In Thorns we lay our trust

Or: preliminary proposal to investigate ficus indica as a potential new crop for the Sahel

During the last two decades, the interest in the ficus indica as a crop has increased significantly with several researches in other parts of the world hailing it as a promising crop for dry and infertile environments (Nobel 1991; Felker 1995; Houérou 1996).

This is not surprising as the cactus optimally suited to thrive in a harsh arid environment. Various opuntia based farming systems in other arid and semi-arid regions have shown that opuntia can be an economically and agronomic attractive option. Especially the documented roles of opuntias as a livestock saver in (Felker 1995; Houérou 1996; Nobel 1991; Basile & Foti 1997; Claudio, Valdez & Osorio 1997; Nefzaoui 1997; Mizrahi, Nerd & Nobel, 1997).

What is surprising however is that the potential of this (fodder) crop for the Sahel has not been investigated[1]. Neither are there any documented references to opuntia cultivation in the Sahel. This raises some important questions, around which this proposal is centered. The three main research questions are:

- What is the potential productivity of ficus indica (and other opuntias) in a Sahelian environment?
- What is the nutritional value of opuntias as a fodder crop and how could the cactus be embedded in the local system to provide a balanced diet?
- What are the possible environmental constraints to the establishment of opuntias in the Sahel?

The broader goal of this paper is to scrutinize and analyze the potential of ficus indica as a farming system. Not only the productivity of ficus indica as a crop but also the cactus' role in an whole system should be taken into account as the comparative advantages of ficus indica in other production systems consists of several factors [2]:

1. It's high water storage capacity (85-90%) makes it an extra source of water in drier times
2. Its high water use efficiency makes it ideal as a buffer crop to overcome drought. It serves as an extra source of energy when no other fodder is available. This is five times higher than average desert production of c3/c4 species.

[1] To the best of my knowledge. No specific reference for the Sahel is found in FAO internet documentation, various search engines and directories (o.a. Northernlight, Altavista, yahoo! Etc.) , Agralin and 'Franco's Miglietta's scientific citation index'.
[2] sources and explanation can be found elsewhere in the proposal:

3. It does relatively well on resource poor and shallow soils. This makes it comparative good crop for the nutrient poor soils of the Sahel.
4. Its relative high growth rate makes it ideal as a windbreak to counter wind erosion and protect the farmers plots. In some parts of Mexico and Tunisia the cactus has traditionally been planted as wind breaks.
5. The fruits can serve as an extra source of nutrition not only for the cattle but also for the farmers themselves. In certain parts of the world (Mexico, Israel, Italy) the fruits fetch a premium market price supplementing the income of the farmers. In the northern parts of Mexico the cactus cladodes are used in salads as well.
6. It has relative low technology and labor requirements. *As the harvest of the cladodes will probably be done during the dry season, the labor requirement of the cactus harvest does not conflict with the labor requirements of the harvests of the other crops.*

Thus, in an overgrazed, resource and technology poor environment, cooping with little and irregular rainfall and with low soil fertility levels, cactus could be the ideal crop.

Objective:

The objective of this thesis is to formulate a preliminary proposal to investigate ficus indica as a potential new crop for the Sahel. This preliminary proposal is based of the mentioned research questions. This report is not a goal initself, but only a tool to facilitate further research.

Approach:

The research questions are investigated by an analysis of the available literature. The paper will concentrate on the following aspects:

Section 1: Brief summary of the ficus indica (and other opuntia) production systems
Section 2: The first research theme: Productivity of ficus indica and other opuntias with a special reference to the Sahel
Section 3: The second research theme: The nutritional value of ficus indica as a fodder crop and how the cactus could be embedded in the local system to provide a balanced diet.
Section 4: The third research theme: Potential ecological constraints analysis to the establishment of opuntias in the Sahel
Section 5: Some notes concerning experimental modeling
Section 6: Conclusions and possible feasibility

Terms of Reference

This report is written as a draft proposal for a potential FAO project. The FAO's international orientation, long experience with agriculture on marginal lands and its general appeal as a center of excellence makes it the ideal organization to guide this potential project to a successful conclusion. Furthermore, conducting this study under the auspices of the FAO, offers the best guarantee that the gained knowledge and experience is spread to all who could benefit from these endeavors.

This study forms an integral part of Martin Schiere's studies and is cataloged as a Masters of Science thesis of nine points under the administrative number F300-704. It is conducted under the guidance of the department of 'theoretical production ecology' of the university of Wageningen. It is Martin Schiere's third and final Masters of Science thesis.

Section 1: General description of the use of opuntia cactus.

Nopal Cactus [3] and the use of cactus originally came from the New World. The important role of ficus indica in Mexico is reflected in its agriculture and cooking where the cactus is used in a variety of ways: To name but a few, it is eaten as a vegetable and fruit; it is used for forage, fuel and fences, as well as in medicines, cosmetics and in ceremonies; it produces grana, a natural dye; and it helps to control erosion (Claudio A., F. Valdez & G. A. Osorio 1997).

Ficus Indica, the most widely used cactus from the opuntia genus was introduced to the Old World by Columbus' first voyage in 1493. From the 17th to the 19th century Ficus Indica spread rapidly through the Mediterranean basin. Especially in Spain the Ficus Indica plant proved to be popular, as it was an effective and efficient cure for scurvy, an often deadly disease common on long sea voyages. Nowadays, it forms such a integral part of the Mediterranean landscape that many consider these plants to be native to the Mediterranean basin region. (Le Houérou 1994) (Mizrahi, Y., A. Nerd, & P.S. Nobel, 1997).

The plant's cam pathway resulted in a unique flexibility that made it possible for this plant to prosper in various eco-climatic zones in America, Europe, Africa and Asia. It tends to thrive in arid and semi-arid areas where most non-cacti plants are at a disadvantage (Basile & Foti 1997) due to their lower WUE (Basile& Foti 1997) (Mizrahi, Nerd, & P.S. Nobel, 1997).

The key to water conservation by Cam (Crassulacean Acid Metabolism) is their nocturnal stomatal opening which causes the most of their water loss to occur at night. As the temperature at night is lower than during the day, the difference in water vapor deficit between the plants and the surrounding air is smaller. Thus the loss of water through transpiration is smaller than with C3 and C4 plants (Nobel 1995).

Not only are CAM plants drought resistant but they also have a relative high WUE (see section on productivity and WUE). Again, this is not a direct result of the enzymology of the CAM pathway-C4 plants also use PEP carboxylase for the initial CO_2 fixation-but rather to the stomatal opening at night (Nobel 1988).

Around the world there are currently three main uses of Ficus Indica. The first two uses, the cultivation of cactus pear fruit and the cultivation of Ficus Indica are discussed in more detail below. The third use: the production of dye either directly through the use of its seeds, or indirectly through being a host to the cochineal insect is not considered part of this proposal.

In many traditional farming systems, the role of ficus indica into one of the three categories is not so clear cut however. In Mexico's home garden and orchard systems and also in Ayacucho in Peru, the ficus indica cactus is used as multiple-use plants in

[3] Cacti with flat pieces of cactus belonging to the Opuntia & Nopalitas. Ficus Indica is the most prominent example of the use of cladode cactuses

integrated farming systems. (Claudio A., F. Valdez & G. A. Osorio 1997) (Hoffmann 1995)

The cultivation of cactus pear for human consumption

In Mexico

In Mexico not only the fruits are used for human consumption but also the cladodes cactus stem segments. These are mostly used as vegetables after being slightly cooked. In Mexico the whole scala of cactus utilization can be found, from wild nopalas silvestres gathering systems to modern highly intensified plantations (Barbera G. 1995, Claudio A., F. Valdez & G. A. Osorio, 1997)

Of all the cactus uses, the wild noplares silvestres found in Zacatecas, San Luis Potosí and Jalisco were the first to be used and are the most prevalent. They cover about 3,000,000 ha (see Table 1).

