SOIL PHYSICS AND AGRICULTURE

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1 INTRODUCTION

The approach that integrates knowledge is very important in Agriculture, including farmers, extensionists, researchers and professors. The specialists, including the soil physicists, must have a global view of the crop production system. Therefore, their expertise can be useful for the society. The Essence of scientific knowledge is its practical application.

The soil physics is a subarea of Agronomy. There are many examples of this specific subject related to Agriculture. This paper will focus, in general, the following cases: (i) erosion, environmental pollution and human health, (ii) plant population and distribution, soil fertility, evapotranspiration and soil water flux density, and (iii) productivity, effective root depth, water deficit and yield.

2 EROSION, ENVIRONMENTAL POLLUTION AND HUMAN HEALTH

Normally, at dry season, from May to August, the air temperature and rainfall are limitantes for economical Agriculture under Brazilian politic (no subsides to Agriculture). For these reasons, the cover crop is not common to all farmers. Therefore, the soils present high erodibility.

The exploration of almost all Brazilian annual crops (without irrigation) occurs on wet season, where the main criteria is based on the maximum probability of rainfall to be equal or superior to evapotranspiration at flowering period. Therefore, the majority of sowing dates is done between September and December, where there is tropical precipitation with high intensity (high erosivity) when the leaf area has low value.

The combination of high rainfall erosivity and high soil erodibility is responsible for about 10,000 to 15,000 $kg.ha^{-1}.year^{-1}$ of erosion on maize, for example. This first millimeter of the soil, in Agriculture, represents chemical products (herbicides and fertilizers, mainly) in the rivers and less soil fertility (less organic matter and nutrients).

The human water consumption in Brazil is around 100 to 500 liters per day per person, where the water caption from the river is common. The environmental pollution caused by erosion prejudices water quality and human health. Therefore, the water and diseases treatments in the cities are necessary.

The alternative crop system and agricultural politic to minimize the soil losses problem is a challenge for the soil physicists (under economical, social and environmental view). The no tillage system could be a option, because the cover crop can protect the rainfall drop impact on the soil, responsible for about 95% (energy balance) of the erosion process. Some changes in the sowing dates and agricultural politic (subsides) must be done to make mulching. It will be benefic for the environment, farmer and the whole society.

3 PLANT POPULATION AND DISTRIBUTION, SOIL FERTILITY, EVAPOTRANSPIRATION AND SOIL WATER FLUX DENSITY

The understanding of relationship of plant population and distribution, soil fertility, evapotranspiration and soil water flux density is fundamental to optimize the soil resources. This soil physicists, with agricultural system global vision, could develop techniques to become the crop production system more adequate for each specific environment.

The increasing of plant population demands more water and better plant distribution. The increasing of evapotranspiration requires more soil water flux density. The soil fertility depends on the soil volume per plant (plant population and distribution), evapotranspiration (leaf area, specie, wind, air temperature and relative humidity, mainly) and soil water flux density.

The maximum water requirement occurs at flowering. The correct plant population is defined as function of the probability of soil water flux density to be equal or superior to maximum evapotranspiration any day in the whole crop cycle.

For high population, the plant distribution becomes more important. The soil physicist must minimize intra specific competition for water and nutrients. The better plant distribution maximizes the soil volume per plant, and the critical content values for all nutrients (soil fertility) are lower. Consequently, the fertilizer requirement decreases.

The corn grain production per plant is constant when there is no intra specific competition for water and nutrients, and the grain production per area has linear increment with the increasing of plant population (phase A – Figure 1).

The corn grain production per plant decreases when there is intra specific competition for water and nutrients, and the grain production per area has potential (less than linear) increment with the increasing of plant population (phase B – Figure 1). The grain production per plant decrement rate is lower than the plant population increment rate, then the grain production per area increases.

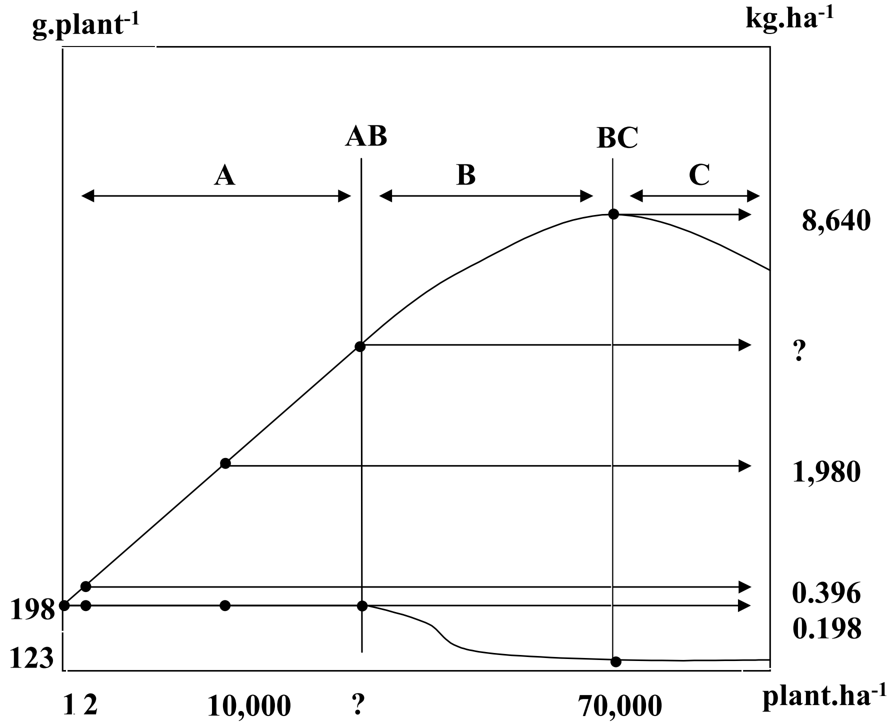


Figure 1. Corn grain production per plant (g.plant^{-1}) and per area (kg.ha^{-1}) as function of plant population (plant.ha^{-1}).

