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Land evaluation for irrigated rice in the West African Sahel

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Abstract
Land evaluation of the West African Sahel is carried out for irrigated rice at small and at semi-detailed scale. A general overview is obtained by applying both a qualitative and a parametric method, based on the dominant soil units of the FAO/Unesco Soil Map of the World. To highlight the heterogeneity of the rice growing environments, the parametric method is also applied to a sample area of the Senegal Valley. Implications of the soil variability on crop water requirements are investigated, using the water management model BIRIZ.

Key land characteristics are inventoried using the fertility capability soil classification (FCC) system. Most common soil constraints in the Sahel are: limited soil depth, erodibility, soil and high phosphate fixation. The qualitative method leads to a less stringent evaluation than the FCC-based parametric approach Lowland soils are classified as the most suitable for irrigated rice in the qualitative method. Consequently, no differentiation comes out for the major basins in the Sahel. According to the parametric evaluation, most suitable dominant soil units are found in the Chad basin and, in the inner Niger delta and along some of the Niger tributaries. The study of the Senegal Valley reveals the complexity of the interactions between soil environment and water management. Higher located, lighter textured soils require lower investment but may lead to unsustainable farming systems. Irrigation schemes based in the back-swamps require higher investments but may improve the soil quality when properly managed.

Introduction

Land evaluation entails the collection and interpretation of soil, vegetation, climatic data and other aspects of land so that constraints for specified kinds of use can be identified. A direct interpretation of a soil map enables a qualitative assessment. With the advent of micro-computers, process-based modeling linked to geo-referred databases is increasingly used for quantitative assessment. Entire quantitative analysis of land suitability however requires sophisticated models and a host of accurate data (Driessen and Konijn 1992). Soil suitability is a more restrictive term, and indicates that the evaluation is mainly based on soil properties.

Land evaluation studies in the West African Sahel have been limited in the past to the overall assessment of the population carrying capacity (FAO 1982) and to ad hoc studies of specific areas for the purpose of agricultural development projects. Andriesse and Fresco (1991) presented a general characterization of the rice-growing environments in West Africa. Their classification is based on climate, soils, toposequence, land types and rice cropping systems, and is essentially qualitative. A general state of the art on inland valley agro-ecosystems in West Africa has been provided by Windmeijer and Andriesse (1993). Andriesse et al. (1994) presented a multi-scale description of the inland valleys in West Africa. These studies were all confined to the zones with a growing period longer than 90 days. Hence, they partly left out the Sahel zone, taken here as the zone with a growing period between 75 and 180 days.

In a preceding paper (Deckers et al. 1995), a review of the soil patterns in the different geomorphological regions of the West African Sahel was given. How these soil patterns translate in terms of soil suitability for irrigated rice in the Sahel is the focus of this study. The option was made to give an overview of the whole Sahel based on the FAO/Unesco Soil Map of the World, rather than to limit ourselves to areas along the main streams. The Soil Map of the World is the most detailed and ready available inventory of the natural resources covering the whole area. If we would only retain the areas in the vicinity of the major streams, areas with minor water sources but with reasonable potential would "a priori" be left out. A multi-scale approach is taken here, in order to provide a general view and to highlight the heterogeneity of rice-growing environments.

Materials and methods

Soil suitability for irrigated rice in the West African Sahel was assessed for the dominant soil units (DSUs) based on the digitized version of the Soil Map of the World (original scale 1/5 000 000; FAO 1991). This was done according to two commonly used methods: (i) a qualitative assessment of the soil mapping units in terms of major soil limitations and landscape features; and (ii) a parametric assessment whereby key land characteristics of the DSUs are weighed. Parametric methods are transitional between qualitative and quantitative models (Driessen and Konijn 1992).

To illustrate the effect of the generalization, as a consequence of retaining only the DSUs of a small scale map (1/5 000 000), the parametric method is also applied to a sample area of the Senegal Valley south of Podor (sheet Podor 3a, scale 1/50 000; SEDAGRI 1969). The study area (11.8 thousand ha) was selected for its representativeness of the Senegal Valley. A typical soilscape of the Senegal Valley, including back-swamps, levees, breakthrough delta, river bank, red dunes and marine terraces as described by Deckers et al. (1997), are found in the study area. The water requirements of five distinct soil types were calculated using the water management model BIRIZ (Raes et al. 1995) for well leveled fields.