The nopaleros de solar or home garden system is mostly based on the Ficus Indica Mill. and its hybrids. The home garden systems form the backbone of the Ficus Indica gene pool. A fact that is becoming more appreciated with the renewed interest in Ficus Indica in the agronomic/botanic community. The fruits and nopalitos are mostly grown for home and local market consumption. Although the nopalitos growing areas around Mexico City export a 'small percentage' to the USA and Japan. The family and garden systems are still common in the states of Cohauila, Duranggo, Zacatecas, San Luis Potosí, Aguascalientes and Guanajuato (Losada, H., M. Neale, J. Rivera, et al., 1996, Claudio A., F. Valdez & G. A. Osorio, Barbera G. 1995).

According to Mondragon-Jacobo et al., (1996), small orchards northwest of Mexico City produce a yield of 8-10 t/ha. In the semiarid regions the growers obtain a yield of less than 5 t/ha with low labor inputs and low crop management.

During the 1940's commercial intensive plantations were set up. They currently produce the greatest amount of fruit and vegetable nopal, which supplies the domestic and international markets (Claudio A., F. Valdez & G. A. Osorio 1997). Most commercial plantations use 'Blanca varieties' (Pimienta-Barrios & Munoz-Urias 1995).

According to Claudio et al. the area occupied by these plantations is more than 200,000 (See table 1). Barbera (1995) states the hectarage of the commercial plantations to be around 50.000. This large discrepancy could be the result of different definitions used by the Barbera and Claudio et al. Judging from the production figures, Barbera probably only lists the fruit production plantations while Claudio lists the different plantations used for Forage, Fruit and Nopales.

Table 1: Period in use, products and total area cultivated under each nopal production system at present in Mexico

Production System	Period in use	Products	Area (ha)
Wild Communities	20,000 BC to present	Forage Fruit	3,000,000

Family orchards	3,000 BC to present	Vegetable Forage Fruit	Unknown
Intensive Commercial Plantations	1945 to present	Vegetable Forage Fruit Vegetable Grana	 10,400 56,856 150,000 100

Source: Claudio A., F. Valdez & G. A. Osorio 1997

According to Barbera (1995) commercial plantation production peaked in the 1970's at 80.000 ha but declined in the 1990 to about 50.000 as a result of inappropriate cultural techniques and/or unfavorable environmental conditions.

Barbera states the plantation yield in the central-northern areas to be between 3-15 t/ha. In the states of Hildago and Mexico the yield is between 10-15 t/ha. The difference in intensification levels and the amount of rainfall (350-500 mm/yr for the former regions and 400-700 for the latter region) are the reason for this. According to Basile F & V.T. Foti, (1996) Mexico currently produces 260 million kg of cactus fruit on 44,000 ha[4].

Italy,

Italy produces around 66.6 million kg. of fruit about 15% of world production. The Italian cactus pear cultivation is centered in Sicily where 95% of the fruits are cultivated (Basile F & V.T. Foti, 1996). Cactus was already an important crop in Sicily in the 18th century serving the Sicilians as a multifunctional fodder and fruit crop. Indeed cactus pear played such an important role in the life of the Sicilians that a visiting French agronomist in 1875 found the cactus: "are to Sicily what the banana trees are to equinoctial countries and what breadfruit trees are to the Pacific islands. And that ficus indica is: "the bread of the poor people", "the blessing of Sicily" (Buiso 1875 as quoted in Barbera 1995).

Currently the use of cactus pear is mostly for fruit production in modern high tech plantations or in family orchard plantations. The fruit production centers around three different regions, with each a different technological production level. The San Cono Hills production area is the largest and most high tech. It accounts for 46.7% of total production. The San Cono Hills area is mostly responsible for the increase in cactus pear production in Sicily with an increase of 200% over the last 25 years. The successful cultivation and expansion in this region is the result of a beneficial climatic and pedogenic environment on one hand and a higher innovation level on the other hand. The latter is characterized by a higher user frequency of the available technological mains such as water, fertilizer and sprays. In the San Cono hills, the yields, return on labor and net profits are the highest of the three regions (See table 2).

In the Southwest Etneo and Belice Valley regions cactus pear cultivation follows more traditional patterns although the cultivation system in the Belice Valley is also slowly transforming into a high input plantation system. The yield, economic returns

[4] This figures presumably does not include cactus used as fodder or forage

and net profits are somewhat lower in these two areas than in the San Cono Hills area. Nevertheless, profits and return of labor are quite respectable (See table 2).

Dimension	San Cono Hills	Southwest Etneo	Belice Valley
Production (q/ha)	155	130	125
Prices (US/q)	37.2	40.3	37.2
GSP (US/ha)	5.767	5.240	4.651
Production costs (US/ha)	4.341	4.155	3.907
Profits (US/ha)	1.426	1.085	0.744
Labor productivity (kg/ha)	76.4	58.0	67.6
Labor productivity (US/hour)	28.4	23.4	25.1

Source: Basile F & V.T. Foti, 1996

Notes: q=quintal=100 kg, G.S.P.= Gross Saleable Product

In Italy almost all the plantations and orchards use the Gallia cultivar. Of this Cultivar there are three main types of fruits categorized according to the color. The 'yellow' type pear is the most popular accounting for 80-85% of production. The 'red' and 'green' type account for 9-12% and 6-8% of total production respectively. Different clones of these three are recognized and commonly called Trunzara (Pimienta-Barrios & Munoz-Urias 1995, Basile F & V.T. Foti, 1996)

The amount of labor needed per hectare varies between 124 and 264 hours. The most time consuming activities are pruning, scozzolatura[5] and thinning. With these farming practices account for about 70-75% of the total labor costs. (Basile F & V.T. Foti, 1996)

Chile

In Chile the hectarage occupied by ficus indica is about 1000 ha, mostly in the Central part of the country near Til-Til, Noviciados and Pudahuel. This region is characterized by its mild climate and a rainfall pattern of 400 mm. In the intensive fruit plantation two yields per year are obtained with the aid of irrigation and fertilizer techniques. The first yield is between 6 and 9 tons per hectare. The second, more appreciated yield is between 2 and 4 per hectare (Barbera 1995).

General description of various fodder/forage systems around the world.

With the coming of the Spaniards in the 16th Century cactus *(ficus indica and other Opuntias)* became used as a forage crop in the Americas. Today in the arid zones of Mexico, opuntias are of prime importance. Also in the South Western United States, Opuntia's role as a fodder and forage crop is becoming increasingly important (Claudio A., F. Valdez & G. A. Osorio 1997).

In Mexico and in the US, the amount of opuntia species are utilized are numerous and they are used to feed cattle (milk and meat), goats (meat and milk), sheep (meat and

[5] Cultivation practice: Removal of flowers and new cladodes at bloom to force a second crop

wool), horses (transportation and draft), and wildlife. (Claudio A., F. Valdez & G. A. Osorio 1997. Felker 1995).

In the Near East, Ficus indica as fodder crop only came into use in the 1920's. The fodder lands where almost entirely based on the spineless version of the ficus indica (L.) Miller version, *F. inermi.* Apart from the above, mentioned ruminants, the Ficus Indica in the Near East is used to feed camels (Houérou 1996). Some preliminary studies and field observations have shown that ficus indica is also an realistic alternative for rabbit feed (Ruiz-Feria, C. A., S.D. Lukefahr & P. Felker, 1998. Personal observations on Linosa).

In South Africa there are two main varieties that are used as livestock feed; the green leaf O. ficus indica varieties and the blue-leafed O. robusta varieties. Of the robusta variety there are three recognized cultivars " Robusta", "Monterrey" and "Chico". The first two have slightly higher yields (Felker 1995).

