CHAPTER 2

LITERATURE REVIEW

2.1 DEFINITION OF MARGINAL LAND

The word “marginal” can be defined as that which is close to the limit, especially of profitability, something that is barely adequate. Marginal land is the expression of the quality of land as a function of soil productivity, climate and landform and to some extent the production economics as well as the management of resource inputs. Hence the definition of marginal land requires a carefully selected set of criteria and units to measure quality of land itself. According to Hensley *et al.* (2000), marginally arable land refers to that in which sustainable long-term productivity is only possible with specific production techniques efficiently employed.

Schoeman and Scotney (1987) defined agricultural potential as a measure of possible productivity per unit area per unit time, achieved with specified management inputs. This definition is very appropriate, considering the continuous technological innovations whereby plant and soil amelioration result in a tremendous improvement in crop yields. This implies that a portion of land may be regarded as marginal under a specified production system but may not necessarily be judged the same under a different production system. This also makes the spatial demarcation of such land more complicated because of the fact that there are no permanent boundaries as such.

According to Eswaran, Almaraz, Van den Bergh and Reich (1997) the production potential of an area is determined by the interaction between precipitation and evapotranspiration, crop characteristics and soil conditions. In other words potential is determined by the atmosphere-plant-soil (APS) system that, according to Hensley *et al.* (2000), depends on three natural resource factors, i.e. climate, topography and soils. Thus, for a given crop and level of management input it follows that agricultural potential is largely determined by climate, soil and terrain form, mainly slope. In South Africa research efforts have been focused on high potential land where higher yields can be obtained with a higher degree of certainty. Smith (1998) regarded high potential land in South Africa as comprising all areas with favourable climate, soils and terrain and where actual performance of adapted crops ranks high in national perspective. According to him the climatic lower limit for such land is approximately 700 mm mean annual rainfall (MAR). Less than 550 mm MAR was classified as unsuitable for crop production. Unsuitable land for maize crop production includes the non-arable soils with mechanical limitations such as large rocks, shallow soils on rock/ weathered rock as well as soils occurring on steep slopes and in streambeds.

Larson, Roloff and Larson (1988) defined marginal agricultural land as land with cropland soils that are inherently unproductive for agricultural crop production and are subject to significant soil productivity loss from erosion. However there are many instances whereby land is rendered marginal for crop production by other factors like water deficit, steep slopes, lack of effective soil rooting depth and extremely cold or hot temperatures. Thus the criteria for determining marginal land are not only based on soils, but also on climate as well as landform. The general perception is that at lower than 550 mm MAR, land is regarded as unsuitable for crop production. However, the maize yield potential of some soils occurring in such regions can be quite high even below 500 mm MAR for example in the Northwest Province, especially with adapted crops and appropriate management practices.

2.2 THE CONCEPT OF MARGINAL SOILS

The productivity of land for crop production is primarily a function of the production capacity of soil in the sense that it is only after the soil productivity has been determined that the inputs that are incurred on the evaluation of the other natural resources are justified. The nature and quality of soil is a function of the soil forming factors climate, topography, parent material, living organisms and time. It is difficult to define a marginal soil since soils occur as a continuum and are not neatly divided into groups in nature (McGee, 1984). According to him the term marginal soil is a very wide concept that could include several types and categories of soil and the marginality of soils could be ascribed to several factors mentioned earlier in this report.

The marginality of soil could also be described according to an economic and production oriented definition, which implies that the soil is considered to be marginal when the ratio of agricultural production to the inputs required to achieve it is low. The decision to cultivate marginal soils must be an economic one based on a reasonable possibility to make profit, which implies that cultivation of marginal soil is justified only after a thorough assessment of the economic implications in terms of inputs incurred as compared to expected output. Good quality management is a determining factor to ensure profitability of marginal soils. On the other hand land may be unsuitable for large scale mechanised cropping, but suitable for small scale non-mechanised farming, or *vice versa* (Laker, 1978). In other words improvement in cultivation techniques and other technological inputs such as new cultivars, weed and pest control, etc. could contribute towards production in marginal soils becoming profitable.

Quite large areas are covered by extremely unstable soils in South Africa; hence those marginal soils will have to bear the brunt of crop production (Laker, 1997). He emphasises the need for more research on the performance of different crops under low levels of management on various types of non-ideal and marginal soils. Many soils are vulnerable to various forms of degradation and require special treatment for use (Scotney, Volschenk and Van Heerden, 1990), putting more emphasis on shallow depth, extremes of texture, rockiness, severe wetness and high erosion hazards as the most important limitations. High vulnerability to degradation may also make a soil marginal. High potential land or soil becomes marginal either because of the erosion danger when it is located on too steep slopes or in a vlei where cultivation is inadmissible (Ludick, 1998).

Ludick (1998) described marginal land as low potential soil that cannot maintain economic production under certain climatic conditions, in spite of correct management practices. According to this author a specific soil that could be marginal for a certain crop, does not necessarily need to be so for all crops. For example in the former Highveld a clayey soil, with a depth of 400 mm and an average long term rainfall of 694 mm could be completely economical with regard to the production of grain sorghum or sunflower but could be marginal (risky) for maize production.