The soil types were: Eutric Fluvisols - clayey, non-saline in a backswamp; Salic Fluvisols - clayey, saline in a backswamp; Eutric Fluvisols - poorly drained, non-saline on a low levee; Eutric Fluvisols - moderately drained, non-saline on a low levee; and Eutric Fluvisols - sandy, on a breakthrough delta.

All operations were performed on IBM-compatible micro-computers. The geographical information system Arc/Info 3.4D (ESRI 1990) was used for handling the geographical information.

Qualitative assessment of soil suitability for irrigated rice

The dominant soil units are grouped into three classes on the basis of soil properties and landscape features, deducted from the map. The class definitions are given in Table 1.

Parametric assessment of soil suitability for irrigated rice

In the parametric method, soil suitability is appraised by a formal weighing of key land characteristics (LCs) for a specific land utilisation type (LUT). The overall assessment is

Table 1. Soil suitability classes for irrigated rice in the West African Sahel related to landscape features.

Class	Denotation	Soil properties	Landscape feature
I	Suitable	moderately or poorly drained, and good fertility status	lowlands along rivers, lakes and depressions
II	Suitable with limitations	moderately or poorly drained but with salinity, sodicity, plinthite, ferrolysis, or acidity	lowlands along rivers, lakes and depressions
III	Not suitable	well to excessively drained and/or with sandy or stony texture	uplands far away from water sources

usually obtained by multiplying relative scores attributed to each land characteristics. The multiplicative model has the advantage that it observes the law of minimum. The resulting index allows a ranking of the land units for the given land utilization type (Driessen and Konijn 1992). The key land characteristics were identified following the Fertility Capability Soil Classification (FCC) system (Sanchez et al. 1982).

The fertility capability soil classification system

The FCC system consists of three levels: (i) type (surface soil texture), (ii) sub-strata type (subsurface texture) and (iii) modifiers, presenting specific constraints. The combination of this information leads to a general fertility capability classification.

The surface soil texture (type) of the DSUs can directly be derived from the FAO soil mapping units which gives the soil texture classes: S = sandy topsoil, loamy sands and sands (by USDA definition), (corresponding to coarse textured soils in the FAO legend); L = loamy topsoil, < 35% clay but not loamy sand or sand, (medium textured soils); C = clayey topsoil, > 35% clay, (fine textured soils); and O = organic soils, > 30% organic matter to a depth of 50 cm or more (not used in what follows, as Histosols are not occurring as DSUs in the Sahel).

The texture classes of the subsurface (sub-strata type) can be inferred from the 'FAO soil units' definition, as a function of profile development. A simplified definition of the modifiers of the FCC system is presented in Table 2. The status of the modifiers could be derived from the soil units definition. A boolean classification was used to characterize the properties of the DSUs. This is presented for a sample of the DSUs in Table 3.

By combining the information on the texture of the surface, the subsurface and the slope, a quick assessment of the soil erodibility was obtained, following the procedure proposed by Sanchez et al. (1982). Medium textured soils are generally considered more sensitive than fine textured soils which in turn are considered more sensitive than coarse textured soils. Soils where coarser material is overlying fine materials are assumed to be more sensitive to erosion.

Soil suitability for irrigated rice

Soil suitability for irrigated rice was assessed by weighing the physical and chemical land characteristics. Scores on an ordinal scale (ranging from 0.1 to 1) were attributed to each of the land characteristics (Table 4). A score of 1 is given when a characteristic is not a constraint, else a lower score is given, depending on the severity of the constraints. Reference was made to soil requirements available in literature (FAO 1978; Sys 1985; EUROCONSULT 1989). In the

Table 2. Simplified definition of the FCC modifiers.

