.000   Annual grasses

4.000   Herbs

3.000   Legumes

2.000

1.000

        1   2   3   4

        N Concentration (%)
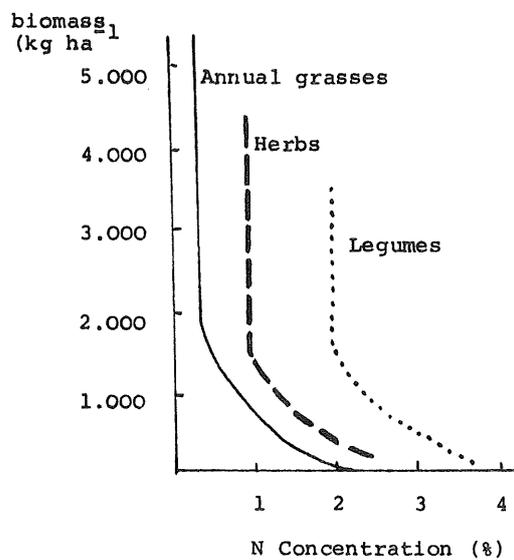
Fig 3.   The relation between the biomass at the end of
         the growing season and N concentration, for 3 species
         groups.

- Regions where infiltration equals precipitation: the
vegetation is quite homogeneous throughout hill tops and
valleys, and is often dominated by rapidly germinating
grasses. These zones are little exploited because of
lack of surface drinking-water.
- Regions with runoff: runoff leads to considerable
difference in the soil water balance over short distance.
As a result, the vegetation is heterogeneous in
productivity and consists of a relatively high number of
species including many more trees. The stability in
species composition in case of drought is fairly large,
but species are replaced by others if exploitation
pressure increases. This sensitivity to exploitation
increases at lower levels of annual precipitation. Many
of the natural differences in fertility of soils are
masked by the gradient of precipitation, fire and
exploitation, all of which have a north-south gradient.

The Influence of Fire

6.09   Large parts of the Sahel and the savannah are exposed
annually to fire, generally created by man. For a dry,
homogeneous biomass, the minimum aeric mass of
vegetation needed to support a fire is about 1000 kg
ha^{-1}. Consequently, the frequency of fire is
particularly high in homogeneous vegetations on sandy
soils, and less on loamy soils. Fire is uncommon on
relatively small, clayey depressions because their
vegetation has not yet dried up when the surrounding
area is dry and burns.

6.10   For cattle, fire has a positive effect on the
productivity and on the botanical composition of
savannahs. By volatilizing N and sulphur (S), fire has
a negative effect on the fertility of the soil, though
it can be positive for the availability of P. The
positive effects outweigh the negative effects in the
actual animal production system. The positive effects
of fire on early regrowth of perennial grasses seems to
be that of elimination of shade only. Very important
is also that fire makes the new sprouts more accessible
to the animals.

Exploitation

6.11   While it is possible to relate total biomass production
to the soil and environmental factors without much
emphasis on the species that make up the vegetation,
this is not so for the use that animals make of it.
Morphological features (spines), chemical features
(taste, digestibility) and the stage of development of
the plants influence what is available to cattle. Soil
fertility, through its effect on the N content of plants,
affects biomass digestibility because protein content
and digestibility are closely correlated. The average

quality of the biomass is often too low for animals at
the end of the growing season. Field heterogeneity,
which results in a fraction of the biomass having a much
higher N concentration and exceeds the minimum quality
level, is therefore very important.

6.12 These ideas have been translated into a set of simplified
cases for different zones in the Sahel and are presented
in the original report. Some conclusions are given here.
The amount of forage of a fair quality and available to
cattle appears not to increase as much as precipitation
when going from north to south. Forage availability
reaches its maximum in September in the northern Sahel,
and later further south. The most difficult month in the
south is May, while it is July and August in the north.
The forage situation on the flood plains is quite
different: the worst is around January-February, the
best in July.