The use of cactus as a fodder crop in the arid and semi arid zones of Mexico and the Southwestern US.

According to Claudio et al., the use of nopal as forage and fodder in Mexico depends mostly on the utilization of wild cactus communities and less on the cultivated fodder, fruit or vegetable plantations.

In the arid and semi-arid regions of Mexico, the cacti have to overcome a dry spell of more than seven months. The total annual precipitation ranges from 150 to 600 mm and the average annual temperature is around 15-25 ° C. Vegetation consists of grasslands and shrub lands, and the plant cover is less than 70%. The utilization of the nopal is carried out by large, medium and small rangeland ranches. It plays an especially important role in sub-desert region undergoing a desertification process with the opuntias being one of the few crops potentially able to mitigate the effects of the desertification (Claudio, Valdez & Osorio 1997).

Under normal circumstances nopal is used to overcome the dry season of the year but due to a four year long drought, the opuntias have been used throughout the year, resulting in deterioration of the nopal communities and a depletion of the resource. This drought however highlighted the importance of nopal as fodder crop. Or in the words of Claudio et al.: " The drought, however, did serve to underline the benefits of using nopal as a feed for livestock on the rangelands. In the last three years, 650,000 head of cattle died in northern Mexico as a consequence of the drought. In general, the ranchers with nopal did not suffer great losses compared with those who did not have or ran out of nopal. Moreover, reproduction rates and levels of production of cattle, sheep and goats are superior when the ranchers supplement the normal diet of the livestock with nopal during the dry season."

Forage or Fodder

The difference between forage or rangeland systems and fodder systems is subtle. In the first, the animals are brought to the crops. In the latter, the crops are brought to the animals. In northern Mexico there are about 3 million ha of rangelands with an additional 150,000 ha of nopal planted by ranchers and small producers with government support (Claudio A., F. Valdez & G. A. Osorlo 1997).

Forage or ranching system

In Mexico's ranching system, nopal is either directly consumed by the animals or first burned to neutralize the spines and clochids. In Mexico all the cacti used as forage have at least some spines. Also in the US where spineless versions are available, the ranchers prefer the spiny opuntias as they are generally considered more resistant to drought. A second advantage of the spiny genotypes is the flexibility in timing. The cacti remain untouched till needed. The damage caused by rodents is also less.

According to Claudio et al., the best way to burn the nopal is to cut of the nopal pads and place them on the ground and then burn the thorns off. Nevertheless, this is a rather cumbersome and labor intensive method. In economies where the cost of labor is high, manually chopping the cladodes first is probably not the best option.

Burning the whole plant by lighting some brush at the base of the plant is more labor efficient but often damages the plant so severely that recovery is difficult. Furthermore the amount of cactus wasted is considerable as the livestock nock down many of the cacti plants.

In Mexico the edges of the nopal, with the highest concentration of spines are simply cut off. Mechanically chopping the cladodes, sometimes followed by fermentation, also makes them palatable to livestock (Claudio A., F. Valdez & G. A. Osorio Mizrahi, Y., A. Nerd, & P.S. Nobel, 1997).

Both in US as in Mexico a kerosine 'packpack' burner is often used to burn the nopal. In Texas propane became available in the fifties. Although relatively expensive in Mexico's ranching system, that can draw on a relative cheap labor pool, the use of packpack burners in southern Texas is an economically realistic option. This option is 30% to 40% cheaper than the cost of available relief food provided during drought. The great advantage of using the burner is that it is labor efficient and allows greater selectivity (Claudio A., F. Valdez & G. A. Osorio, Felker 1995, Mizrahi, Y., A. Nerd, & P.S. Nobel, 1997).

Table 2: Main opuntia species used as forage and fodder in Mexico and the Southwestern US.

Forage species used in N. Mexico rangeland system (Claudio et al.,)	Fodder species used in Mexico's confined livestock system (Claudio et al.,)	Fodder/forage species used in Mexico according to (Fuentes-Rodriguez 1991)	Fodder/forage species used in the US (Felker 1995)
	Besides all species listed for the use of forage :		
O. streptacantha	**Especially used for forage plantations:**	0. rastera (Weber)	0. lindheimeri (Engelm.)
O. leucotricha	O. lindheimerii	0. robusta (Wendland in Pfeiff.)	
O. robusta	O. engelmannii	0. engelmanii (Salm-Dyck)	
O. cantabrigiensis	O. rastrera	0. megacantha (Salm-Dyck)	
O. rastrera	**Used in multipurpose farmily orchards:**	0. phaeacantha (Engelm)	
O. microdasys	O. robusta (Wendland		
O. lindheimeri	O. streptacantha		

O. engelmannis	**Fodder from fruit and vegetable plantations**
O. azurea	O. amyclaea
O. stenopetala	O. ficus-indica
O. imbricata	Nopalea cochillinifera
O. fulgida	
O. choya	
O. macrocentra	
O. chrysacantha	
O. lucens	
O. duranguensis	
O. tenuispina	

Source: Claudio, Valdez & Osorio; 1997 Felker (1995) and Fuentes-Rodriguez 1991 as stated in Felker (1995)

The fodder or confined livestock system

As mentioned above the cacti used as fodder in Northern Mexico are mostly obtained from wild rangelands. An additional source of nopal comes from specialized forage plantations. In the Central regions the cladodes from pruning from the commercial fruit and vegetable nopal plantations are an additional source of fodder.

In the fodder system, the nopal is cut, transported, placed in piles or spread out on the ground and then slightly burned to remove the spines. The cladodes are subsequently cut in smaller strips manually or on larger farms by special cutting machines. According to Claudio et al., the cacti are mostly cut of at the base of the plant. This hampers the plant's recovery. Burning is either done by gas or kerosene burner. If any kerosene drops are left on the cladodes, the cattle refuse to eat it. (Claudio, Valdez & Osorio 1997, Felker 1995).

In contrast to the spine versions, the spineless versions have to be protected by fencing. In Brazil where about 300000[6] ha. of spineless cacti are planted in the arid north eastern states of Paraiba, Pernambuca and Alagoas, a 1.2 m high wire or wooden fence is sufficient. In northern Mexico and Texas the fencing needs to be more robust "2.4-m-high netwire fence with 5 cm. Mesh at the bottom". (Felker 1995)

In Mexico the typical feeding volumes would be around 30-40 kg per day for cattle and to goats and sheep around 6-8 kg. (Claudio A., F. Valdez & G. A. Osorio 1997).

Although an opuntia diet does decrease animal output (in meat and milk) somewhat, the overall savings in feed costs makes the use of cacti profitable or in the words of Claudio et al.: "The results obtained when cattle are fed with nopal have been shown to reduce the total milk or meat production per animal. However, the cost per unit of production is less. Thus, the utilization of nopal offers a good alternative for feeding cattle during the dry season and for lowering milk production costs."

The use of cactus as a fodder crop in the arid and semi-arid zones of North Africa.

[6] Note: Barbera 1995 states the total hectarage to be 400000.

In North Africa, the use of Ficus Indica as a fodder crop developed rather late. In the 1920's the first fodder plantations of Ficus Indica (f. inermis) were setup for the dairy farms near the big cities along the Mediterranean coast and soon the use of cactus proved it's worth in North Africa or in the words of Houérou (1996):
"In the early 1930s, under the colonial land allotment of Gamouda near Sidi Bouzid, in Central Tunisia, land ownership was only granted under the condition that the contracting beneficiaries, *inter alia*, planted 10% of the allocated land with spineless cacti as an emergency standing fodder crop. This proved to be a very wise governmental decision as those farmers went through a devastating drought in 1946-48 virtually without livestock loss, whilst the small stock in the arid lands was decimated by 70-75%." The potential of Ficus Indica was again demonstrated in the 82-86 drought that hit western Algeria. Thus, with only a mean annual rainfall of 250 mm, enough biomass could be produced to avert disaster.