Symbol	Modifier
g	gley
d	dry (Ustic, Aridic, Xeric soil moisture regime)
e	low cation exchange capacity
a	Aluminum toxicity or $pH(H_2O) < 5$
h	acid (Al-sat 10-60 % or $5 < pH(H_2O) < 6$)
i	high P-fixation by free iron
x	X-ray amorphous clay minerals (allophane dominance)
v	swell and shrink properties (vertic soils)
k	low K reserves
b	basic reaction (free $CaCO_3$ or pH >7.3)
s	salinity ($EC \geq 4$ dS m^{-1})
n	natric (≥ 15% sodium saturation)
c	cat clay ($pH(H_2O) < 3.5$)
'	gravel, interpreted here as shallow soils or soils with a stony, lithic petric or petroferric phase
%	slope class following the FAO class symbols: (a) = 0 - 8%, (b) = 8 - 30% and (c) > 30%

Note: see Sanchez *et al.* (1982) for full definitions.

Table 3. Characterization of the dominant soil units in the West African Sahel (shortened from the original list of 32 for this illustration).

Soil unit[a]	SST[b]	Modifier[c]												
		g	d	e	a	h	i	x	v	k	b	s	n	c
Eutric Gleysols	-	1	0	0	0	0	0	0	0	0	0	0	0	0
Eutric Fluvisols	-	0	1	0	0	0	0	0	0	0	0	0	0	0
Calcaric Fluvisols	-	0	1	0	0	0	0	0	0	0	1	0	0	0
Thionic Fluvisols	-	1	0	0	0	0	0	0	0	0	0	0	0	1
Pellic Vertisols	C	0	1	0	0	0	0	0	1	0	0	0	0	0
Chromic Vertisols	C	0	1	0	0	1	1	0	1	0	0	0	0	0
Solodic Planosols	L/C	1	1	0	0	0	0	0	0	0	0	1	0	0
Orthic Solonchaks	-	0	1	0	0	0	0	0	0	0	0	1	0	0
Orthic Solonetz	L/C	0	1	0	0	0	0	0	0	0	0	0	1	0
Cambic Arenosols	-	0	1	1	0	0	0	0	0	0	0	0	0	0

[a] according to the FAO/Unesco legend (FAO, 1974).
[b] SST = sub-surface texture; C = clay; L = loam; / = or; - = undefined.
[c] see Table 2 for definition.

Table 4. Scoring of the land characteristics for irrigated rice.

Land characteristic	Score				
	1	0.8	0.5	0.3	0.1
Slope	a	a/b	b	b/c	c
Texture	C	L/C	L	L/S	S
Depth (')	0	1	-	-	-
Swell & shrink properties (v)	0	1	-	-	-
Drainage (g)	1	-	0	-	-
Low CEC (e)	0	-	1	-	-
Low K (k)	0	-	1	-	-
Acidity (h)	0	1	-	-	-
Al toxicity (a)	0	-	1	-	-
P fixation (i)	0	-	1	-	-
Acid sulphate (c)	0	-	1	-	-
Basic (b)	1	0	-	-	-
Salinity (s)	0	-	1	-	-
Sodicity (n)	0	-	1	-	-

Legend: Slope classes: a = 0 - 8%; b = 8 - 30%; c = > 30%; Texture: C = clay; L = loam; S = sand; / = or; 0 = not present, 1 = present.

Table 5. Demarcation of soil suitability classes for irrigated rice.

Class	Rating (r)
Highly suitable (S1)	$r \geq 0.8$
Moderately suitable (S2)	$0.8 > r \geq 0.6$
Marginally suitable (S3)	$0.6 > r \geq 0.5$
Not suitable (N)	$r < 0.5$

to salinity, pH range between 4.0 and 7.5, high tolerance to water logging.

A few examples will show how the scores were attributed. A poorly drained soil is not a problem for irrigated rice, therefore it gets a score of 1; otherwise it gets a score of 0.5. In the cases where a soil characteristic implies some minor negative effect, (e.g. swell and shrink properties, or limited soil depth) a score of 0.8 is given. When a property is estimated to be a serious disadvantage a score of 0.5 is given (e.g. slope of ≥ 8%), or even lower when worse. The soil moisture regime (d) was not taken into account in this calculation. As proposed in the

Table 6. Soil suitability classification for irrigated rice in the West African Sahel.