Likewise, a sandy soil with an E-horizon at 400 mm depth and a Soft Plinthic B horizon (indicating a fluctuating water table) which is located in the **summer** rainfall Eastern Highveld and has a long term average rainfall of 663 mm, will be marginal for maize and grain sorghum (summer crop) cultivation. Yet winter wheat could be economically produced on the same soil, because the extra water stored in the soil will benefit this crop grown in the non-rainy season.

A soil could become marginal if production costs rise or if the prices of products fall as well as if it does not produce economically in the long term during seasons with an average rainfall. Further a certain depth phase of a soil family could for instance be marginal in the North West, with a rainfall zone of 450 mm, but not marginal in an area with a 600 mm precipitation that is well distributed. The final decision as to whether the land or soil is suitable for dryland grain crop production is determined by the economy. Ludick (1998) explained marginal land or soil from the economic point of view in the following ways:

- The yield potential for grain production of land or soil should justify the production costs. If the expected income from the crop is lower than the production costs, then the land or soil will be classified as economically unsuitable for that particular crop.
- When a decision has to be made regarding which crop is to be cultivated on a certain piece of land, it is necessary to do gross margin analyses (gross income minus production costs). Taking into consideration constraints or limitations for each crop applicable to the production thereof, it can be decided which soil or portion of land is marginal for which crop.

2.3 CRITERIA USED TO DETERMINE THE PRODUCTION POTENTIAL OF LAND FOR RAINFED ANNUAL CROPPING

FAO (1983) described land evaluation as the assessment of land performance when used for specified purposes. It provides a rational basis for taking land-use decisions based on analysis of relations between land use and land, giving estimates of required inputs and projected outputs. According to FAO (1976), land comprises the physical environment, including climate, topography, soils, hydrology and vegetation to the extent that these influence potential for land use. Land is wider than just soils and landforms. However, the variation between these is often the main cause of differences between land mapping units within a local area. Hence it is impossible to assess the fitness of soils for land use in isolation from other aspects of the environment and it follows that it is land which is employed for suitability evaluation. Agricultural potential can be described as an expression of possible production per unit area over a period of time and the production techniques used to achieve this production (Schoeman and Scotney, 1987). Wright (1977) believes that in its simplest form, land evaluation involves the assessment of selected land characteristics for particular purposes, whereas Nix (1968) believes that land evaluation means assigning values to different land units or to crop management combinations, preferably in economic terms. Regardless of the different concepts all these authors agree that the procedures of land evaluation involve the interpretation of biological resource inventories in relation to categories of use.

The function of land evaluation is to bring about an understanding of the relationships between the conditions of the land and the manner in which it is utilised (Beek, 1980). Hence there is a need to predict favourable and adverse effects resulting from the use of land as well as the required management inputs. Land evaluation is also concerned with the present performance of land, particularly as this affects changes in the use of land and in some cases changes in land quality. Extremely important when determining the agricultural production potential of land, is to specify the level of management or production system, which will be applied to achieve the specified objectives. Beek (1977), cited by Laker (1978) highlighted the fact that there are levels of management, namely; (i) primitive or low level, (ii) intermediate and (iii) modern or sophisticated. According to Laker (1978) it is important to realise that some soils with high potential for crop production under sophisticated management if they are in areas where it is easy to acquire modern technological aids, may be very unfavourable for crop production under conditions of primitive, simple or intermediate technologies or if they are in areas where it is difficult or expensive to acquire modern technological aids. On the other hand, some soils with only moderate crop production potential under sophisticated management may be relatively good soils under primitive or simple management. The author further explains that

sometimes areas, which are unsuitable for crop production by means of mechanised techniques, are well suited for crop production under non-mechanised systems.
It follows that an indication of the management inputs required for achieving a stated potential must be given. FAO (1983) gives a generalised description of the three different levels of inputs and management:

i. Low input level: This is usually rainfed cultivation of presently grown mixture of crops. No significant use of purchased inputs such as artificial fertilizers, or improved seeds, pesticides or machinery. Use of local cultivars, fallow periods practised and no soil conservation. High family labour intensity with family based infrastructure. Very low to low capital intensity. This is common in the developing countries.
ii. Intermediate input level: These are methods practised by farmers who follow the advice of agricultural extension services but have limited technical knowledge and capital resources; improved agricultural techniques; inputs adequate to increase yields but not to achieve maximum yields or maximum economic return; some fallow and some conservation practises. Use of improved cultivars and possibly some use of chemical weed, disease or pest control. They depend on the availability of credit for capital resources. The market orientation is of subsistence with commercial sale of surplus.
iii. High input level: Methods applied at this level are based on advanced technology and high capital resources; fertilizers at levels of maximum economic return; chemical weed and pest control at advanced technical levels; modern mechanisation methods applied to maximise yields or economic returns. Appropriate conservation practices and investments in ecosystem management; high utilisation of credit; highly commercial market oriented; frequent exchanges with extension service and peers. Use of high yielding varieties.

For a given crop and level of management, agricultural potential is largely determined by the interaction of climate, soil and terrain. Natural agricultural resources may be employed as properties or criteria for evaluating the production capacity of a portion of land and therefore can also be applicable for defining marginal land. Only a few can be mentioned here. This is not a complete listing of everything involved.