With about 300,000 hectares under ficus indica cultivation, Tunisia is the largest producer of cactus fodder crops in North Africa. With the aid of the FAO and the WFP on one hand and government loans and subsidies on the other, acreage expanded by about 70,000 between 1970-1975. Similar but smaller schemes were carried out in Algeria with other North African countries following suit.

"These plantations were first established mainly on communal lands but recently more and more were established on mixed crop/livestock farms and private land. Opuntia and shrubs are planted in wide rows allowing cereal cropping (mainly barley) in between. Animals may therefore graze the increased herbaceous biomass between the rows during spring, and stubbles during the summer time. The seasonal supply of feed is then better adjusted to the animals' needs, and livestock feeding is based more on farm resources than on commercial feeds. Indeed livestock farmers, and especially small herd owners, face dramatic difficulties during the frequent drought seasons. They are often forced to sell a large number of their flock in order to buy either rarely available expensive straw and hay or imported cereal-based feeds." (Nefzaoui 1997)

Experience has shown that in Tunisia, restocking with cactus on private lands has been more successful than on communal lands. The communal lands are prone to overgrazing and less well managed (Nefzaoui 1997).

According to Le Houérou (1996) the reasons for ficus' relative strong presence in the western part of the Mediterranean are partly historical and have partly to do with climatelogical factors.

As mentioned earlier, ficus indica, in the Old World was first established in Spain. The expansion of Spanish power into the western part of the Mediterranean was probably the catylizator for the use of the plant in this area. With the fall of the last Moorish bastions in Spain and the subsequent exodus of Moors to their ancestral homeland of North Africa, the crop also found a new home on these shores.

Furthermore, the western part of the Mediterranean, like the genetical homeland of ficus indica on the high plains of Mexico, has a bimodal rainfall pattern of 400-700 mm. The eastern part of the Mediterranean however has a monomodal rainfall pattern resulting in a prolonged dry period (Houérou 1996 & Mondragon-Jacobo et al., 1996).

In the Mediterranean basin, fodder planting density depends on the methods of exploitation harvesting and transportation. 3000-5000 plants per hectare in forage systems or traditional cut and carry fodder systems. Modern mechanized plantations have a lower plant density of 1000-2000 plants per hectare.

Fodder production responds strongly to manure and nitrogen while for the cultivation of fruits, phosphorus in more important. (Houérou 1996). Even under arid conditions with only 200 mm of rainfall the fertilizer effect is quite significant. Indeed, for many crops there is an interactive effect between nutrient and water efficiency. An increase in the supply of nutrients often results in a higher WUE. For soils that are characterized by a lack of soil nutrients, this is not surprising (A. Uzo Mokwunye, A. de Jager and E.M.A. Smaling, (eds), 1996).

Like in Mexico and Southern-western US, the cut and carry system prevents wastage and overgrazing. Harvesting of the cladodes takes place every second or third year, reflecting the trade-off between quantity and quality of the fodder: A larger harvest interval increases the harvest yield but decreases the protein level (a/o.) of the cladodes Plantations are exploitable after 4-5 years and fully grown after 7-10 years. If properly managed the ficus indica plantations can last 50 years (Houérou 1996).

Ficus Indica also plays an socio-economic role in North Africa. In many Arab countries, no official land registry exists and ownership of tribal lands is based on whoever cultivates the fields. Thus cactus is often planted to stake out or solidify a claim on a particular piece of land (Houérou 1996).

Ficus indica as a wind and water erosion control mechanism.

In the Near East cactus also plays an influential role in the fight against erosion. It increases the soil organic matter and nitrogen content of the soil by 40-200% compared to adjacent fields. On the island of Linosa soils under ficus indica seemed to have a 50% higher som (soil organic matter) and nitrogen content than the second highest non ficus indica sampling site (Schiere 2000& Houérou 1996) of the island. Thus the soil structure and texture are enhanced resulting in a lower susceptibility to wind and water erosion. A higher som level also increases the water holding capacity of the soils (Schiere 2000).

The effect of ficus indica hedges as an erosion control mechanism has two components. The first, directly by breaking the speed of the wind and/or water second, indirectly by stabilizing the soil.

According to Houérou (1996) planting cacti shrubs is; "the easiest, quickest, and safest way to rehabilitate them {degraded rangelands}". Degraded rangelands in the Mediterranean have a RUE of 1 to 3 kg $DM*ha^{-1}year^{-1}mm^{-1}$. Land rehabilitated with cactus or saltbushses have a RUE of 10-20 for the arid (200-400 mm) range and 15 to 30 for the semi-arid range (400-600).

Section 2: Productivity of ficus indica and other opuntias

Although the experimental details and data behind these encouraging results are unfornately lacking it is clear from these figures that opuntia's have an immense production potential and that there relative production potential increases, upto about 200mm of yearly rainfall (Houérou 1996).

In 1965 Barientos developed a new forage clone 'Copena F1' which produced a fresh weight of 400 ton freshweight/ha. Blanco (1957) reports yields of 100 to 200 ton freshweight/ha with a 40% harvesting of the plant every two years (Felker 1995) [7].

In a well documented field trail on the effectivity of N and P fertilizer on (a.o.) biomass, Gonzalez (1989) noted a yearly boimass production of 247.5 tons freshweight/ha[8]. Without fertilizer the biomass production under the same conditions was still app. 53 tons freshweight/ha.

In the third year of the experimetn Gonzalez' suffered a drought in whicht the rainfall fell back to about 320 mm per year. Under these conditions and withouth the use of fertilizer, Gonzalez' stil achieved a biomass production of about 26 ton freshweight per hectare.

Also in South Africa, de Kock (1980) showed that local cultivars can obtain yields of 10.5 ton DM /ha with a 483 mm moisture regime. It should be noted however that with opuntia's high drought resistancy and WUE, the mean monthly precipitation figures are more important than the yearly figures (Nobel 1991).

In South Africa experimental fields under natural rainfall conditions (750mm) showed the yields of different cultivars to vary between 2.712 DM t/ha and 4.80 DM t/ha. Only the terminal and sub terminal cladodes where harvested as seems to be the usual procedure in South Africa[9] (Pretorius CC, N.F.G. Rethman & A.B. Wessels 1997)

Kay & Kay, 1990 reported a yield 96 ton/ha of fresh weight on a 'typical' unfertilized 50-ha plantation after 5 years in Southern Texas. This represented a feeding value of US$434/ha.

In South Africa in the area of Uitenhage an average fruit crop from dense wild ficus indica is 12 tons/ha of which 40% was readily acceptable to any picker.

According to Felker a yield of 100 ton Fresh weight can be achieved with the proper management. With a daily opuntia consumption of 50 kg/day, 1 hectare with 100 ton kg would provide a reserve of 2000 animal days. This amount to 5.5 animals per year.

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[7] Barientos' results were achieved with using 100 ton of cow manure/ha, 200 kg N /ha, two harvests, abundant moisture and a spacing of 1*0.25 m. Full experimental details of these trails are not available.

[8] In the fifth year after planting with 2* (223 N & 112 P kg/ha), plot size: 12m*12m, 11 rows/plot, 46 cm apart in row. Yearly rainfall 430mm but fifth year 'above average'. Other: Optimal conditions

[9] Harvesting only the terminal and sub-terminal cladodes results in a much smaller harvest than when the whole plant is harvested (entire biomass production). No data on spacing and moisture

Felker further states that the greatest factor effecting productivity is weed control. Felker measured a 300% increase in O. Lindheimerii productivity with weeding and herbicides. The importance of weeding is further substantiated by Felkers' personal observations in Brazil.