6.13 Exploitation influences the rangelands negatively
through biological, physical and chemical processes. The
structure of the soil can deteriorate and crust
formation is enhanced by elimination of vegetation.
These have a negative effect on the water balance. It is
estimated that a biomass of about 700, 1600 and 2000 kg
ha^{-1} at the end of the growing season is the minimum biomass
required to protect the most sensitive soils against
further degradation at the 250, 400 and 500 mm yr^{-1}
isohyets, respectively.

6.14 The botanical composition of the biomass also changes
under exploitation. This is related particularly to the
increase in runoff. As a consequence, annuals replace
perennials, species with a low and heterogeneous
germination pattern dominate and the vegetation becomes
heterogeneous. Trees and shrubs are often much
stimulated by intensive exploitation because the grass
vegetation is then insufficient to exploit fully the
soil water.

The Carrying Capacity and Degradation

6.15 Application of the equilibrium situation equation
described above leads to the unorthodox view that any
increase in the intensity of exploitation results in a
lowering of the production of the rangelands and to a
lower equilibrium level of rangeland production. To
indicate the current carrying capacity of the rangelands
and to what extent it changes due to exploitation, it is
necessary to determine to what degree the factors water,
N and P are limiting productivity in that particular
case. For cases where N limits productivity, the notion
of an equilibrium situation provides the key to the
carrying capacity: the annual input of N into the
rangelands equals the amount lost by grazing, fire,
volatilization, etc. The amount of biomass that

corresponds with this level of influx of N can be calculated. The carrying capacity can then be found by dividing the amount of biomass with a suitable concentration of N by a standardized daily intake of animals (6.25 kg TLU^{-1} d^{-1} at a maintenance level of the cattle, or a higher level if one aims at growth, TLU = Tropical Livestock Unit). The fraction of the biomass available as forage is that with a concentration of N equal to or exceeding 1.2%.

6.16 For the cases where P limits productivity, calculating the carrying capacity from the fraction of biomass with a concentration of N exceeding 1.2% overestimates its value because animals require about 0.2% of P in forage, while plants often contain lower values. The biomass at the end of the growing season should be used to calculate the carrying capacity. Its value will diminish from year to year as a result of exploitation.

6.17 When water is the limiting factor, the quality of the biomass is high and all can be used. The carrying capacity is then also calculated from the biomass at the end of the growing season. The amount of biomass required to protect the soil is relatively large, and should receive particular attention.

6.18 The method developed has been used to calculate the carrying capacity of pastures in the Sahel for typical situations, to draw conclusions for normal and dry years. It turns out that the carrying capacity is $10-20$ ha TLU^{-1} and does not depend on the average annual rainfall up to a certain amount of annual rainfall and increases rapidly at higher precipitation levels. The dependence upon actual precipitation starts at the 400 mm yr^{-1} isohyet in normal years, and at the 250 mm yr^{-1} isohyet in dry years. Such conclusions agree with other reports. Traditional methods for estimating the carrying capacity do not take into account the reduction in biomass due to exploitation. Therefore, they overestimate the carrying capacity considerably if the calculations are based on data of little-exploited areas. In addition, they do not recognize that the carrying capacity may remain more-or-less constant in relatively dry years, because the fraction of good quality forage is then larger.

6.19 The process of degradation of rangelands is continuous at almost any degree of exploitation. On sandy soils, particularly in the north, local degradation leads to barren sand enclosed in a ring of species with a very short growth cycle. On loamy soils, degradation in its final stages leads to basically barren plains with a hard crust, carrying only few microdunes with vegetation. However, a zone should not be labelled 'desert' if shortage of precipitation is not the cause of absence of

vegetation. As there is no indication that the annual
precipitation diminishes, degradation in the Sahel
should not be called 'desertification'. To do so would
be to misrepresent the situation, which leads to
inadequate countermeasures.