2.3.1 CLIMATIC CONDITIONS

Climate is the basic criterion for distinguishing various units of utilisation and the suitability of different localities for different crops. According to Schoeman and Scotney (1987), precipitation and solar energy are two of the important factors that influence agricultural potential in the sense that the interaction between precipitation and temperature, crop characteristics and soil conditions determine the productivity of a given area. Rainfall determines mainly the availability of moisture for the growing crop, while radiation, temperature, humidity and wind determine the moisture usage by the crop (evapotranspiration) (Jordaan and Du Plessis, 1998). In addition to this, Scotney *et al.* (1990) highlighted that latitude and altitude together with oceanic influences are responsible for the wide range of climatic conditions. High summer temperatures also influence evapotranspiration. Miller (1979) listed the following climatic properties:

- Precipitation regime:- amount, duration, intensity and sequence of distribution.
- Temperature:- Solar energy flux and distribution during frost-free period.
- Air quality:- Wind velocity, duration, humidity and inversion potential.

Mantel and Kauffman (1995) listed the following climate based land qualities that determine to a greater degree the production potential of land:

- Hailstorms, wind and frost.
- Length of growing season.
- Drought hazards during growing season.

2.3.1.1 PRECIPITATION

Rainfall is the most important climatic factor and the greatest limiting factor for crop production in South Africa, particularly in the semi-arid and arid regions. The annual fluctuation of rainfall makes planning of a crop farming enterprise more difficult. Rainfall distribution over the season enables the decision maker to determine the best planting date and therefore allows him to avert the so-called mid-summer drought, which occurs during the most critical period of the crop's developing process (Jordaan and Du Plessis, 1998). Moisture deficiencies in the plant give rise to moisture stress conditions which could have great detrimental effects on production, should they occur during certain critical phases in the plant's developing process. For a production of 3 ton.ha^{-1} maize 350 – 450 mm rain is necessary during the growing season.

The effectiveness of rainfall is also an important factor. Large amounts of rain in areas with steep slopes or strongly crusting soils are not effective due to water run-off. Strongly crusting soils are widespread throughout South Africa. Infiltration is severely restricted in soils which form surface crusts or seals, thus causing soil profiles to be dry. This explains why Hattingh (1998) puts so much emphasis on the improvement of the infiltration rate of soils to improve the effectiveness of rainfall.

Hattingh (1998) states that a soil with a compacted layer at 20-40 cm depth will inhibit the penetration of water to the depths where it is needed. However, in the sandy soils of the western Highveld area, which includes the Northwest Province, subsurface compaction will not seriously limit water infiltration (Laker, 2000 personal communication). Instead, its effect is preventing root penetration into the layers below it; hence they cannot utilise water stored in these deeper layers. It is common under such conditions to find plants suffering severe drought stress in soils that are very moist (even at field capacity) in the lower layers. The roots are boxed into a very shallow soil layer with a very small total water storage capacity. High fine sand content is listed as one of the factors affecting the susceptibility of soils to compaction and soil crusting (Bennie and Krynauw, 1985).

2.3.1.2 TEMPERATURE

According to Jordaan and Du Plessis (1998), temperature is one of the key factors regulating growth, primarily through the direct influence on the rate of metabolic processes but also indirectly through influencing physical processes such as evapotranspiration. Temperature also determines the duration of the growing season, which in turn determines the selection of the crop cultivar suitable for a particular area. Differences in altitude and latitude, as well as rainfall and humidity, are the main factors responsible for the difference in temperature between various regions and even between different localities within a given area. High temperature combined with low humidity can impact negatively on crop production. At Vaalharts, close to the area of the study reported here, Boedt and Laker (1985) found that under such conditions maize plants wilt by 10:00 am even in irrigated soils that are at field capacity.

2.3.1.3 WIND

Strong winds interfere with the water utilisation of the plant in the sense that it carries off the vapour in the air, thereby causing the replacement of moist air with dry air, resulting in higher evapotranspiration. The plant that is subject to such conditions reduces its turgor pressure in the cells of the stomata and eventually these cells close completely with the consequent effect on water uptake. Strong wind can also cause great erosion damage especially on sandy soils. By far the most serious problems of wind erosion on arable land are caused by losses of plants due to sandblast, requirement of additional tillage to combat it and loss of fertility. According to Joubert and Ludick (1990), at least 2 million hectares of cultivated land in the western Highveld region is susceptible to wind erosion and a further 300 000 ha in the Ditsobotla, Lehurutse and Molopo districts within the study area.

2.3.2 TERRAIN FORM

Major proportions of the developing areas in Southern Africa are characterised by steeply undulating landscapes, which are dominated by slopes that are both steep and long. Further, in most developing areas of Southern Africa, especially in semi-arid and sub-humid regions, the lower landscape positions are dominated by very unstable duplex and pseudo-duplex soils which are extremely vulnerable to soil erosion (D'Huyvetter and Laker, 1985). Terrain form and slope have a marked influence on agricultural production potential and management practices. According to Miller (1979), slope gradient, complexity, length and aspect, are the major properties that affect workability, access and micro-climatic conditions of a particular piece of land. In the study area this is not a significant factor as it is dominated by large plains.