Suitability	Dominant soil unit [a]
Class I	Eutric Fluvisols, Calcaric Fluvisols Eutric Gleysols, Humic Gleysols Pellic Vertisols, Gleyic Cambisols
Class II	Thionic Fluvisols, Chromic Vertisols, Eutric Planosols Gleyic Solonchaks, Orthic Solonchaks, Orthic Solonetz Vertic Cambisols, Gleyic Luvisols, Plinthic Luvisols
Class III	Cambic Arenosols, Ferric Arenosols, Luvic Arenosols Eutric Cambisols, Calcic Cambisols, Haplic Yermosols Orthic Luvisols, Chromic Luvisols, Ferric Luvisols Eutric Regosols, Solodic Planosols, Ferric Acrisols Eutric Nitosols, Dystric Nitosols, Haplic Phaeozems Lithosols, Dunes or shifting sands

[a] according to the FAO/Unesco legend (FAO-Unesco 1974).

original FCC system it is too crude for application in the Sahel. Moreover for irrigated rice it is of little relevance.

By multiplying the individual scores, indexes ranging from 0.0016 to 0.8 were obtained. To facilitate further interpretation - but without affecting the ordinal rating - these indexes were re-scaled by a linear transformation such that the lowest index corresponded to 0.30 and the highest to 0.95. These ratings were subsequently grouped into four soil suitability classes as defined in Table 5.

Results and discussion

Qualitative assessment

Table 6 gives the breakdown of the dominant soil units (DSUs) of the Sahel in three suitability classes, based on inherent soil properties and landscape features. Their geographical distribution is presented in Map 1.

The most suitable soils (Class I) for irrigated rice are Fluvisols, Gleysols, Vertisols and Cambisols in alluvial (14% of the Sahel). They occur in the Rio de Oro area in the Senegal Delta and Valley, the alluvia of the Sine Saloum and the Gambia rivers (Deckers et al. 1995). In the Taoudenni basin, Gleysols account for the larger share of the soil suitable for irrigated rice. In the basement complex, the alluvia surrounding the Nazinon and the Mou-Houn rivers are suitable for rice as well as the lowland Vertisols in the Chad Basin. At this scale no distinction can be made however of the flooding hazard which may be a serious problem in certain lowland systems, e.g. in the inner delta of the Niger river.

Soils presenting serious limitations for irrigated rice (Class II) cover 174 thousand km^2 or 10% of the West African Sahel. Typical soils in this category are Solonchaks and Thionic

Fluvisols in the Senegal Delta, the Plinthic Fluvisols of the upper Nazinon/Mou-Houn river systems and Eutric Planosols surrounding lake Chad. Less suitable soils may also be in upland position (e.g. Chromic Vertisols) where the distance to the water source becomes a constraint.

Seventy-six percent of the land (1328 thousand km²) in the West African Sahel is classified as unsuitable for irrigated rice (Class III). It encompasses land units which are too far from water sources (e.g. Ferric Acrisols), or coarse textured soils (Arenosols) or soils affected by severe stoniness (Lithosols).