Under optimal experiment conditions in Chile, yields of 50 ton DM*ha^{-1}*$year^{-1}$ were even achieved. (Garcia de Cortazar, Nobel. 1992)

According to Houérou's studies (Le Houérou & Dumont, 1964, Monjauze & Le Houérou, 1965, Le Houérou & Froment 1966, Froment 1970, Delhaye et al., 1974, El Hamrouni & Sarson, 1974, Schweisguth, 1974 Romano 1974, Dechelotte & Romano 1975) yields of 20-60 tons freshweight/ha (3-9 DM ton/ha) are obtainable in arid zones with a mean annual rainfall of 200-400 mm on a deep and sandy soil. Under semi-arid conditions (400-600 mm) in extensively managed conditions yields are in the order of 60-100 tons of freshweight/ha (9-15 tons of DM/ha).

Productivity & water use efficiency

Houérou's figures mentioned in the above paragraph, correspond to a rain use efficiency of 15 to 25 kg of above ground $DMha^{-1}year^{-1}mm^{-1}$. This is 3 to 5 times as much as the best rangeland crops under similar conditions. In intensely managed conditions plantations with cultivation and fertilization the REU can reach a factor of 30-40 and with irrigation the REU can even reach a factor of 50-60 (Houérou 1996).

As already mentioned, rangeland rehabilitated through cactus and saltbushes have a RUE of 10-20 $DMha^{-1}year^{-1}mm^{-1}$for the arid range (200-400) up from a RUE of 1 to 3 $DMha^{-1}year^{-1}mm^{-1}$ for degraded rangelands

The water use efficiency is also quite high. De kock (1980) states a WUE of 1 kg. DM/250 kg H_2O in the Karoo province of South Africa. Houérou & El Barghati (1982) mention a water use efficiency of 1 kg DM/300 kg H_2O[10]. This corresponds to a WUE in between 3.3 and 4.0 $mgDMg^{-1}H_20$. This is about in the same order of magnitude as for water efficient plants such as pearl millet and sorghum. An additional strong advantage of ficus indica is that the plant can obtain it's high WUE under drought and arid conditions. Under these conditions the overall ficus indica water consumption is 3 to 5 five times lower for sorghum and pearl millet (Houérou 1996; de Cock as in Houérou 1996 & Nobel 1988).

The WUE efficiency as stated by Nobel (1988) has already been discussed in the section concerning CAM metabolism. As Nobel discusses the WUE efficiency in net CO2 uptake in mol CO_2/mol H_2O transpiration, it is not practical comparing Nobel's figures to Houérou's. Especially since the exact relationship between CO_2 net uptake and DM plant tissue formation for oppuntias is not known. Table 4 shows the WUE measured according to different criteria as stated in Nobel (1988).

[10] Above ground DM

Over a 24-hour cycle the typical WUE of ficus indica would be 0.0101 CO_2/H_2O, whereas daily WUE under optimal environmental conditions averages about 0.0009 CO_2/H_2O for C_3 and 0.0016 CO_2/H_2O for C_4 plants[11].

For agronomic purposes, the seasonal or in this case annual WUE is more important. The difference between the annual WUE of CAM on the one hand, and the annual C3 and C4 species on the other hand is probably substantially larger than the figures mentioned in the above paragraph as the average environmental conditions over an entire season or year would be less optimal.

Table 4: Water-use efficiency for ficus indica for instantaneous value at midnight, entire nighttime, 24-h period and Annual.

	WUE (mol CO_2/mol H_2O)			
Source of data in brackets	Instantaneous value at midnight	Entire nighttime	24-h period	Annual
O. ficus indica (Acevedo, Badilla and Nobel, 1983; Noble and Hartsock, 1983)	0.0131	0.0119	0.0101	0.0059

Source: Nobel 1988

Nobel (1988) summarizes his studies on the WUE of cacti and agave with the following words: "We can summarize our discussion on how WUE varies among taxa by saying that it tends to be two to six times higher for agave and cacti than for C_3 and C_4 plants."

[11] Note: WUE depends on air humidity and air temperature.

Section 3: Nutritional value

Around the world, the use of opuntias as livestock feed has successfully been established and indeed in many parts of the world, feeding livestock with cacti is part of the local farming tradition[12]. Cacti are used to feed cattle (meat and milk), goats, (meat and milk), sheep (meat and wool), Camels and in some cases also horses rabbits, and hogs[13]. Although this is proof enough that the system is agronomically and economically beneficial for the farmers in arid and semi-arid regions a closer look is warranted.

The feeding value of cacti as fodder is ideal to overcome seasonal or exceptional periods of droughts but not as a permanent and only supply of feed (Claudio, Valdez & Osorio 1997; Felker 1995; Barbera 1995; Losada, Neale, Rivera, et al., 1996; Mizrahi, Nerd, & Nobel, 1997; Losada, Neale, J. Rivera, et al., 1996; Nefzaoui 1996; etc.)

As noted elsewhere, the spiny opuntia varieties first have to have their spines removed before it can be fed to the animals. This can done by burning, manual removal or in some cases fermentation (Felker 1995, Claudio, Valdez & Osorio)

According to Houérou (1996), the spineless ficus indica varieties need no special treatment before being fed to the animals (cattle and sheep). The clochids which are present on all the opuntias are neutralized by the saliva and other juices in the digestive tracts of the animals. This stands in contrast to Felker (1995) who states: "As a result, spines and clochids become lodged in their gastrointenstinal tracts and bacterial infections of these lesions may follow." Maybe this difference can be explained by the difference in the type of fodder. In Texas (Felker 1995) the feed plants are 0. Lindheimeri and in North Africa these plants consists of spineless O. ficus indica varieties.

Opuntias as water reservoir

Under normal circumstances the water content of the cladodes is between 85%-95%. At the end of the summer in North Africa the water content declines to 75%-85% and during extreme water stress the moisture content may drop to 60% (Mizrahi, Nerd, & Nobel, 1997; Felker 1995;Houérou 1996, Felker 1998).

It is not surprising that with such a high water content a substantial part of an animal's water requirements can be fulfilled through opuntias. Indeed Felker 1995 states an intriguing example of the water providing potential of opuntias. During the civil war, oxen had to pull wagonloads of cotton to the southern tip of Texas to escape the union's embargo. The oxen were fed on cactus and subsequently only needed to drink once a week in the winter and twice or three times a week in the summer.

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[12] Mexico, US, Brazil, Chile, Peru, Bolivia, Spain, Sicily, Tunesia, Algeria, Marrocco and South Africa. See else where in the rapport.

[13] Note: Data on hogs is based on only experiment in 1905 (Griffiths). Only one reference to horses was found (Claudio et al.,)

In cactus and other shrub feed trials documented by Le Houérou in 1983 and 1992, the use of cactus decreased water intake for all combinations of cacti with other kinds of feed by at least 50%[14] and reduced water intake to almost zero in winter and spring.

In published (1996) experiments conducted with sheep by Salem, Nefzaoui, Abdouli and Ørskov; "Sheep required practically no drinking water at all when more than 300 g DM of spineless cactus were included in straw-based diets. Similar finding were reported by Terblanche. 1971"

Felker (1995) states that in South Africa sheep don't have to drink water due to the high water content of Opuntia cladodes.

Nutritional value

Table 5: Typical values for cladode composition for use in animal feed

Dry matter content(%)	10-15
Crude protein (% of DM)	5-12
Phosphorus (% of DM)	0.08-0.18
Calcium (% of DM)	4.2
Potassium (% of DM)	2.3
Magnesium (% of DM)	1.4
Energy (Mcal/kg)	2.61
Carotenoids ('mu'g/100 g)	29
Ascorbic acid (mg/100g)	13
In vivo digestibility	
Protein (% of tot. Protein)	72
Dry matter (% of tot. DM)	62
Crude fiber (% of Crude fiber)	43
Organic matter (% of OM)	67
In vitro digestibility	
Dry matter (% of DM is digestable)	75

Notes: In vivo digestibility, values derived from digestibility in cattle
In vitro digestibility, values derived from digestibility in laboratory analysis
Dry matter=Organic matter + ash (minerals oa. mentioned above).
Source: Felker 1995. Data based on 0. lindheimeri (Engelm.)