The corn grain production per plant decreases when there is intra specific competition for water, nutrients and light, and the grain production per area decreases with the increasing of plant population (phase C – Figure 1). The grain production per plant decrement rate is higher than the plant population increment rate, then the grain production per area decreases.

The point AB (Figure 1) shows when the intra specific competition for water and nutrients starts. The correspondent plant population can be larger in better plant distribution, and the maximum grain production per area also can be larger in higher plant population (point BC – Figure 1), when the intra specific competition for light starts.

The soil resources (physical and chemical attributes) optimization (plant distribution) is a soil physicist subject (see item 3.1).

The soil physicists could start with dynamic focus instead static emphasis. An example is the critical value for potassium (soil fertility) (see item 3.2).

3.1 Plant population

To define better maize plant population (P, $pl.ha^{-1}$), the following assumptions were done:

(i) there is a critical population (Pc, $plant.ha^{-1}$) where the production per plant (Y, $g.pl^{-1}$) is constant and production per area has linear increasing (R, $kg.ha^{-1}$)

$$Y = Ym \ (1 \leq P \leq Pc) \tag{1}$$

$$Ym = \Pr_M .Fe_M .Gf_M .Mg_M \tag{2}$$

where Ym ($g.plant^{-1}$) is the maximum production per plant, Pr_M is the maximum prolificity ($ear.plant^{-1}$), Fe_M is the number of grain rows per ear ($row.ear^{-1}$), Gf_M is the maximum number of grains per row ($grain.row^{-1}$) and Mg_M is the maximum grain mass ($g.grain^{-1}$).

(ii) the production per plant (Y, $g.plant^{-1}$) and the production per area (R, $kg.ha^{-1}$), when plant population is larger than critical population (Pc, $plant.ha^{-1}$), follows the next equations:

$$Y = \frac{Ym}{\left\{1 + \left[\alpha(P - Pc)\right]^m\right\}^n}, \ (P>Pc) \tag{3}$$

$$R = \frac{Y.P}{1000}, \ (P>Pc) \tag{4}$$

where α, m and n are the empirical parameters.

Therefore:

$$R = \frac{Ym.P}{1000\left\{1 + \left[\alpha(P - Pc)\right]^m\right\}^n}, \ (P>Pc) \tag{5}$$

Table 1. Maize plant population optimization.

Case	Restriction	Mathematical expression
1	$1 \le P \le Pc$	$Y = Ym$
2	$P > Pc$	$Y = \dfrac{Ym}{\left\{1 + \left[\alpha\left(P - Pc\right)\right]^m\right\}^n}$
3	$P > Pc$	$\lim_{P \to \infty} Y = 0$
4	$1 \le P \le Pc$	$\dfrac{dY}{dP} = 0$
5	$P > Pc$	$\dfrac{dY}{dP} < 0$
6	$1 \le P \le Pc$	$\dfrac{d^2Y}{dP^2} = 0$
7	$Pc < P < Pi$	$\dfrac{d^2Y}{dP^2} < 0$
8	$P = Pi$	$\dfrac{d^2Y}{dP^2} = 0$
9	$P > Pi$	$\dfrac{d^2Y}{dP^2} > 0$
10	$1 \le P \le Pc$	$R = \dfrac{Ym.P}{1000}$
11	$P > Pc$	$R = \dfrac{Ym.P}{1000\left\{1 + \left[\alpha\left(P - Pc\right)\right]^m\right\}^n}$
12	$P = Pm$	$R = Rm$
13	$P > Pm$	$\lim_{P \to \infty} R = 0$
14	$1 \le P \le Pc$	$\dfrac{dR}{dP} = \dfrac{Ym}{1000}$
15	$Pc < P < Pm$	$\dfrac{dR}{dP} > 0$
16	$P = Pm$	$\dfrac{dR}{dP} = 0$
17	$P > Pm$	$\dfrac{dR}{dP} < 0$
18	$1 \le P \le Pc$	$\dfrac{d^2R}{dP^2} = 0$
19	$P > Pc$	$\dfrac{d^2R}{dP^2} < 0$

The first derivation of (5):

$$\frac{dR}{dP}=\frac{Ym}{1000}\left\langle\frac{\left\{1+\left[\alpha\left(P-Pc\right)\right]^{m}\right\}^{n}-Pn\left\{1+\left[\alpha\left(P-Pc\right)\right]^{m}\right\}^{n-1}m\left[\alpha\left(P-Pc\right)\right]^{m-1}\alpha}{\left\{1+\left[\alpha\left(P-Pc\right)\right]^{m}\right\}^{2n}}\right\rangle \tag{6}$$