Parametric assessment

Soil constraints

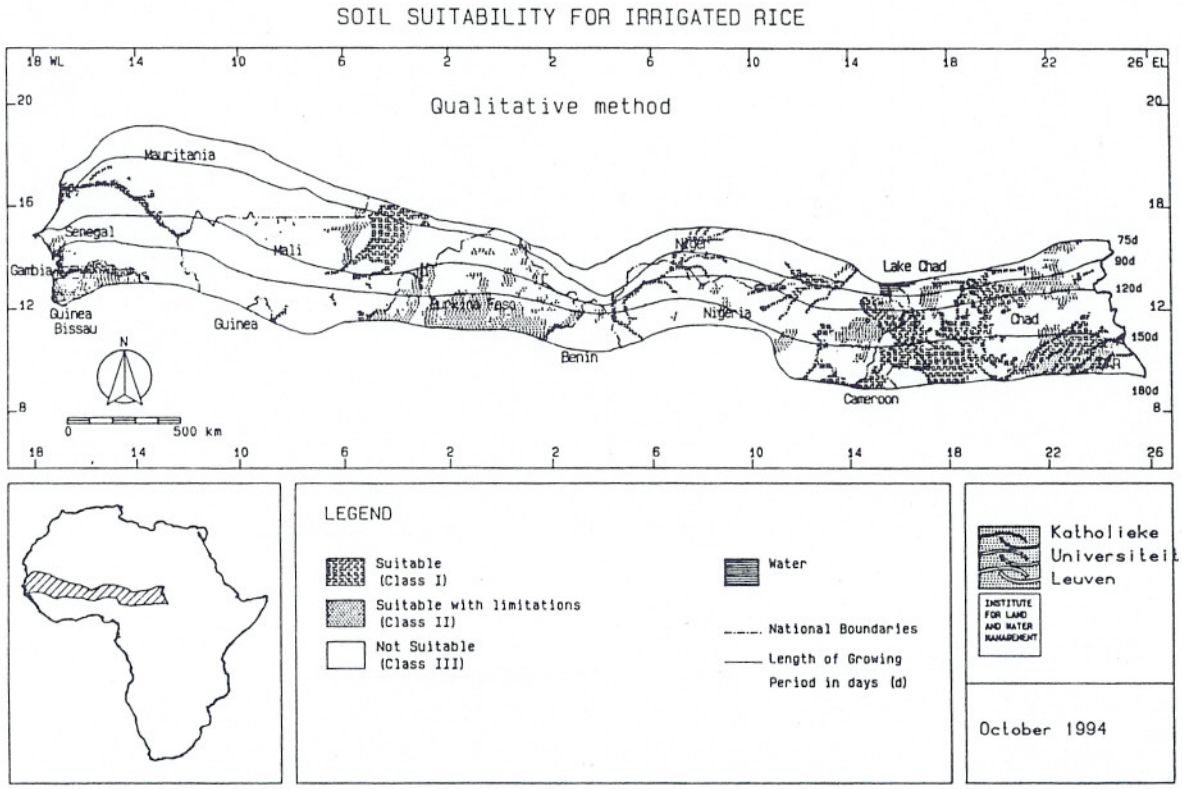
The extent of the major physical and chemical soil constraints in the West African Sahel according to the surface soil texture of the DSUs is presented in Table 7. Major constraints for the entire area are: limited soil depth (37% of the West African Sahel), erodibility (37%), soil acidity (40%) and high phosphate fixation (23%). Soil erodibility may have little direct influence on the soil suitability for irrigated rice in the Sahel. However, knowing that 37% of the area may be susceptible to erosion gives an indication of the physical limitations to the farming systems were irrigated rice may fit in.

Soil suitability for irrigated rice

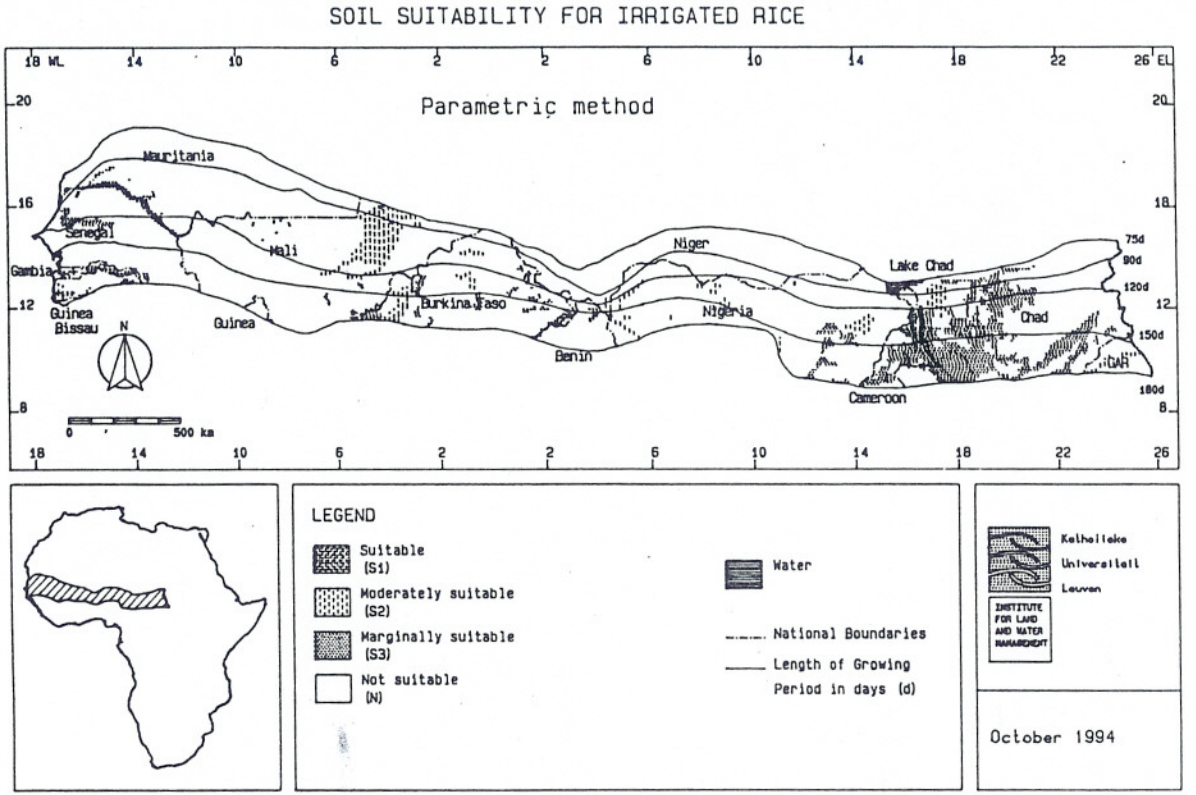
The soil suitability for the DSUs in the Sahel is summarized in Map 2. In Table 8 the suitability classification of a sample of the DSUs of the West African Sahel is given. Soil units which are considered highly suitable, according to the qualitative approach (e.g. Eutric Gleysols), do not necessarily fall under the same FCC unit (L/Cg(a) and Sg(a)). Consequently, they get two entirely different suitability ratings (0.82 versus 0.36).