Table 5 shows the nutritional value of cactus cladodes. According to Mizrahi, Nerd & Nobel (1997): "In nutritional value, cladodes are similar to immature maize silage on a dry matter basis (Maltsberger 1991); they are relatively high in fiber (average of 18%) and minerals (19%), low in fats (1-4%), and medium in proteins (generally 4-8% total, with 1-2% digestible). Digestibility of cladodes is high (72%), and carbohydrates can account for up to 71% of their dry weight". Furthermore they have an important amount of carotenoids, vitamin A and C precursors. The precursor

[14] Daily DM intake of cacti ranged between 0.9 kg and 1.1 kg for free grazing or pen fed ewes in various combinations with other livestock feed.

figures are not particular high compared to other green fodder but in times of drought when no other source of fresh vitamins are available, the caratonoids are a welcome addition Felker (1995).

N fertilization can increase the protein levels in the cladodes and according to Mizrahi, Nerd & Nobel (1997), a clone of Opuntia stricta Haworth has been identified with high nitrogen and phosphorus contents that satisfy the feed requirements of cattle.

In Texas, cottonseed cake is considered a good source of additional protein. It should be noted that in many Francophone Sahelian countries there is a sizable dry land cotton production sector (a/o. Burkina Faso, Mali, Niger etc) (Schiere 2000b).
The exclusive use of cladodes can cause diarrhea after about 6 weeks in cattle and after about 8 weeks in sheep. This problem can however easily be overcome by adding about 1% of the animal's bodyweight in roughage to the diet. This roughage should have a minimum DM content of 35% (hay, straw browse grazing). Houérou (1996). Mizrahi, Nerd & Nobel (1997) state that the diarrhea can be avoided by gradually increasing the cactus proportion in the diet.

Nefzaoui (1997) and Houérou (1996) both studied and suggested using saltbushes (Atriplex spp.) to supplement the cactus diet. Saltbushes have a high nitrogen content, are endemic to North Africa and are drought resistant.

Section 4: Potential Ecological constraints

It cannot be stressed enough that no reference to actual cactus growing or cactus experiments in the Sahel can be found. Several authors have explicitly or implicitly mentioned the benefits cactus might have for the Sahel. Felker (1995) and Houérou (1996) suggested several ecological constraints that could be the underlying factor of this blind spot in botanical and agronomic science.

Soils

According to Noble (1995) the ficus indica commonly grows on dry sandy loam soils. Houérou (1996) states the best soil types for cactus growing as 'sandy'. Inglese (1995) mentions a wide range of soils on which the species occurs: "from Vertisols, Luvisols and Feozem in Mexico: to Lithosols, Regosols, Cambisols and Fluvisols in Italy. Soil pH fluctuates from sub-acid (Luvisols in Mexico) to sub-alkaline (Lithosols in Italy) showing the adaptability of the species. In general all the authors agree that opuntia's need well drained soils with a low clay content. Inglese mentions a clay content of 20%.

In the Sahel sandy soils cover vast tracks of land. They are slightly acidic with a pH of 6.0 to 6.5 and often labeled as Cambic and Luvic (Houérou 1983). Nobel (1995) mentions a nitrogen level of 0.07% at which the maximal net CO_2 uptake is halved. The soil levels of P and K leading to half of the maximal growth of opuntias are relatively low: 5 and 3 ppm. Thus, with the Sahel's notoriously low nutrient status, cactus growth is sure to be limited (Houérou 1988, FAO, 1996. *Food production and environmental impact*, Mokwunye, de Jager and Smaling, 1996). No reference was found to any absolute minimal nutrient levels necessary to sustain cactus plant life.

Nobel's fundamental research into the cactus production enigma has led to a formula in which the effect of nutrient limitation can be calculated. Hence a regional 'limiting nutrient productivity index' can be calculated for various parts of the Sahel. This modeling exercise will be a useful tool to estimate the potential cactus production in the Sahel.

Unlike most arid environments around the world, the Sahel is not hampered by high salinity levels. The salinity problems that do exist are often local and the result of faulty irrigation procedures (Houérou, 1983). This is fortunate as the opuntia is not a very drought resistant plant. For those areas in the Sahel where salinity is a production constraint, gypsum (Ca.) can be used to negate the ion toxicity[15] in sandy loam soils (Mizrahi, Nerd & Nobel, 1997).

Mizrahi et al. (1997) further suggest using the few available salt tolerance cultivars for breeding programs for saline areas. In this respect a study by Ferreyra, Aljaro, Ruiz and Rojas (1997), could be interesting. In a Ficus Indica irrigation system in central Chile which uses relative saline irrigation water. Ferreyra and his companions reported a salinity of 24 dS/m without any major effect on the plant. This stands in

[15] Salinity stress has two major components: water stress and ion toxicity. Cacti are relatively tolerant of water stress but are sensitive to salinity (Mizrahi, Nerd & Nobel, 1997).

contrast to Berry and Noble (1985)[16] who mentioned that a ca. 14 dS/m (about 0.149mM NaCl.) decreased shoot growth by 60% in their observations.

This higher salt tolerance mentioned by Ferreyra (1997) could be due to farmer selection and experimentation with local ficus indica plants and hence the selection and breeding of a salt tolerant variant[17].

Temperature

The maximal thermal limit in the field has been little documented. Felker stated that perhaps the continuos high temperature experienced in the Sahel is an impeding factor for opuntia establishment (Felker 1995). According to Houérou (1996) however, there are 'thriving' O. Ficus indica plantations in Azizia, Libya where maximum recorded temperatures reach 50° C or even 58°C, the highest temperatures recorded on earth under standard meteorological shelter. The mean maximum of the hottest month is in the order of 38-45°C. Surely, these temperatures are much higher than what can be experienced in most of the Sahel.

Barbera (1995) further states that ficus indica is also grown in Southern Marocco which high temperatures are endured as well. Under experimental conditions Nobel (1995) measured the CO_2 uptake of ficus indica under different temperature regimes. With a day and night temperature regime of 30°/20° C[18]. CO_2 uptake is only reduced by 18%. With a temperature regime of 35°/25° C, CO_2 uptake is reduced by 60% from its maximal value. Nobel goes on to state that Opuntias are generally well adapted to tolerate high temperatures and in laboratory experiments, ficus indica was survived a temperature of 65° for more than an hour.

Atmospheric humidity

According to Houérou (1996) the atmospheric humidity is the factor blocking the use of ficus indica cactus in the Sahel. Houérou (1996) states that as a CAM plant opuntia is sensitive to a high atmospheric saturation deficit. No further details were given on the precise effect of a low air humidity on oppunitias or cam plants. Houérou's empirical observations led him to conclude that ficus indica is eliminated from areas where the average relative humidity remains below 40% consecutively for more than a month as is the case in the Sahel.

Table 6 taken from Leroux (1983)[19] shows typical Sahelian air moisture values for the Sahel. The air moisture is relatively uniform for the whole region with exception of the Atlantic coastal zone.

Table 6. Monthly mean, minimum and maximum air moisture (%) for the Sahelian region.