If $\frac{dR}{dP}=0$, then:

$$\left\{1+\left[\alpha\left(Pm-Pc\right)\right]^{m}\right\}^{n}=m.n.Pm.\alpha^{m}\left(Pm-Pc\right)^{m-1}\left\{1+\left[\alpha\left(Pm-Pc\right)\right]^{m}\right\}^{n-1} \tag{7}$$

$$m.n.Pm.\left(Pm-Pc\right)^{m-1}-\left(Pm-Pc\right)^{m}-\frac{1}{\alpha^{m}}=0 \tag{8}$$

To obtain the solution, the general iterative Newton-Raphson procedure can be used, creating the following function *f(Pm)*:

$$f\left(Pm\right)=m.n.Pm.\left(Pm-Pc\right)^{m-1}-\left(Pm-Pc\right)^{m}-\frac{1}{\alpha^{m}} \tag{9}$$

and:

$$f'\left(Pm\right)=m.\left(Pm-Pc\right)^{m-1}\left[n+\frac{Pm.\left(m-1\right).}{Pm-Pc}-1\right] \tag{10}$$

Therefore:

$$Pm_{k+1}=Pm_{K}-\frac{f\left(Pm_{k}\right)}{f'\left(Pm_{k}\right)} \tag{11}$$

To verify the modeled conditions of maize plant population optimization, the second derivation of (5) is given by the following equation:

$$\frac{d^{2}R}{dP^{2}}=\frac{Ym}{1000}\left\langle\frac{g'\left(P\right).\left\{1+\left[\alpha\left(P-Pc\right)\right]^{m}\right\}^{2n}-g\left(P\right).2.m.n.\alpha^{m}\left\{1+\left[\alpha\left(P-Pc\right)\right]^{m}\right\}^{2n-1}\left(P-Pc\right)^{m-1}}{\left\{1+\left[\alpha\left(P-Pc\right)\right]^{m}\right\}^{4n}}\right\rangle \tag{12}$$

where:

$$g\left(P\right)=\left\{1+\left[\alpha\left(P-Pc\right)\right]^{m}\right\}^{n}-m.n.\alpha^{m}h\left(P\right) \tag{13}$$

and

$$g'\left(P\right)=m.n.\alpha^{m}\left(P-Pc\right)^{m-1}\left\{1+\left[\alpha\left(P-Pc\right)\right]^{m}\right\}^{n-1}-h'\left(P\right) \tag{14}$$

where

$$h\left(P\right)=P\left(P-Pc\right)^{m-1}\left\{1+\left[\alpha\left(P-Pc\right)\right]^{m}\right\}^{n-1} \tag{15}$$

$$h'\left(P\right)=\left(P-Pc\right)^{m-1}\left\{1+\left[\alpha\left(P-Pc\right)\right]^{m}\right\}^{n-1}+P.s'\left(P\right) \tag{16}$$

$$s\left(P\right)=\left(P-Pc\right)^{m-1}\left\{1+\left[\alpha\left(P-Pc\right)\right]^{m}\right\}^{n-1} \tag{17}$$

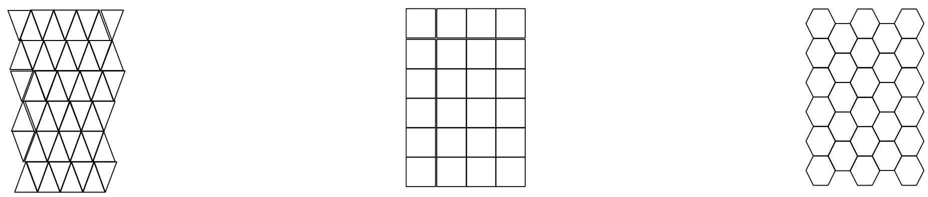
$$s'(P) = (m-1)(P-Pc)^{m-2}\left\{1+[\alpha(P-Pc)]^m\right\}^{n-1} + (P-Pc)^{m-1}(n-1)\left\{1+[\alpha(P-Pc)]^m\right\}^{n-2} m[\alpha(P-Pc)]^{m-1}\alpha \qquad (18)$$

3.2 Plant distribution

3.2.1 Assumptions

To define the better maize plant distribution, the following assumptions were done:

(i) in the nature, there are only three regular polygons that can stay side by side without empty space: triangle, square and hexagon (a fourth possibility is the rectangle)



(A) (B) (C)

Figure 2. (A) Triangulate, (B) square and (C) hexagonal plant distribution.