Most suitable land (S1 and S2) for irrigated rice are located in the Chad basin (Cameroon, Chad and north-eastern Nigeria), in the Niger inner delta, and along tributaries of the Niger in eastern Burkina Faso and north-western Nigeria. The DSUs along the Senegal and Gambia rivers are classified as marginally suitable (S3). As the distance to water sources is not taken into account some caution has to be taken. This is for instance the case for the region of Cayor in Senegal, where DSUs are Calcic Cambisols. This soil unit was rated as marginally suitable (S3), but as no major water sources are available in this region, classifying them as conditionally unsuitable would be more appropriate. However, the construction of a canal through this area, linking the Senegal river with the Dakar region, is under consideration.

In general, a more stringent evaluation is obtained with the parametric than with the qualitative method. Only 5% of the total mapping units are classified as highly (S1) or moderately (S2) suitable, while 14% was classified as suitable (Class I) by the qualitative method. With the parametric method, all available information on the land characteristics can be integrated. Since land characteristics, such as slope or phases, were only provided for the DSUs associated soil units were neglected. The overall picture may under or overestimate the area of the potentially suitable land. The qualitative method allows a quick identification of potentially suitable areas, and has the advantage to integrate "expert knowledge", e.g. expected location in the landscape.



Map 1. Soil suitability for irrigated rice. Qualitative method.



Map 2. Soil suitability for irrigated rice. Parametric method.

Table 7. Extent (10^3 km²) of major soil constraints in the West African Sahel according to surface soil texture.

Constraint	Texture			Total	%
	Coarse	Medium	Fine		
Depth	262	381	-	643	37
Drainage	41	88	10	139	8
Swell and shrink properties	-	15	106	121	7
Moderate erodibility	71	529	2	602	35
High erodibility	16	15	-	32	2
Acidity	449	227	16	691	40
Al toxicity	-	8	-	8	< 1
Low CEC	175	6	-	180	11
P fixation (and low CEC)	150	233	14	396	23
Salinity or sodicity	6	52	-	57	3
Total	820	789	116	1725	

Source: calculation based on the FAO/Unesco Soil Map of the World (FAO 1991).

Zooming in on the Senegal Valley

So far, the discussion has been based on the FAO/Unesco Soil Map of the World. The DSUs in the Senegal Valley were found less suited for irrigated rice than for instance some of the DSUs in the Chad basin (S1) or in the inner Niger delta (S2). Nevertheless, substantial part of the soils in the Senegal Valley are useable -- and are actually used -- for irrigated rice. Actual yields may reach up to 10 thousand kg ha^{-1} $year^{-1}$, i.e. aggregated over two growing seasons (SAED 1990) and up to 16 thousand kg ha^{-1} $year^{-1}$ under good management (WARDA 1993). How do the different soils within the Senegal Valley reflect in terms of suitability and water requirements for rice?