Month	J	F	M	A	M	J	J	A	S	O	N	D	YR
Minimum	20	15	10	10	20	30	40	60	40	30	20	20	25

[16] as in Ferreyra et al. (1997)
[17] Note: there were also other reasons mentioned for this high salt tolerance.
[18] Note: For cam plants such as opuntias, the nighttime temperature is far more relevant than day temperatures.
[19] Leroux (1983) as stated in Houéroux 1988

Maximum	30	25	20	25	40	60	70	85	70	60	40	30	45
Average	25	20	15	17	30	45	55	72	55	45	30	25	35

Source: Leroux (1983) as stated in Houérou 1988

As can be seen in table 5, the average air humidity is lower that 40% for 7 months. This is a major point that warrants further experimental investigation:

Felker (1995) mentions cactus plantations and forage stands in Northwest Texas, an area known for its dryness. And according to Nobel (1991) there are agave (also a cam species) in the Sonoran Desert, California. Various other authors mention the use of opuntias in the south western US and northern Texas under dry conditions (see elsewhere in this study). Furthermore Brutsch, (1997) mentions thriving ficus indica communities in Tigray, a dry province in northern Ethiopia. Unfortunately, only an abstract from Brutsch article was available making it difficult to provide more information on ficus indica cultivation in Tigray. It should also be noted that Houérou's observations focus on O. Ficus Indica and not on other Opuntia species that are commonly used as forage and fodder crops in the America's.

No other sources of literature could be found on the constraining effects of low air humidity. Maybe although unlikely, the low air humidity in combination with the high temperatures could result in a too high transpiration rate or too low WUE. If this was the case, the effects on transpiration or WUE

would probably have been noticed in other parts of the world. Furthermore the cactus is a drought resistant plant with extremely low values for minimal water vapor conductance (0.2 mmol $H_2Om^{-2}s^{-1}$) due to an nearly impervious cuticle, low frequency and tight closure of the stomata. Nevertheless, this point should be investigated.

This study therefore suggests the first step to any feasibility study is to elaborate and expand Houérou's empirical observation to the whole world and all the opuntia species. For all the dry areas in the world where opuntias grow either cultivated or in the wild, the air humidity should be studied and categorized. This should provide more data on the humidity factor. It could also result in a potential world opuntia map. Apart from the Sahel there are plenty of other dry areas that could benefit from opuntia's potential such as the Middle East, India etc.

Section 5: The modelling option; Some Notes

After some preliminary studies of the modeling work done by Nobel and others, it can be concluded that the modeling principles are still in it's experimental phase and that substantial amount of work needs to be done to uncover the enigmas behind the growth and development of oppuntias. This is especially true for the nutrient part of the model. As the Sahel is notorious for its low soil nutrient status (See section 4) it is doubtfull that the current state of knowledge could result in accurate model simulation of the production potential of oppuntias in the Sahel. Prof. Nobel pionering work needs to be continued.

This section briefly discusses the current state of the principles and how they can be adapted to the Sahelian situation. This part of the study draws on Nobel's 'Environmental biology of agaves and cacti, 1988' and the following five articles: Garcia de Cortazar,Acevedo & Nobel, 1985; Berry & Nobel 1985; Nobel, 1989; Nobel, 1990; Nobel 1995.

Rudimentary Description of the model.

The basic version of the model is based on three productivity indixes, a temperature index, a PPDF (productive wavelengths of 400-700 nm) index and a water index. These three indices are multiplied with each other to form the environmental production index. All three indices are primarly based on experiments in which the effect of one of the indices on net CO_2 uptake was measured.

Thus the production index is a simplification in which the interactive effects between the various indices are not taken into account. In environments where only one of the production factors is limiting the model apperently works well in pridicting productivity. It can be questioned however if the model works well in environments where two or more factors are strongly limiting in some point in time and were a strong interaction can be expected. The Sahel is such an environment. Temperature (too high), and water would probably both be a significantly limiting factor at the end of the growing season and in the dry season.

The environmental production index looks like this:

$EPI = H_2O$ Index*TEMP Index*PPFD Index. (Equation 1)

With this production index the annual productivity of a commercial ficus indica plantation in Chile was predicted within 5% when the stem area index (total area of both sides of the cladodes per unit ground area) was 1.4. It should be noted that the water, temperature and nutrient conditions were near optimal values.

The water index is maximal when the soil water potential exceeds –0.5 Mpa, below which the water potential decreases with time as the soil dries, becoming 0.00 after 40 days. Noble used conventional soil water balance for rainfall, evapotranspiration, perculation and representive hydraulic characteristics. Thus for the water index different soil types (texture) from the Sahel can be used. If no daily water fall patterns are available, climate models to generate daily rainfall patterns from monthly rainfall patterns are available.

The temperature index was determined from its temperature response curve for total daily net CO_2 uptake, which is maximal at an average nighttime temperature of 15°C. Thus, different minimal night temperatures for different parts in the Sahel can be used. If no night temperatures are available, day temperatures can be used with a 'average reduction' to get night temperatures.

To calculate the PPFD index, it is assumed that the plant spacing and planting density are optimal. Thus, for 33° latitude the plants were arranged in rows north south with the cladodes facing east west. The rows are spaced at 0.25m intervals along the rows, resulting in a stem area index of 4.0. The relationship between PPFD and CO_2 uptake is determined by laboratory experiments.

As the PPFD is based on optimal density and cladode orientation towards the sun, different productivity scenarios for different uses of opuntia should be introduced. In the Sahel, the cacti can also be used as erosion breaks along contours or faced squarely against the prevailing wind direction. Thus, their row orientation won't allow for the maximal radiation interception. By planting the plants around gardens and plots, the maximal planting density probably won't be attainable. This can be incorporated in the modeling by developing difference PPFD indices for one site. Each index represents an option (such as maximal wind control or maximal cladode production). The model calculates the PPFD index under optimal planting densities. How the model can be adapted to calculate the PAR for les than optimal planting densities or less than full canopy cover is not known. This is a major modelling constraint as will be explained further on in this section.

Nutrients and Salinity

For Nobel's mind catching article about worldwide opuntia production (Nobel 1991), only the temperature, water and PPDF indices were used.

One of the main limiting factors in the Sahel is nutrient availability. Obviously this factor has to be included in any productivity assessment for this region of the world. Based on laboratory experiments Nobel derived the following equation.

$$(1.418 + 0.348 \ln N) * [1 + 0.1195 \ln (P/60)] * [1 + 0.117 \ln(K/250)] * (B^{0.213}) * (1 - 0.00288\ Na) \qquad \text{(Equation 2)}$$

The laboratory experiments were seperated into a few different tests. In each test the nutrient content of one mineral was tested. Thus no interaction effects between the different minerals were analyzed. Furhtermore the tests consisted of increasing the supply of a nutrient from a given level; no lower limiting nutrient levels were tested. As mentoined before the interaction between the nutrients and other production factors were also not tested.

Furthermore, Nobel states that the nutrient factor can be included into the general productivity index by multiplying equation 1 and 2. This implies that a lack of nutrients further limits growth even when the growth of the plant is already limited and thus the need for more nutrients. This automatic interaction is questionable.

The use of existing mechanisic models for assessing potential productivity.

The current state of knowledge of the underlying fundamentals is probably still too basic for the application of existing models. Nevertheless, mechanisic models would be a powerfull tool to asses the potential productivity of the 'new' crop for arid environments.

The first major constraint to using mechanistic models is that the interactions between production factors such as water, temperature and nutrients is still not properly understood. Especially for environments where more than one of these factors is severly limiting such as the Sahel or other hot, arid environments the interactions could proove to be substantial. Especially the way soil minerals effect the CO_2 uptake of 'desert succulents' such as oppuntia's is incomplete.

A second major constraint is that opuntias have complex three dimensional structures in which the number of cladodes can change rapidly as dry matter from underlying cladodes is translocated to the new cladodes. The dry-weight/volume ratios differ from those of the older ones. The cladodes often grow at a vertical angle and have two photosynthetic survaces. Although once full canopy cover is reached, it should be easier to model PAR as most of the PAR on a given horizontal plane in the crop will be absorbed.