2.3.3 SOIL PROPERTIES

Miller (1979) listed the following soil properties that are applicable to defining classes of agricultural land quality:

- Texture: - particle size distribution, coarse fragments make-up.
- Organic matter: - cation exchange capacity (CEC), water holding capacity and biological activity.
- Structure: - tilth
- Consistency: - degree of firmness and friability.
- Pore space: - total, size, shape, water holding capacity and bulk density.
- Depth: - rooting volume, moisture storage capacity.
- Drainage: - behaviour of soils in ridding itself of excess water.
- Chemical properties: - CEC, pH, Eh, ESP, electrical conductivity, and base saturation.
- Mineralogy: - nature of clay fraction.
- Erodibility: - degree of erosion potential and actual erosion loss.

2.3.4 SOIL PHYSICAL FACTORS AFFECTING THE POTENTIAL OF SOILS

2.3.4.1 SOIL TEXTURE, STRUCTURE, INFILTRATION AND RUNOFF

Soil texture is an indication of the relative proportions of various particle size fractions in the soil, namely: sand, silt and clay. In sandy soils, i.e. soils in the sand, loamy sand and sandy loam texture classes, the sand grade (coarse, medium, fine) is also very important. Unless crusting plays a role, the general trend is that the infiltration capacity of a soil decreases with increasing clay content. Soils with high clay contents in their topsoil, especially swelling clays, have low infiltration capacities. Consequently they have high runoff, which means low rain efficiency. For this reason sandy soils have higher cropping potential than finer textured soils in areas where rainfall becomes marginal for cropping. However, the low plant available water storage capacities of deep, excessively drained **coarse** sandy soils must also be kept in mind (Laker, 2000 personal communication).

Soil structure refers to the arrangement of the primary soil units into secondary structural units or peds. A soil is referred to be structureless when there is no observable aggregation or natural lines of weakness. A strong structure is where peds are well formed and durable and distinctly separate from one another in an undisturbed soil. A weak structure occurs where peds are indistinct and poorly formed, whilst a moderate structure occurs where peds are well formed and durable, but not distinctly separate from one another in undisturbed soil (Hattingh, 1998).

Soils with high organic matter content possess soil structures superior to those of soils with a low organic matter mainly because the organic matter stabilizes the structural units against breakdown. Consequently, a soil with a good and stable crumb structure usually has a high infiltration rate and is not susceptible to crust formation. A soil with stable structural units is not readily susceptible to soil erosion. However, where coarse strong structure is encountered, roots cannot penetrate the structural units, but only penetrate in between units, which negatively affect the crop production potential of such soils (Hattingh, 1998).

2.3.4.2 FIELD CAPACITY, WILTING POINT AND PLANT AVAILABLE WATER

Field capacity (FC) is the amount of water held in the soil against the force of gravity and is also the upper point of plant available water. The FC values usually increase with increasing clay content. For example, a soil with high clay content will require much rain in spring before the soil reaches field capacity. For this reason Hattingh (1998) recommends that the coarser textured soils should be utilised first for spring planting, because these soils reach field capacity sooner. Once the soil has reached field capacity all subsequent rain will simply drain from the soil and be wasted if there is no crop to utilize some of the stored water to create space for further rains. However, in marginal rainfall areas like the Northwest Province, it hardly rains enough to bring the soils to field capacity before planting. Therefore if farmers have to wait until the soil water content reaches field capacity before they could plant, they would have to plant very late, which then shortens their growing season and reduces yields.

Soil dries out due to evaporation from the soil or transpiration by plants until the plants will start wilting to a point where plant growth is inhibited because of shortage of water unless the soil is again moistened. The wilting point (WP) value, like FC, rises as clay content increases. Hattingh (1998) also stated that soils with a high clay content need much rain in spring before exceeding the wilting point values. All water present in the soil below wilting point is not available for plants. The soil water content held between field capacity and wilting point is referred to as plant available water (PAW) and is the amount of water that the plant can utilise. Particularly clay and silt content influence the plant available water storage capacity of the soil. In sandy soils the sand grade is very important. At Vaalharts the **fine** sandy soils, with only about 10% clay, have plant-available water storage capacities of about 125 mm/m, which is very high.

2.3.4.3 EFFECTIVE SOIL DEPTH

"Effective soil depth" is defined as the depth to which roots can penetrate without being severely restricted by some limiting layer. This is thus the depth to which air, water and plant nutrients are available for plant growth. Soil must be able to store sufficient water in the root zone during early summer and also in autumn and late summer when the evapotranspiration of the plant is relatively low, to provide the water needed by the crop during times when the evapotranspiration is high and the rainfall is low. The latter situation occurs in the Northwest Province in the form of midsummer drought, usually in January when the water requirement of the maize plants is highest.