(ii) the maize plant explores circular area

(iii) the better plant distribution, for a fixed plant population, maximizes explored soil area per plant

(iv) higher soil area per maize plant minimizes stress

(v) the gross soil area explored by plant (Ap, $m^2.plant^{-1}$) is calculated as function of plant population (P, $plant.ha^{-1}$):

$$Ap = \frac{10000}{P} \qquad (19)$$

3.2.2 Triangulate plant distribution

For the triangulate distribution (Figure 3), the space between rows (e_1, m) can be calculated as follow:

$$e_1 = \frac{x}{2} \qquad (20)$$

By triangle ABC (Figure 3):

$$x = 2r\sqrt{3} \qquad (21)$$

Substituting (21) in (20):

$$e_1 = r\sqrt{3} \tag{22}$$

The space between plants (e_2, m) can be calculated as follow (Figure 3):

$$e_2 = 2r \tag{23}$$

The explored useful area per plant (Au, $m^2.pl^{-1}$) is calculated as function of the inscribed circle radius *r* (Figure 3):

$$Au = \pi r^2 \tag{24}$$

The gross explored area per plant (Ap, $m^2.plant^{-1}$) can be also calculated according to triangle BDE (Figure 3):

$$Ap = \frac{3xr}{2} \tag{25}$$

Substituting (19) and (21) in (25):

$$r = \frac{100}{3^{\frac{3}{4}} P^{\frac{1}{2}}} \tag{26}$$

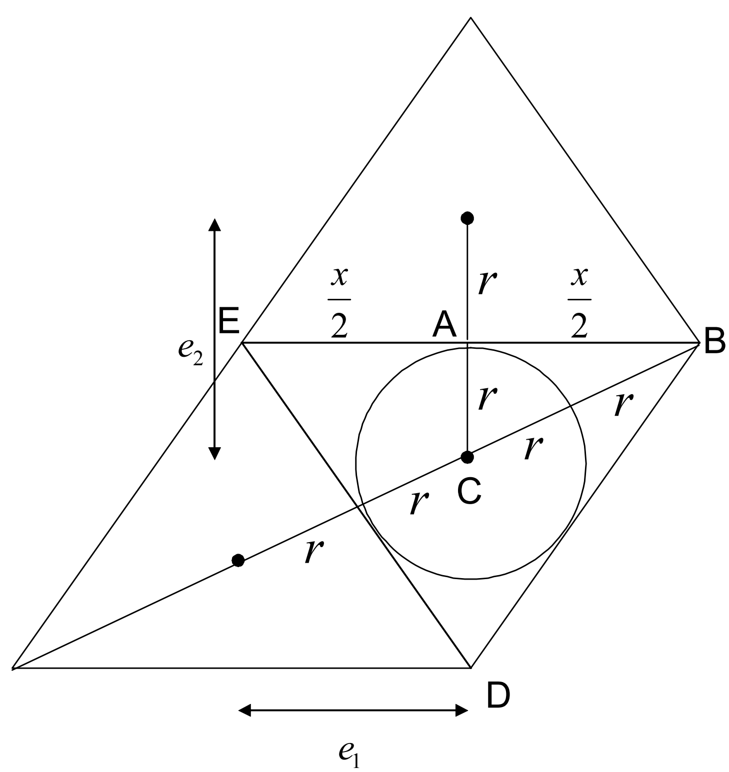


Figure 3. Triangulate plant distribution.

Substituting (26) in (22) and (23):

$$e_1 = \frac{100}{3^{\frac{1}{4}} P^{\frac{1}{2}}} \tag{27}$$

$$e_2 = \frac{200}{3^{\frac{3}{4}} P^{\frac{1}{2}}} \tag{28}$$

3.2.3 Square plant distribution

For the square distribution (Figure 4), the space between rows (e_1, m) and between plants (e_2, m) can be calculated as follow:

$$e_1 = 2r \tag{29}$$

$$e_2 = 2r \tag{30}$$

The explored gross area per plant (Ap, $m^2.plant^{-1}$) (Figure 4):

$$Ap = x^2 \tag{31}$$

Therefore:

$$x = \frac{100}{P^{\frac{1}{2}}} \tag{32}$$

and

$$x = 2r \tag{33}$$

The explored useful area per plant (Au, $m^2.plant^{-1}$) is calculated as function of the inscribed circle radius *r* (Figure 4):

$$Au = \pi r^2 \tag{34}$$

Substituting (32) and (33) in (34):

$$Au = \frac{2500\pi}{P} \tag{35}$$

Substituting (32) and (33) in (29) and (30):

$$e_1 = \frac{100}{P^{\frac{1}{2}}} \tag{36}$$

$$e_2 = \frac{100}{P^{\frac{1}{2}}} \tag{37}$$

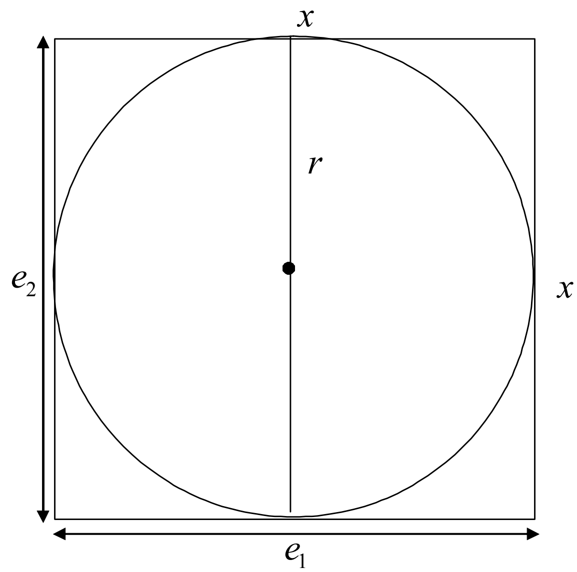


Figure 4. Square plant distribution.