Untill full canopy is reached however, modelling the PAR will be difficult as from the moment of planting the time an oppuntia crop reaches full canopy the plants changes its morphology quite radically. This ofcourse effects PAR. Furthermore plant spacing will probably be less dense in nutrient and water limited environments. This could result in a longer period of time untill full canopy cover is reached.

Maybe a few different plant establishent stages could be developed, with a corresponding PAR for each stage. The PAR for each stage could be estimated by using ray tracing computer models.

Section 6: Conclusions and possible feasibility.

From this brief literature study it can be concluded that the production potential of opuntia cactus for the Sahel is immense. Its three major assets are: A high drought tolerance, a high WUE and a relative well developed ability to thrive on nutrient poor soils. Unfortunately there has been no experimenting or testing done on Opuntia for the Sahel.

The main value of opuntias for the Sahel is as a buffer to alleviate the dry period or exceptional periods of drought. The long droughts in Mexico and in Tunisia have proven opuntias value as a live-saver for animals. It's a cheap, efficient and highly economical source of energy and water.

The nutritional value is too low to sustain animal populations year round however. Cottonseed cake or old man's saltbush (a drought resistant tree endemic to North Africa can alleviate the worst nutritional deficit of a lack of nitrogen. In dry times however, when there is no other green fodder around however, the opuntias can be a valuable additional source of (pre-) Vitamin A and C for the cattle.

The use of opuntias as anti desertification tool to combat wind and water erosion is the second important aspect. It should be noted that tens of thousands of hectares have been planted in Tunesia to combat the degradation of rangelands that is the result of excessive grazing and erosion.

The use of opuntia as food crops can be seen as extra additional benefit. Cactus fruit cultivation is contrary what many people think a knowledge intensive practice. The main focus should be on fodder/forage production as this relieves the most pressing problems and is the simplest system.

Several environmental factors have been mentioned as the possible constraint for opuntia (ficus indica) production. Temperature and lack of moisture does not seem to be the problem. Lack of nutrients will probably decrease production but won't kill the plant. The wide range of soils, opuntia is currently cultivated on, shows that the opuntia won't have major problems adapting itself to sandy nutrient poor soils in the Sahel.

The extreme dry air humidity in the Sahel could be the constraint that impedes ficus indica cultivation. This needs to be properly investigated. Houérou (1996) made his humidity observations and negative conclusion for ficus indica not for all the opuntia types. In many dry parts of the US and Mexico (such as the dry Sonoran desert) other opuntia crops are the main cactus fodder/forage crops. The humidity factor for these crops is not known and to the best of my knowledge not mentioned.

Various research and breeding strategies have been suggested to increase the use of opuntias (especially ficus indica) worldwide with no reference to humidity. Thus, this aspect has absolute priority.

The first step in a Cactus for the Sahel project should be to analyze the monthly average, maximum and minimum air humidity levels for <u>all</u> the regions in the world, where opuntias grow. This might illuminate any possible lower limits to air humidity for the cultivation of opuntias. The results could then be compared to the humidity levels of the Sahel and clarify Houérou's observations about the humidity constraint. Furthermore such an agro-ecological map can be also be used for other arid environments around the world.

The second step would be to try to adapt an existing mechanistic model to oppuntia cultivation. This could shed some light on the production potential for the Sahel. But as mentioned before the existing state of knowledge would probably severely limit the scope and validity of such a model. Especially, the nutrient part of the model is still very rudimentary. As the lack of nutrients is one of the main production obstacles in the Sahel, this issue can't be overlooked. In this case the second step would have to incorporated into the third step; the establishment of field trails. Or to put it more precisely the third step would have to adapted in such a way as to provide more knowledge into the basic fundamentals of oppuntia production and development. Especially the interaction between the production factors under limited conditions needs further attention.

The third step and most important step is to set up field trials. As there is no literature available to relieve this lack of knowledge there is no other option. Humidity should be at the center of the field trail with additional attention allocated to fill the knowledge gap mentioned in the second step.

Northern Senegal's coastal zone might be an interesting setup area. The coastal area is characterized by a humid climate whose influence declines rapidly further away from the coast. Thirty kilometers inland the climatic influence of the coast is negligible. Thus over a stretch of thirty kilometers different field trails can be set up under different air humidity conditions (Houérou 1996).

The selection of cultivars and varieties should come from the dry regions of the North America and possibly include some South African drought resistant varieties. The selection criteria should foremost be to withstand very low air humidity.

Thus the field trails will have two main goals. First of all to test the potential of different oppuntias for the Sahel directly and second to facilitate the development of mechanistic models by providing a more fundamental insight to oppuntia production in limited environments. The latter point could provide a valuable tool for the assessment of oppuntia productivity in other arid parts of the world.

An integrated system approach; some thoughts

An interesting point for future research that can be incorporated into the project is the use of opuntias in combination with phosphate and nitrogen, to which opuntias react quite strongly. Rock phosphate can be obtained locally in some Sahelian countries. This could mitigate the destructive tandem of lack of nutrient and low and erratic rainfall. If this is possible, the stranglehold of low productivity that holds the Sahel in its grip just might be loosened a bit. Extra opuntia fodder could result in more livestock and thus in more manure. This manure could then be used on the local farming plots. Thus more manure would not only result in higher nutrient values but also in higher som values in general, increasing the water retention capacity of the soil.

By using opuntias as protective hedges around the plots opuntias productive powers could be used to combat wind and water erosion. A similar integrated farming system is observed on the small Italian island of Linosa (Schiere 2000A). From an analytical point of view, this system would make it possible to use the positive interactions between nutrients and water, the synergy between adapting various components such as anti-erosion control, livestock and cropping subsystems into a larger whole. Such a system holds much in store for all the (semi-) arid regions in the world where but obviously, there is still a lot of research work to be done.

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Areas of future research:

(based on a discussion with prof. Rabbinge)

This preliminary research into using cactus as a fodder crop for drier areas has brought some areas to light that need further investigation. Below is a list of points that should be scrutinized in more detail:

1. The effects of relatively warm night temperatures extended over relatively long periods of time on oppuntias should be investigated. The relative high nighttime temperatures in the Sahel extended for periods of up to two months could be a strong detrimental effect hampering the establishment of oppuntias in this region of the world. In this respect an eco-physiological map detailing the average and extreme climatological data (o.a.) of the oppuntia areas in Mexico, the US, Australia, Mediterranean basin area, Southern, Eastern should be made.
2. The eco-physiological map mentioned in the first point should further be used to investigate other potential production areas. Arid areas in the Middle East, India, South America also stand to gain from this 'new' crop.
3. More information should be gathered to scrutinize the high WUE and growth potential. The figures gathered from the different sources are difficult to compare. The oppuntias are grown under different climatelogical circumstances and agronomic conditions. This makes the proper extrapolation of WUE and productivity figures to the Sahel an uncertain exercise. Perhaps some climatelogical modeling can be used to compare and analyze the different growth circumstances.
4. In his work Houérou mentioned that the relative low air humidity as one of the reasons why ficus indica does not grow in the Sahel. This should be further investigated as conventional theory suggests that there are more important factors governing the WUE and productivity of ficus indica than air humidity.
5. More detailed information concerning Ficus Indica's role as a lifesaver during the droughts of 1947-1948 in central Tunesia and in western Algeria in 1982-1986 should be obtained. The sources Houérou (1996) lists were not available in the Netherlands at the time of writing.
6. The fundamentals of oppuntia production are still not understood well enough to develop a mechanistic oppuntia model. Especially the interactions between various production factors such as the water, nutrients and temperature should be investigated. In hot dry environments these interactions could be considerable.