The maximum soil depth utilised by annual grain crops, such as maize, wheat and sorghum, is more than 2 metres in deep sandy soils (Boedt and Laker, 1985). Favourable soil conditions require that water and air should be present in favourable proportions and that the circumstances in the soil favour the absorption of plant nutrients. Effective depth is determined by the presence of layers in the soil which are restrictive to root penetration. These restrictive layers include strongly developed structure, stony, partly weathered material, high water table or impermeable horizons (Table 2.1). Under rainfed grain crop production, the importance of deep soils where enough water can be stored to overcome the periodic drought can never be over emphasised, especially when the rainfall is low and erratic. For example, in an area with high well-distributed precipitation, soils with 400 mm depth can produce a good crop yield, while the same soil will yield much less or nothing in a dry area. This shows the necessity of establishing a minimum plant-available water holding capacity for economical crop production. According to Hattingh (1998) the above even applies for areas with relatively high annual rainfall because in such areas plant populations are usually high. The optimum soil depth is dependant on the type of crop, plant population, annual rainfall and rainfall distribution.

Jordaan and Thiart (1998) estimated that if a quarter of the annual rainfall could be stored at the required soil depth in a profile, the problem with periodic drought would be overcome to a large degree. According to Laker (2000, personal communication) the proportion of the rainfall that can be stored in the soil is a function of (a) the water storage capacity of the soil and (b) the infiltration capacity of the soil. The latter determines the amount of water that will be absorbed by the soil during a rainstorm.

A large percentage of highly productive sandy soils in South Africa possess an impermeable layer (sandy clay to clay) at a depth of approximately 900-1500 mm, which restricts the further downward movement of water by forming a perched water table. The upward capillary movement of water becomes possible, thus increasing the amount of water available to the crop. Water can also move laterally in the zone just above these permeable layers and crops can receive subsoil water from adjoining areas where the subsoils are over saturated (Jordaan and Du Plessis, 1998). These situations are especially important where a fluctuating water table is found, as indicated by the presence of a soft plinthic B-horizon. In high rainfall areas such soils are often too wet during the rain season, but in drier areas crops do better on soils with such horizons than on soils without them because of the enhanced plant-available water. In the Northwest Province enhanced water availability to plants plays a major role in dryland crop production. Consequently more consistent yields during relatively dry seasons are also found in soils with soft carbonate horizons in this area (Louw, H., Unpublished provisional draft of a M.Sc. dissertation, University of Pretoria). This is because much plant-available water is stored in these soft carbonate layers.

TABLE 2.1 Restrictive layers in soil with an explanation for the nature of restriction imposed by each. (Jordaan and Thiart, 1998)

Restrictive layer	Nature of restriction
1. Rock	Root penetration prevented.
2. Weathered rock (gravel)	• As the gravel content increases the soil volume decreases accordingly. The water, air and nutrient holding capacity of the soil is lowered. Effective depth is taken above the layer that is predominantly gravel.
3. Hardpan or soft carbonate horizon	• This horizon is formed through chemical deposition of carbonates in arid and semi-arid regions. A continuous hardpan carbonate layer restricts root and water penetration while a broken one may allow some penetration, though very limited. Calcareous soils may also possess soft carbonate horizons consisting of much soft powder carbonate. Observations have indicated that plant roots can exploit much water from it.
4. Blocky and prismatic structures	• Due to the strong forces of aggregation (cohesion) within these structural units, root penetration through these structures is virtually impossible. Root penetration only occurs along planes between structural units. This implies a decrease in volume of soil from which air, water and nutrients can be extracted. Due to the swell and shrink property of some of these structural units toots may also be injured in this process. Blocky structure in subsoils: The revised South African soil classification system (Soil Classification Working Group, 1991) distinguishes at family level between sub-angular blocky and fine angular blocky structure on the one hand and medium to coarse angular blocky structure on the other hand. The latter indicates very unfavorable conditions for root development and the effective depth is taken to the top of such horizon. The former is not so restrictive to root penetration and can be included in the effective depth, but rated down somewhat (Laker, 2000 personal communication). Prismatic structure in subsoils: Such horizons are very restrictive to root penetration and the effective rooting depth is taken to the top of the horizon.
5. Soft plinthite (mottled grey clay)	• A fluctuating water table in a soil is responsible for this horizon. Red and yellow mottles develop because of the accumulation and localisation of iron and manganese oxides and hydroxides in a particular layer. Eventually they are transformed into iron and manganese concretions. See discussions in the text on the implications of the presence of such horizons under different rainfall conditions.
6. Hard plinthite	• This layer originated from iron and manganese concretions that were cemented together over a period of time to form a hard iron pan. It restricts root penetration.
7. Firm grey clay, pot clay, G-horizon.	As soon as a clay layer develops light grey, dull yellow and / or blue green colours, it is an indication of permanent waterlogged conditions. Such soils are permanently very poorly aerated and therefore extremely unfavorable for the development and functioning of roots. The effective depth is therefore taken where the clay starts to display such colours, which indicate reduced conditions.
8. Grey coloured sandy layers in the soil	• This layer is developed by the reduction of iron oxides, together with a lateral flow of water on top of a restrictive, less permeable layer. This process gives rise to the removal of iron oxides, organic matter and clay particles from this horizon, overlying a restrictive one.
9. Grey coloured sand throughout the whole profile	• The greyish colour of this sand is usually attributed to the colour of the parent material and is not because of an over saturation with water.
10. Plough pan/ tillage pan	• It is caused by the smearing effect due to the particular action of certain implements. This condition can also be caused by wheel compaction. Root penetration is impeded. Fortunately this restriction can be eliminated.
11. Chemical restrictions	• Examples are: Brackish conditions Aluminium toxicity is some instances where the pH of a soil is very low (<5).