Soil suitability for irrigated rice

The soil suitability is investigated by applying the parametric method on data of a semi-detailed soil map. The results are presented in Table 9 and in Map 3. Soil texture and topographical location, reflected by slope and drainage, are key factors determining the suitability of the land units for irrigated rice. The best soils are located in the back-swamps, have a heavy texture throughout the soil profiles and are not seriously affected by salinization. Moderately suited land (S2) are either back-swamp soils affected by salinization or located on low levees or on breakthrough deltas. Soil texture of the latter is lighter. Marginally suited (S3) are soils with a sandy texture on the river banks. The deep and coarse textured soils such as red dunes (shifting sands) are rated as not suitable for irrigated rice (N).

Table 8. FCC units and soil suitability classification of a sample of the DSUs of the Sahel (shortened from the original list of 89 for this illustration).

Soil unit [a]	FCC unit	Soil suitability	
		rating	class
Eutric Gleysols	L/Cg (a)	0.82	S1
Eutric Gleysols	Sg (a)	0.36	N
Eutric Fluvisols	L/Cd (a)	0.56	S3
Eutric Fluvisols	Ld (a)	0.46	N
Calcaric Fluvisols	L/Cdb (a)	0.62	S2
Calcaric Fluvisols	Ldb (a)	0.50	S3
Thionic Fluvisols	Cgc (a)	0.62	S2
Pellic Vertisols	Cdv (a)	0.56	S3
Chromic Vertisols	Cdhiv (a)	0.40	N
Chromic Vertisols	Lcdhiv (a)	0.35	N
Solodic Planosols	LL/Cgds (a)	0.46	N
Orthic Solonchaks	Lds (a)	0.38	N
Orthic Solonetz	L/Cdn (a)	0.43	N
Cambic Arenosols	Sde (a/b)	0.31	N

[a] according to the FAO/Unesco legend (FAO 1974). FCC = Fertility Capability Soil Classification system.

Water management for sustainable land-use

Apart from soil suitability, other aspects such as water availability, cost of the irrigation infrastructure and, sustainability of the irrigation schemes, should be considered when assessing the potentiality of irrigated rice. Soils falling within the same suitability class, may still require a different water management. Due to percolation losses, rice fields located on low levees or on break through deltas need about 10% more water than those in back-swamps (Table 9). Deep percolation of the relatively light textured soils, on levees or on breakthrough deltas, stands at 45% of the water required for the evapotranspiration of rice (ETrice). As a consequence, these schemes do not require an extensive drainage network and are cheaper to build. In the long run however, they may create water logging problems in the depressions. Irrigation schemes located in the back-swamps lose far less water by percolation (20% of ETrice), though extra water is needed for flushing out salts (13% of ETrice). This implies an extensive drainage network, besides flood protection dikes, making the schemes very expensive to build. Over time, the irrigation water will desalinize the topsoil and if the drainage water can safely be disposed of, the soil environment may be improved.

Table 9. Soil suitability and water requirements for irrigated rice in a sample area of the Senegal Valley (south of Podor).