3.2.4 Hexagonal plant distribution

For the hexagonal distribution (Figure 5), the space between rows (e_1, m) can be calculated as follow:

$$e_1 = \frac{3x}{2} \tag{38}$$

By triangle CDE:

$$\alpha = \frac{\pi}{3} \tag{39}$$

By triangle ABC:

$$tg\left(\frac{\pi}{3}\right) = \frac{2r}{x} \tag{40}$$

Therefore:

$$x = \frac{2r}{3}\sqrt{3} \tag{41}$$

Substituting (41) in (38):

$$e_1 = r\sqrt{3} \tag{42}$$

The space between plants (e_2, m) (Figure 5):

$$e_2 = 2r \tag{43}$$

The gross explored area per plant (Ap, $m^2.plant^{-1}$) can be computed as 12 times the triangle ABC area (Figure 5):

$$Ap = 3xr \tag{44}$$

Substituting (41) and (19) in (44):

$$r^2 = \frac{5000}{P\sqrt{3}} \tag{45}$$

or:

$$r = \frac{10.}{3^{\frac{1}{4}}}\left(\frac{50}{P}\right)^{\frac{1}{2}} \tag{46}$$

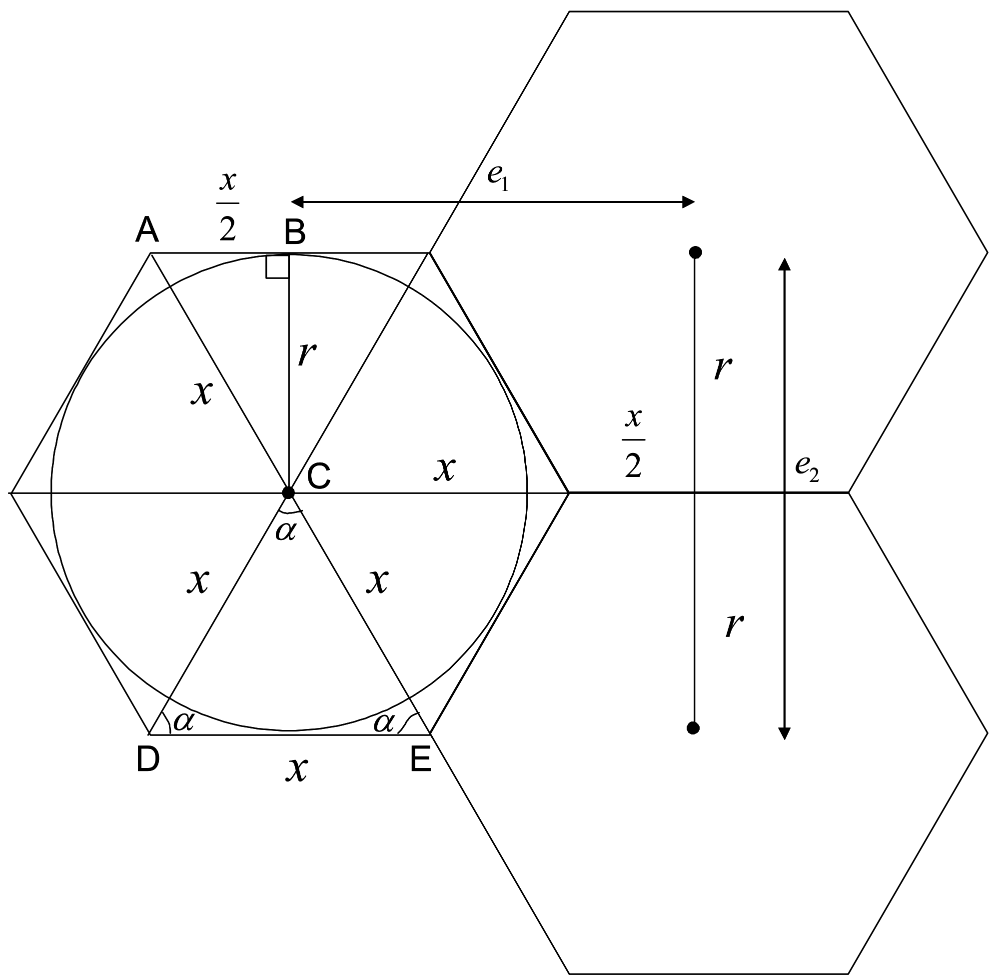


Figure 5. Hexagonal plant distribution.

The useful explored area per plant (Au, $m^2.plant^{-1}$) (Figure 5):

$$Au = \pi r^2 \tag{47}$$

Substituting (45) in (47):

$$Au = \frac{5000\pi\sqrt{3}}{3P} \tag{48}$$

Substituting (46) in (42) and (43):

$$e_1 = 10.3^{\frac{1}{4}}\left(\frac{50}{P}\right)^{\frac{1}{2}} \tag{49}$$

$$e_2 = \frac{20.}{3^{\frac{1}{4}}}\left(\frac{50}{P}\right)^{\frac{1}{2}} \tag{50}$$