CHAPTER 7   A SURVEY OF THE POSSIBILITIES OF A ZONE

7.01   This chapter of the P.P.S. report gives an indication
of how to determine the actual average productivity of
rangelands with a minimum of field observations, and
how to calculate changes in average productivity that
will result from a change in the intensity of
exploitation; a manual that explains in detail how to
go about doing this is being prepared. Several aspects
of productivity are considered: productivity, quality,
the fraction of biomass available to animals, the
minimum value of this fraction during the year and the
availability of drinking-water.

7.02   A first rough evaluation of a large zone can be based
on interpretation of data from literature about the
physical and biological environment, and on generalized
relationships presented in the original P.P.S. report.
A detailed evaluation of a large zone requires the same
type of data as for the rough evaluation, but in more
detail. Aerial photographs are particularly helpful,
while the area has to be visited to describe relief and
texture of the upper soil layers. Similarly, an
impression of the vegetation has to be obtained. A
rough evaluation of a limited zone is to be based on
similar data as indicated for large zones. In addition,
more attention is to be paid to the biomass and its N
and P content, on more locations, also during the
growing season. The data collected are to be exposed
to average data presented in the P.P.S. report, to see
to what extent the zone deviates from an average
situation. The analysis should be repeated for a dry
year.

7.03   For a detailed evaluation of a limited zone, rather
than repeat the observations suggested above, it seems
more useful to make additional observations, in
particular about the frequency of fire, or do some
experiments, such as fertilization trials, to establish
the availability of N and P from the soil(s).

CHAPTER 8   TECHNICAL OPTIONS TO IMPROVE THE
            PRIMARY PRODUCTION OF RANGELANDS

Technical Options

8.01   Suggestions evolved during this study on how to improve
       productivity, quality and utilization of rangelands. In
       the following sections of this chapter we consider the
       most obvious economic aspects of the most promising
       technical options for improvement, excluding
       sociological and political points of view. The direct
       cost of inputs and labour for the options is calculated
       on basis of 1978 prices in Mali, expressed in Franc
       Malien (FM; 500 FM = 1 US $ *). The economic result is
       calculated in terms of meat, valued at 600 FM kg^{-1}.
       The conversion of plant biomass into meat is typically
       in the order of 200 kg dry biomass per kg fresh meat in
       traditional animal husbandry systems, but this ratio
       can be up to 5-10 times more favourable in intensive,
       modern systems.

Installation of Watering Points

8.02   Two methods need to be distinguished: wells and surface-
       water storage. The first have the disadvantage that
       output is not related to the biomass production of
       rangelands, so that overgrazing is easily induced.
       Moreover, wells can only be installed where the water-
       table is not too deep. The amount of water stored in
       temporary lakes or reservoirs is related to the amount
       of biomass produced in that year, because both are
       dependent upon rainfall. This diminishes the risk of
       overgrazing.

8.03   Cattle usually drink once every 1-3 days, so that the
       area exploited around a single watering point is 100-1000
       km^2. About 50% of the territory of Mali has a water-
       table that can be tapped by wells. Wells cost in the
       order of 10 million FM and have an average output of 12
       m^3 d^{-1}, which is enough for a herd of about 500 TLU for
       9 months per year. Overgrazing can be avoided, unless
       wells are installed too close. Opening a virgin area
       with wells to exploitation with cattle is quite
       profitable.

8.04   As an alternative, rain-water can be stored in open or
       closed reservoirs. Collection of water could be done
       in areas with a natural slope. However, in all these
       cases the cost of intervention appears to be too high
       to be economic for animal production. Improved
       maintenance and management of natural water catchments
       is feasible.

*⁄ Ed. At end 1982 FM = US $1⁄

Fertilization and Irrigation

8.05   In zones with an annual rainfall of more than 450 mm,
        fertilization with N and P on rangelands, and also P
        fertilization on legume monocultures, can be considered.
        To make good use of the forage, it should be made into
        hay. In the order of 5000 kg ha^{-1} of a good quality
        hay can be obtained. However, hay making requires
        labour at a time that it may also be needed for growing
        crops on agricultural fields.