2.3.5 SOIL BASED LAND QUALITIES

Mantel and Kauffman (1995) use criteria that are not very different from those mentioned above, but they put more emphasis on the assessment of land qualities to evaluate the crop production capacity of land.

- Potential total soil moisture: - This depends on the interaction between soil, plant, climate and such factors as farm management. According to these authors, potential total soil moisture determines whether the availability of water during the growing period restrains growth and development of a particular rainfed cultivated crop. According to Hattingh (1998) a soil must contain at least 120 mm of plant available water at planting for effective plant growth. If the soil is very dry at the start of the season, in an area where the rainfall is very erratic, it is uncertain whether crop production will be profitable. Hence it is of crucial importance to determine whether there will be enough moisture present in the profile at planting in order to support the crop throughout the growing season.
- Oxygen availability and rooting conditions: - Availability of oxygen for root growth varies considerably depending on the drainability of soil and depth to ground water table. This is a function of rainfall, seepage, soil permeability, surface infiltration rate, internal and lateral movement of water and external surface run off and run on (Mantel and Kauffman, 1995). The underlying factor is the effect of prolonged conditions of water saturation on crop growth. Water logging causes yield losses by creating anaerobic soil conditions.
- Nutrient availability and nutrient retention capacity: - This is basically a function of soil fertility conditions, e.g. effective cation exchange capacity (CEC), exchangeable bases, soil reaction (pH) and soil organic matter. Nutrient elements in a soil may occur in many forms, and are, depending on the certain conditions, more or less available to a crop. According to Mantel and Kauffman (1995), the availability of nutrients does not only depend on soil factors such as soil temperature, pH and moisture, but also on weather conditions and farm management practices. Crops themselves also differ in their demand for nutrients and some crops are more efficient in extracting elements than others.
- Conditions affecting germination and seedling emergence: - This is determined by the size of structure elements, topsoil structure type, sensitivity to surface crusting and surface stoniness. Soil crusting and surface sealing is fast being recognised as

a widespread and serious problem in both irrigated and cultivated areas in various parts of South Africa. Soil crusting leads to poor seedling emergence and poor water infiltration, causing reduced yields on dryland cultivated areas due to a drastic reduction in crop's ability to withstand dry periods. A soil with a good structure usually has a high infiltration rate and is not so susceptible to crust formation. Soil compaction confines plant roots to very shallow depths, making a crop extremely vulnerable to drought and causing poor plant nutrient utilisation.

- Excess salts –(salinity and sodicity): - The occurrence of excess salts is common in arid and semi-arid conditions. Salinity is the excess of free salts and sodicity is the saturation of a significant proportion of the exchange complex with sodium ions. Excessive salts are toxic to plants. They also reduce the water availability to plants through increased osmotic pressure and cause nutritional disorders (Mantel and Kauffman, 1995). Sodium is usually associated with instability of soil structure.
- Soil toxicity (e.g. high aluminium saturation): - This refers to the effects of excess of harmful elements. aluminium toxicity refers to the harmful effects of the high concentration of aluminium in the soil. This is recorded to be a problem in acid soils with a pH below 5.5, when measured in a soil: water suspension or pH 4.5 when measure in 1M KCl suspension. Nutrient excess in soils also results from injudicious fertilization or from the application of pesticides, fungicides and herbicides that raise the concentrations of elements such as P, Zn, N and Cu in soils.

2.4 CROP MODELLING IN LAND SUITABILITY EVALUATION

The principal objective of land suitability evaluation is to compare the performance of a number of land units under a limited number of production systems. Systematically incorporating information into computerized models will be necessary to make realistic projections about future productivity and environmental degradation. Ritchie (1991) justified the use of crop models by stating that they are the principal tools needed to bring agronomic sciences into the information age. Crop simulation models that are generally designed to simulate soil-plant-atmosphere processes at the field level are increasingly being used in the analysis of agricultural production systems (Moen, Kaiser and Riha, 1994).

The development of simulation models to be used in agricultural production systems involves the fitting of functional relationships, which make up the models, and the testing of these relationships and completed models against real-world data (Jones and Carberry, 1994). A reliable prediction of crop yield is essential in quantitative land evaluation studies. Model validation can show how well or badly a model performs in a particular circumstance (Sinclair and Seligman, 1996). This leads to increasing use of crop models as reliable tools in quantitative land evaluation.

Boote, Jones and Pickering (1996) indicated the most important aspects to consider about crop models before their application:

- What is the crop model really designed to respond to?
- What assumptions are made (e.g. what does a model respond to, what does it ignore?)
- For a given simulation comparison, what events occurred in the field that the model may not address?
- What are the limitations of inputs to run the model?
- What are the limitations of the model?