Other solution can be obtained positioning circles minimizing empty spaces (Figure 6A). For this particular case (Figure 7), the height (h, m) and the area of triangle ABC (At, m^2) can be calculated as follow:

$$h = r\sqrt{3} \tag{51}$$

$$At = r^2\sqrt{3} \tag{52}$$

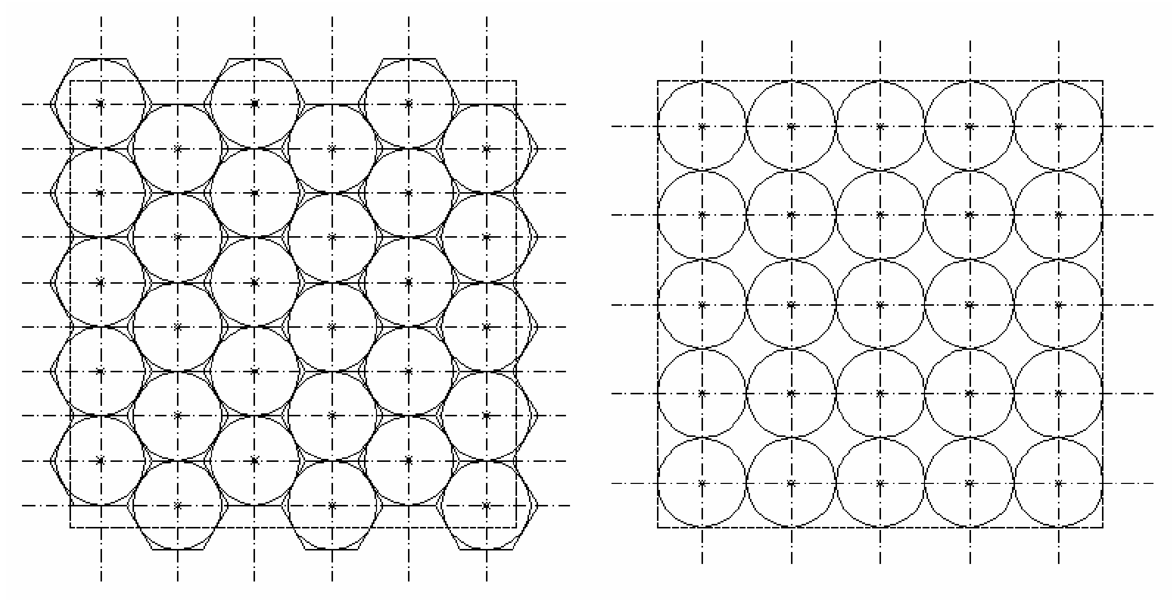
Therefore, there are 2.P triangles ABC per hectare (10.000m^2):

$$2.P.r^2\sqrt{3} = 10000 \tag{53}$$

Then:

$$r = \frac{10.}{3^{\frac{1}{4}}}\left(\frac{50}{P}\right)^{\frac{1}{2}} \tag{54}$$

The equations (46) and (54) are similar.



(A) (B)

Figure 6. Circles (A) minimizing and (B) maximizing empty spaces.

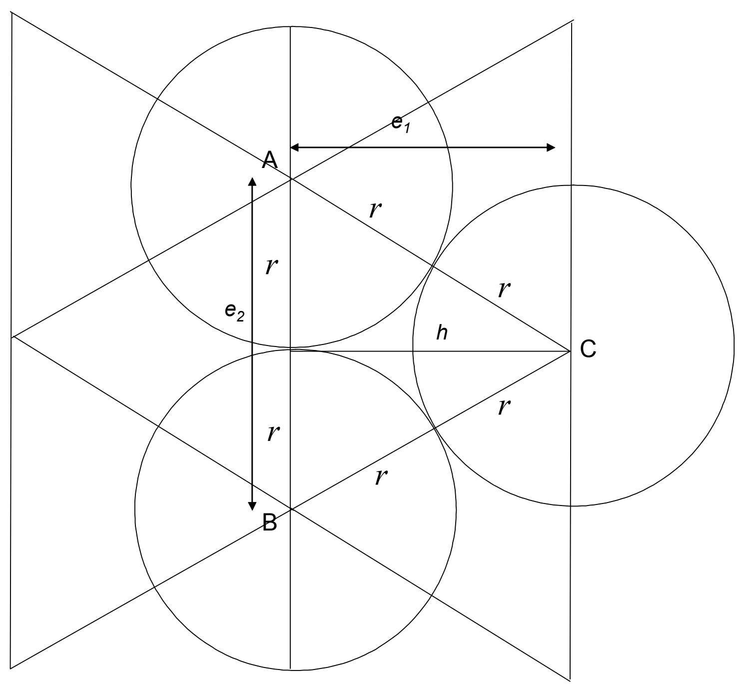


Figure 7. Circles maximizing explored area per plant.

3.3 Potassium availability

The potassium availability in the soil could be express in terms of offer rate (kg $K.ha^{-1}.day^{-1}$) to compare with the crop potassium requirement rate (kg $K.ha^{-1}.day^{-1}$)

(*dynamic focus* – soil physics contribution) (Figure 8) instead critical values for soil potassium content (*static emphasis*) (Figure 9).