8.06   Irrigation of rangeland in the rainy season is hardly
        productive. Irrigation in the dry season leads to low
        yields because the soils are poor, and the biomass
        produced is of a very low quality. Irrigation plus
        fertilization permit intensive cultivation with some 10
        mowings or 2-3 harvests of an annual crop per year.
        The cost of water is then about 25% of the total
        production cost, the cost of fertilizer 50%, and that of
        labour 25%. Legumes provide the same biomass for less
        fertilizer and are thus cheaper than cereals or grasses,
        but they grow at a lower rate. Estimated yields and
        cost per kilogram of forage for production with
        irrigation and/or fertilization are calculated in the
        report. It appears that the cost of all improvements
        seem to be too high to be economical for extensive
        animal husbandry systems. Fertilization of rangelands
        is still one of the best alternatives, also because
        relatively little infrastructure is needed. The use of
        P fertilizer for good legume crops seems promising,
        particularly for farmers close to a market. Irrigation
        without fertilization is always relatively expensive.
        Irrigation with fertilization for production of forage
        as a main product or as a by-product might be worthwhile
        to pursue in an agricultural context.

Stimulation of Leguminous Species

8.07   The number of leguminous species in the Sahel is high,
        but their contribution to the biomass in natural
        rangelands remains generally low. To stimulate their
        growth, the shortage of P in the soil must be eliminated.
        The expected profit in terms of additional animal intake
        was calculated, assuming that stimulation of legumes
        can increase its fraction to 7.5%, or even up to 15%.
        It shows an increase in animal production of 10-30% at
        7.5% and about 100% at the very high level of 15%
        legumes. However, both levels still do not compensate
        for the financial investments to be made.

Regeneration of Degraded Soils

8.08   Most of the barren soils in the southern part of the
        Sahel are loamy soils or lateritic soils. Loamy soils
        can be regenerated to carry a normal vegetation;

lateritic soils are generally too shallow and are
therefore not considered here. Complete protection of
the zone leads to regeneration, but only after 5-10 or
more years: because the crust on the surface causes much
runoff and loss of seeds, the vegetation has difficulty
in installing itself. Scratching the surface
superficially does not yield good results; complete
tillage of the soil gives good results, provided that
sufficient seeds are available from natural propagation
or sowing to permit a full vegetation to develop. To
ensure that the regenerated area does not degrade again
soon, all of the surface should be tilled and a biomass
should be obtained that equals at least the amount
needed for protection of the degradation-sensitive soil.
It should be realized that barren, loamy soils can be
regenerated, but also that they remain as sensitive to
degradation as before. The operation will only be
successful when the cause of overgrazing is eliminated
as well. If this precaution is not taken, the soil
will be barren again soon, and, chemically, in a poorer
state than before.

CHAPTER 9   RANGELAND IMPROVEMENT

The Systems of Animal Production in the Sahel

9.01   The productivity of systems of animal production is
determined to a large extent by the availability of
drinking-water and forage of good quality. The quantity
and quality of forage changes in time very much and in
different ways on different locations. A first
quantification of such aspects has been attempted. This
leads to the view of animal production systems that the
quality of the forage never poses a problem in nomadic
systems, but there is just little of it. Drinking-water
is always scarce. For the transhumance system, the
quality of the forage is too low for 8 months of the
year, and growth of the animals is only possible for
2-3 months. This period could be longer if drinking-
water shortages on the migration routes are solved.
For sedentary cattle, the forage is for 10 out of 12
months of a very poor quality, and even in the remaining
period the quality is lower than that in both other
systems. A basic problem for animal production in the
Sahel is therefore how to find food for the increasing
number of animals, without further degradation of the
environment. Where and to what extent technical options
to improve rangeland productivity can be of practical
use is considered here.