Ritchie (1991) defines crop simulation models as a combination of mathematical equations and logic used to conceptually represent a simplified crop production system. Quantitative assessment of risks related to climate is possible through the use of dynamic crop simulation models. When coupled to input information on soil, weather, and production management, properly validated models improve risk assessment compared to the use of precipitation information alone. According to Dumanski and Onofrei (1989), summary mechanistic models that follow the detailed mechanistic models in principle but simulate only those processes that are critical to describe an agroecosystem are the most realistic and practical tools for land evaluation. These models describe processes in a theoretically sound manner, they require considerably less input data and they are cheaper to run and easier to calibrate. This is why they recommend them to be useful for estimating yield performance over a long-term in terms of probability distributions and to study the effects of extreme events. The basic understanding of the relationship between rainfall, soil moisture levels and crop yields is a fundamental concern.

2.5 THE CYSLAMB MODEL

The Crop Yield Simulation and Land Assessment Model for Botswana (CYSLAMB) has been developed to serve the needs of land evaluation in a semi-arid environment. According to Bekker *et al.* (1994) CYSLAMB is a quantitative method of land suitability evaluation, which uses actual rainfall data for individual years to overcome the problem imposed by the interannual variability of rainfall. By modelling the interaction of environmental variables, physiological responses, inputs and management, CYSLAMB predicts yield of a particular crop production system on a specified land unit. CYSLAMB has been developed as land evaluation software, which is structured in a way that it can also be used to test the impact of changes in input level or management operations on crop yields. For agricultural land evaluation crop yields have proved to be the most reliable estimates of comparative marginal value. Observed or estimated crop yields are often used in physical land evaluation to provide information on land suitability and to monitor changes in productivity and land quality over time (Smith, 1998).

2.5.1 SUMMARY OF THE STRUCTURE AND OPERATION OF THE CYSLAMB PROGRAM

CYSLAMB as a land evaluation software models the performance of a selected crop under a predefined land unit typified by its soil and climatic characteristics, using actual effective rainfall figures for individual years. The simulation results are expressed in quantitative terms (kg.ha^{-1}). Yield levels that are exceeded in a certain proportion of years (yield probability) can be estimated as well as the risk of crop failure. CYSLAMB uses the input data on production systems and characteristics of the selected land unit to simulate crop biomass production and yield for every year required by the run. A theoretical maximum possible crop biomass production for the crop under specified management conditions is calculated assuming that there are no constraints due to soils and rainfall. Solar radiation and temperature determine this theoretical maximum. The model then calculates a moisture balance from the first dekad of each hydrological year, taking into account incident effective rainfall, bare soil evaporation or weed evapotranspiration and water losses due to percolation or runoff.

The criteria for the definition of a planting opportunity are based on effective incident rainfall and stored soil moisture. When these criteria are met, the crop /soil water balance is then simulated through the crop growth cycle. Periods of moisture stress are accounted for in the calculation of the moisture limited biomass production. The moisture limited biomass production is then adjusted to take account of the effects of drainage conditions, nutrient supply and toxicity. The amount of produce is derived multiplying the resulting net biomass production by the harvest index and applying a moisture correction factor.

The yields calculated by CYSLAMB are potential yields, which represent management situations without yield reductions due to pests, diseases and other adversaries. If the model is run over a number of years, the outputs can be analyzed statistically to give estimates of the yield exceeded at stated levels of probability and the risks of crop failure. For each land unit the physically most suitable production system (highest returns) can be assessed and therefore the most suitable land unit in a study area for a given crop production system can be determined. The impact of different scenarios, consisting of various management operations and input levels on the crop yields can be tested in order to make appropriate extension recommendations specific to particular land units. These recommendations can then be adjusted for specific farmer groups, defined on the basis of access to resources (Bekker *et al.*, 1994).

2.5.2 SUMMARY OF FEATURES AND ADVANTAGES OF CYSLAMB

CYSLAMB was developed to serve the needs of land use planners, hence it required a different perspective and set of priorities than other simulation models. Smith (1998) gave the following statements summarizing the features and advantages of CYSLAMB:

- The model is flexible (modular design), which implies that it can be applied to any crop production system, provided the essential crop characteristics are known and the management operations and inputs are defined.
- It is capable of validation – one of the principal advantages of quantitative land evaluation methodology expressing the results as crop yields.
- It has a simple and logical methodology.
- It expresses the prominent role of moisture stress in determining yield, which makes the model appropriate for use in other semi-arid regions.
- It is scale independent and therefore can be applied at micro (household) and macro (provincial/ national) level.
- It includes land related and non-land-related parameters for evaluation, which means that it takes into consideration other aspects relevant to production systems when making assessments.

2.5.3 BASIC ASSUMPTIONS ON THE WATER BALANCE OF A SOIL-PLANT SYSTEM FOR CYSLAMB

The complexity and importance of the processes in the soil-plant-atmosphere system, which consist of the six water balance processes, require that its functioning be well understood. According to Hensley *et al.* (2000) a reliable model makes it possible to describe how the system functions in the long term under the conditions of large annual fluctuations in the climate component of the system. The moisture balance module of this model has been subject to the most stringent testing because moisture stress is the single most important yield determining factor in the semi-arid environments for which the model was developed (De Wit, Tersteeg and Radcliffe, 1993).

Some of the basic assumptions made with regard to the development of the water balance equation at field level for the model include the following:

- It is assumed that at the level of a farmer's field, run off and run-on compensate each other (=0) in the sense that very low net losses of water occur in rural rangeland where run-off from one site normally results in run-on to another site of the same micro-environment. Run-off mostly results in infiltration or temporary surface storage somewhere else in the same field.