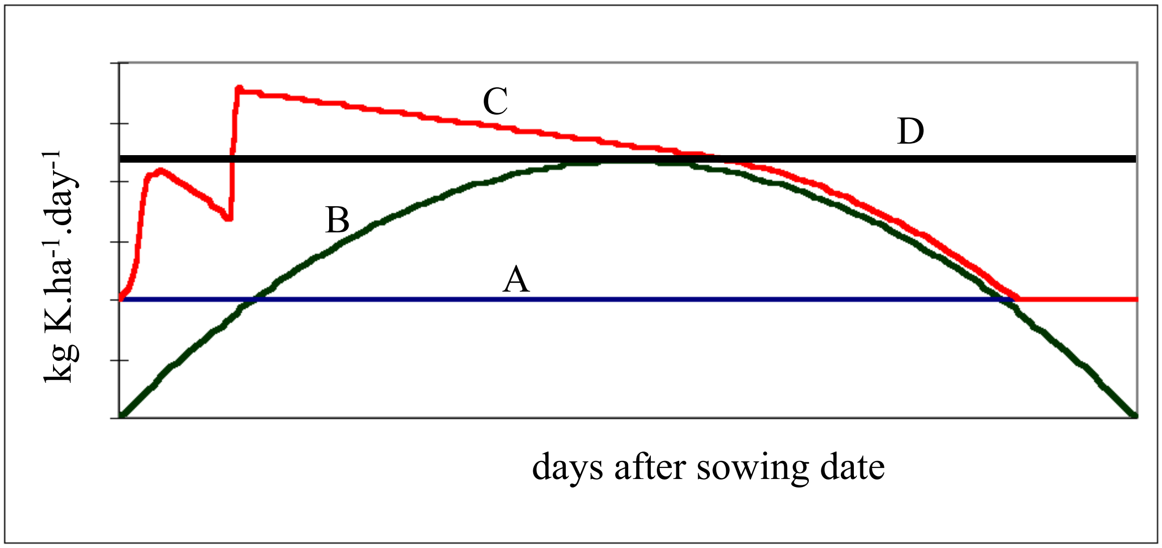


Figure 8. The potassium availability in the soil express in terms of offer rate: (A) deficient soil fertility, (C) deficient soil fertility with two fertilizations, (D) sufficient soil fertility, and (B) the crop potassium requirement rate (kg K.ha^{-1}.day^{-1}).

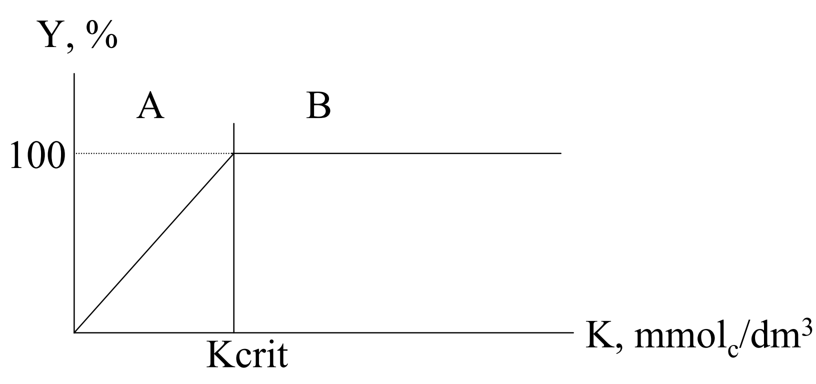


Figure 9. The relative grain yield (Y, %) as function of soil potassium content (K, mmol$_c$.dm^3): (A) deficient soil fertility, (B) sufficient soil fertility, and the critical soil potassium content (Kcrit, mmol$_c$.dm^3).

Actually, there is an unique value for the critical soil potassium content (Kcrit, $mmol_c.dm^3$) independently of the soil type, specie and weather conditions. This *static emphasis* was important in the past, but must be replaced per *dynamic focus* by the soil physicists. It will be an important contribution (it optimizes the fertilizer utilization) for Agriculture.

4 PRODUCTIVITY, EFFECTIVE ROOT DEPTH, WATER DEFICIT AND YIELD

Yield means the grain (or other part of the plant) production per area ($kg.ha^{-1}$), and the productivity will be defined as the potential yield. Then, the productivity depends only of the genotype and weather (soil water content in the *field capacity*), and yield depends on the genotype, weather and biotic (weeds, diseases and pests, mainly) and abiotic interference.

For practical purposes, the first step is the definition of target yield and price that defines technology level. Then, the first components for agricultural planning at farm scale are: genotype, weather condition (depends on the sowing date), water availability, plant population and nitrogen fertilization.

The water deficit occurs when the soil water flux density is lower than the maximum evapotranspiration (Figure 10). The decreasing of evapotranspiration causes stress. The plant stress reduces yield and increases cost with weeds, diseases and pests control, and decreases profit.

For practical purposes, the soil water holding capacity per unit of effective root depth defines the plant population support with no irrigation agricultural system. When the soil water content is lower than the critical value (θcrit), the soil water flux density (q) is lower than maximum evapotranspiration (ETm) and real evapotranspiration (ETr) decreases (Zone A – Figure 10).

If the soil water content is larger than θcrit, the soil water flux density (q) is larger than maximum evapotranspiration (ETm) and real evapotranspiration (ETr) is equal to ETm (Zone B – Figure 10).

The water deficit reduces effective root depth (Ze), because there is no sufficient water to make more roots (the consumption of new cells require more water than old cells).