9.02   On the basis of criteria discussed in the report,
4 possible strategies are identified:

- To increase the efficiency of transformation of
invested N into N in meat and milk. The actual
efficiency of transformation, averaged for cattle and
small ruminants, is estimated to be 5%. The absolute
maximum efficiency in intensive production systems is
about 20%. This is extremely high, and a maximum
attainable level of 10% is more likely.
- To minimize the losses of N through volatilization,
fire and insects. Volatilization from plants can be
avoided by making hay; this yields the highest
equilibrium biomass. An alternative way to avoid
losses by these processes is to increase grazing by
cattle to a high intensity. Reduction of losses of N
from the biomass grazed seems only possible by increasing
the degree of retention of N by the animals.
- To increase the annual input of N into the system.
The fraction of legumes in the biomass cannot be
stimulated above a level of 7.5-15%. This makes the
potential gain of that option too small. In principle,
stimulation of perennial grasses may also increase the
annual influx of N, and possibly to the same level as
that of legumes if the perennials dominate the
vegetation completely. The input of N can also be
increased by means of manure and fertilizer.
- To increase the grazed area by installation of wells
in the north or elimination of tsetse from infested
areas in the south.

9.03 The following comments may be made about those 4
strategies.

- The maximum results that can be achieved by such
measures range from 0.3 to 15 kg ha^{-1} yr^{-1} of meat N,
but most are less than 1.0 kg ha^{-1} yr^{-1}.
- Lowering the overall intensity of exploitation will
be difficult to achieve in practice: although the
productivity of the pastures will increase and possibly
also that of individual animals, the total animal
productivity will probably decrease slightly. The major
advantage will thus be a more stable environment.
- Replacing nomadism and transhumance by sedentarism
will have a very negative effect on animal productivity.
The most promising measure seems to be harvesting of the
vegetation at the time of flowering, feeding it and
returning the manure to the rangeland. However, this
does not seem to be feasible in practice.
- Fire prevention is profitable for the environment, but
must be accompanied by other measures to make good
quality forage available to animals early.
- To expand the area of grazing is the most direct way
to improve availability of forage. But it should be
remembered that in doing so the annual production of
biomass of unexploited areas will always decrease under
exploitation and that a concomitant increase in forage
should occur for that part of the year that the herds are
away from the new pastures.

- Regeneration of completely degraded rangelands does
not seem profitable. Reconstitution of perennial grasses
and a tree population will increase animal productivity
only little, although the environment will be more
resistant to degradation. However, such
reconstitutions are only effective at relatively low
levels of exploitation, and hence of animal production.
- Introduction of legumes does not seem profitable at
the current prices.

9.04   To investigate how much improvement of __management__ of
herds can increase productivity, a comparison of animal
productivity per hectare, per hour of work and per
amount of fossil energy was made. By comparison with
livestock production systems in other parts of the
world, a transhumance system in Mali was found to have
a high productivity per unit landsurface, but a low
productivity per labourer. The productivity of this
system as such cannot be increased by further
intensification, because it is the low and decreasing
fertility of the rangeland soils that forms the
ultimate limit to the animal production. When fewer
persons are involved, the transhumance system could
produce its output cheaper, but at the expense of
increased unemployment.

9.05   __Innovations__ have been proposed in the P.P.S. report to
__intensify__ the system and to raise its secondary
productivity. An example is the 'integration and
stratification strategy', which implies that young
animals are produced in the transhumance system and
finished in intensive systems in the southern Sahel
or savannah. This strategy seems feasible in the long
run, but it will lead to minimalization of prices of
young cattle, sheep and goats, to replacing pastoralists
by fences, and to further degradation of the
environment.

9.06   As an alternative, it is proposed to __stimulate__
__agriculture__ in the southern Sahel and savannah, among
others by using fertilizers. By-products that are
relatively rich in protein will then become available
for supplementary feeding of animals. The only way to
combat further degradation is improvement of rangelands
and simultaneously assuring pastoralists of a living.
Only then does intensification of animal husbandry lead
to a substantial increase in production and avoid
further degradation of the environment.