- The gains and losses due to lateral seepage at farm level are equal (=0).
- Ground water tables in Botswana usually occur at considerable depth often exceeding 30 m. Therefore the contribution of groundwater to the arable profile is omitted.

The latter assumption is rather questionable in the context of the study area considering the occurrence of the impermeable subsoil horizon viz. soft plinthite. Soils with such characteristics develop a zone of periodic saturation and have high water storage capacity. This moisture plays an important role in providing a favourable soil moisture regime in these drier regions of the country.

2.6 SENSITIVITY ANALYSIS AND CALIBRATION OF CYSLAMB

According to Boote *et al.* (1996), model calibration refers to adjusting certain model parameters or relationships to make the model work for a particular site or sites. Model validation determines whether the model works with totally independent data sets that are intended to find whether the model can accurately predict growth, yield and processes. A sensitivity analysis was conducted to see how the model (in terms of simulated yield) responded to changes effected in the crop characteristics.

These were the Kc factors (crop-coefficients) and the yield response factors (Ky). The values were adjusted to the point where results obtained showed a constant agreement with the observed yields. There was no available data that could be found on these cultivar specific factors. However, the values used are within reasonable estimates when compared with the generalised information on maize used in the ACRU model published by Smithers and Schulze (1995) (Tables 2.2 and 2.3). Crop coefficient (Kc) is the coefficient used to calculate potential maximum crop evapotranspiration (ET_m) from the evapotranspiration of a reference crop. According to De Wit *et al.* (1993), the main characteristics affecting Kc values are the adaptation to control crop transpiration, crop height, crop roughness, crop reflection, percentage groundcover, crop planting date, rate of crop development, length of growing season, and, especially during the early growth stage, the frequency of rainfall. As already mentioned earlier, planting in the western parts of the province is usually delayed until December, whereas in the eastern parts, early planting is usually expected to give better results. Table 2.4 shows the values used in the simulations for this exercise. One of the most important management decisions in the marginal areas is the choice of plant populations or plant density classes. For example, what is regarded as a low plant density in high and moderately high potential areas represents a high plant density class for the low potential areas.

Table 2.2 Generalised information of maize crop coefficients in Southern Africa (dryland condition) (Smithers and Schulze, 1995)

Planting Date	*Jan*	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sept*	*Oct*	*Nov*	*Dec*
October 10	1.01	0.56	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.37	0.80	1.08
October 20	1.07	0.79	0.37	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.64	1.04
November 1	1.10	0.95	0.46	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.46	0.92
November 10	1.07	1.02	0.62	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.37	0.79
November 20	1.07	1.00	0.47	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.70
December 1	1.01	1.08	0.70	0.36	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.48

Table 2.3 Seasonal distribution of crop coefficients used for maize planted early (October 2) or late (December 15) in all areas (after Green, 1985), cited by Smithers and Schulze (1995)

Crop Coefficient	Planting dates	
	October 1 Days after planting	December 15 Days after Planting
0.4	1 – 20	1 – 17
0.7	21 – 40	18 – 34
1.0	41 – 60	35 – 51
1.1	61 – 100	52 – 86
0.9	101 – 120	87 – 103
0.5.	121 – 140	104 - 120

Table 2.4 Crop (Kc.) coefficients used for the CYSLAMB runs.

Plant Density classes (Plants.ha^{-1})		Maize crop coefficients	
		Kc. 1	Kc.2
Low	<16000	0.38	0.30
Medium	16000-20000	0.49	0.45
High	>20000	0.90	0.85

Kc. 1: The coefficient used to calculate crop moisture requirements at the end of the vegetative stage.
Kc. 2: The coefficient used to calculate crop moisture requirements at the end of the ripening stage.

The yield response factor (Ky) expresses the sensitivity of the crop to moisture stress. According to Bekker *et al.* (1994) the response of yield to water stress relates relative yield decrease to relative evapotranspiration deficit, of which the latter may either occur continuously over the total growing period of the crop or over one of the individual growth periods. In general for the total growing period the decrease in yield relative to the increase in water deficit is proportionally greater (Ky>1) for more drought sensitive crops such as maize. For the individual periods, the decrease in yield due to water deficit during that growth period is relatively small for the vegetative and ripening periods, and relatively large for the flowering and yield formation periods.

The following values were applied in the runs for this study:

Early vegetative stage	(Ky1a)	:0.34
Late vegetative stage	(Ky1b)	: 0.52
Flowering	(Ky2)	: 0.70
Yield formation	(Ky3)	: 0.60
Ripening	(Ky4)	: 0.29
Flower and yield formation*	(Ky23)	: 1.10
Total crop cycle*	(Ky14)	: 1.38

* These are the compound Ky Factors used by CYSLAMB, in such a way that in the event of moisture stress exceeding 50% at flowering or during yield formation, Ky 23 is used rather than the two individual Ky factors for these stages. This is done to accommodate the ability of the crop to apportion the adverse effects of moisture stress over these two, highly critical yield response periods. The Ky14 is given as an average reduction occurring throughout all crop development stages.