The water excess also reduces Ze, because the oxygen diffusion is limiting (the oxygen diffusion in the air is larger than in the water) (Figure 11). The agricultural management must improve effective root depth to optimize natural resources. Each 1 cm soil depth holds around 12,500 $L.ha^{-1}$ of water (see the modal soil in the nature Figure 10).

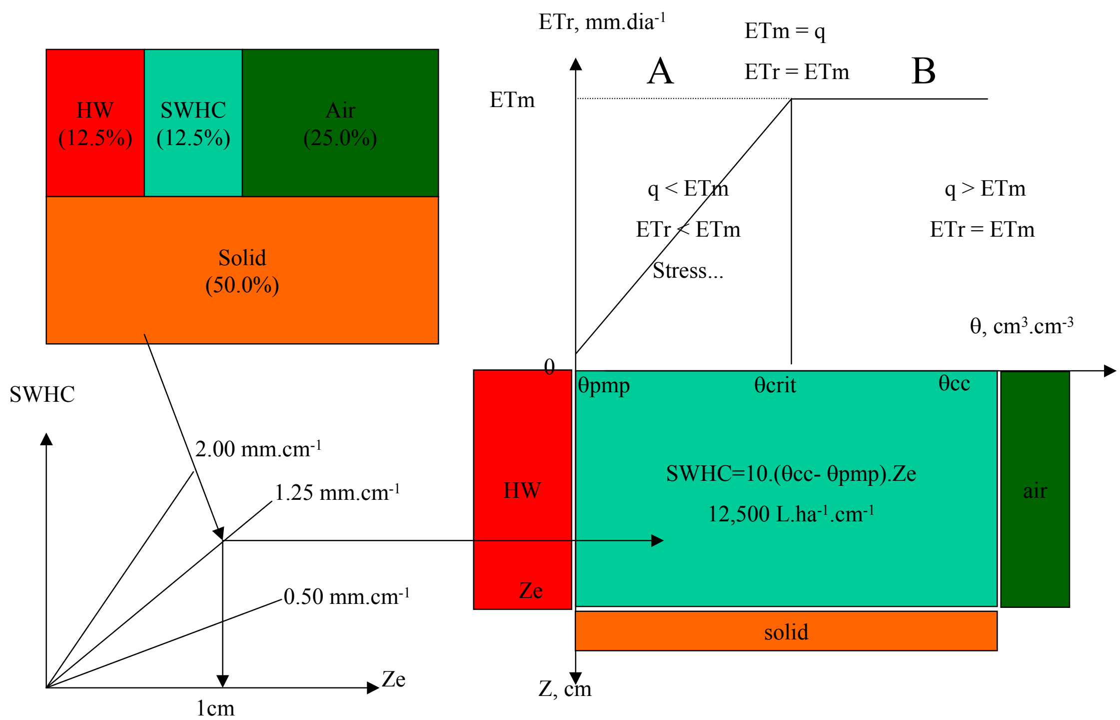


Figure 10. The modal soil physics properties in the nature. HW: hygroscopic water, SWHC: soil water holding capacity, θ: soil water content, ETr: real evapotranspiration, ETm: maximum evapotranspiration, Ze: effective root depth and q: soil water flux density.

For more details related to grain productivity, effective root depth, water deficit and grain yield, see the capther “agroclimatic mapping of maize crop based on soil physical properties” and the references.

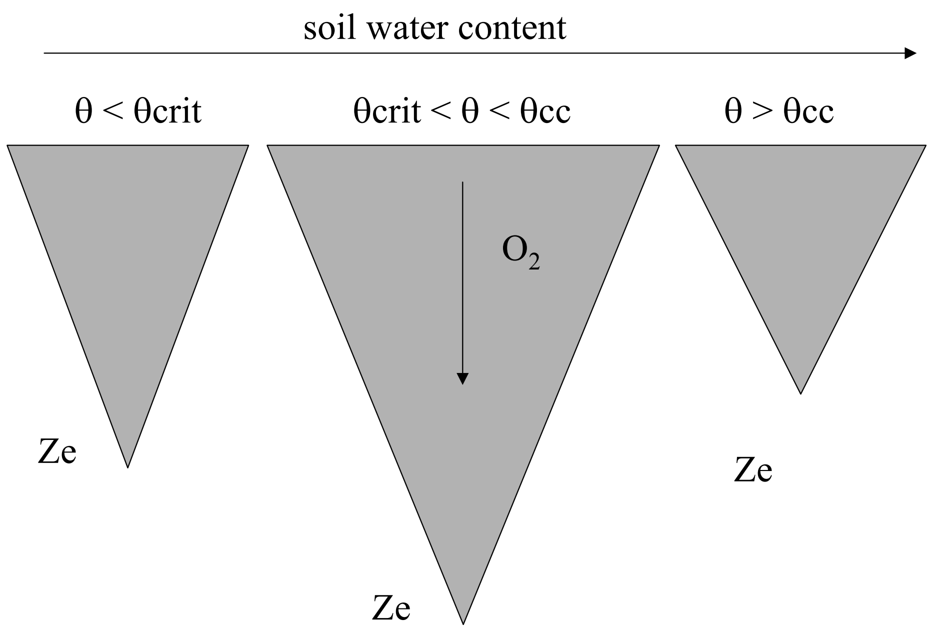


Figure 11. Relationship between oxygen diffusion (O_2), soil water content (θ) and effective root depth (Ze).

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