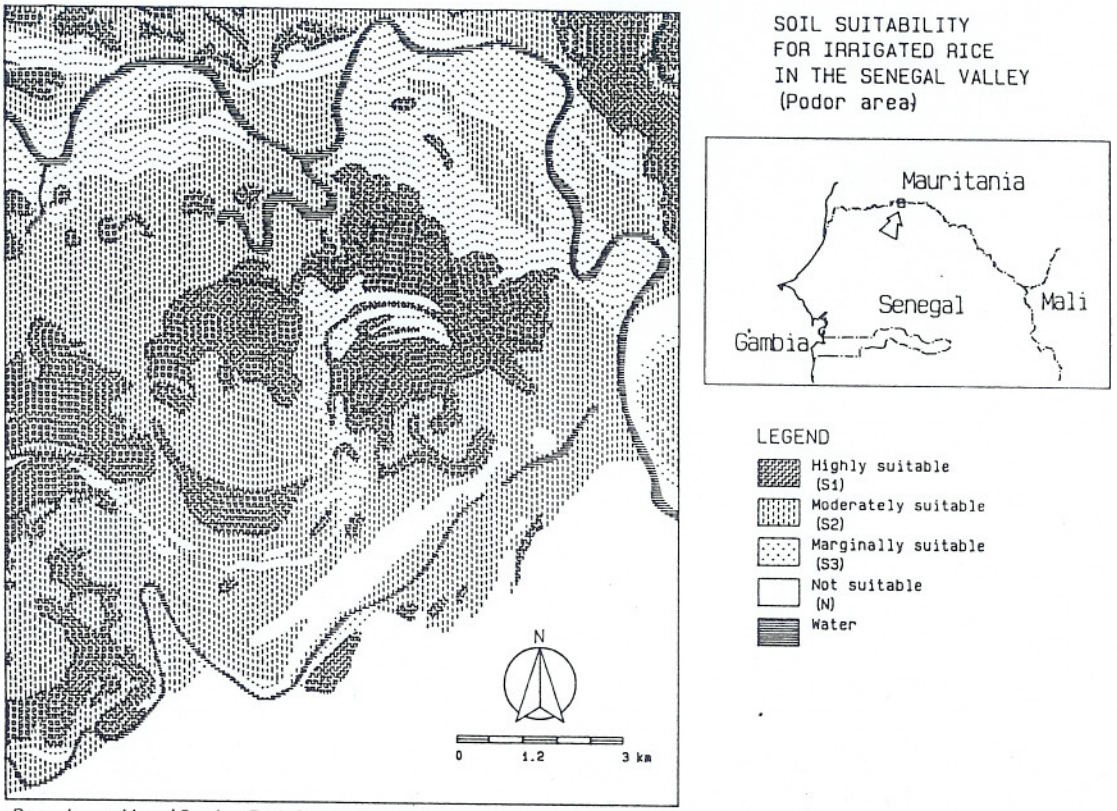
Suitability class	Soil unit[a]	Soilscape	Water requirement (10^3 m^3 ha^{-1})		Area	
			Dry season	Rainy season	(10^3 ha)	(%)
S1	Eutric Fluvisols	back-swamp	19.2	14.5 - 15.7	2.0	27
	Eutric Fluvisols	low levee	20.6	15.7 - 16.9	1.3	
S2	Eutric Fluvisols	low levee	20.6	15.7 - 16.9	2.0	45
	Eutric Fluvisols	BT delta[c]	23.3	17.9 - 19.3	2.9	
	Salic Fluvisols	back-swamp	20.9	16.4 - 17.7	0.2	
	Eutric Fluvisols	back-swamp	-	-	0.2	
	Eutric Fluvisols	river bank	-	-	0.1	
S3	Eutric Fluvisols	river bank	-	-	2.5	21
N	Eutric Fluvisols	river bank	-	-	0.1	5
	Eutric Fluvisols	marine terrace	-	-	0.2	
	Protic Arenosols[b]	red dunes	-	-	0.3	
Total	-	-	-	-	11.8	100

[a] according to revised FAO/Unesco legend (FAO 1988).
[b] according to World Soil Reference Base for Soil Resources (FAO 1994).
[c] BT delta = break through delta.

Conclusions

The land evaluation methods used in this study enable us to rank land units based on the dominant soil units of small scale as well as semi-detailed maps. This provides insight in the geographical distribution of potentially suitable areas for irrigated rice in the West African Sahel, which should be useful for setting research and development priorities. The Fertility Capability Soil Classification (FCC) proved to be very useful for interpreting key land characteristics. Most extended soil constraints in the Sahel are: limited soil depth (37%), erodibility (37%), soil acidity (40%) and high phosphate fixation (23%). The system was easy to adapt for assessing the soil suitability for irrigated rice.

The study illustrates how different land evaluation methods may lead to diverging results. With the qualitative method 14% was classified as suitable (Class I) and 10% as suitable with limitation (Class II). According to the parametric method only 5% of the total area is classified as highly and moderately suited (S1 and S2) and 9% as marginally suitable (S3). With the available data the qualitative method, may result in a too generalized and too optimistic picture, whereas the parametric method may be too stringent. Soils which are typical for lowland areas



Map 3. Soil suitability for irrigated rice in the Senegal Valley (Podor area).

are classified as the most suitable for irrigated rice in the qualitative method. Consequently, no differentiation comes out for the major basins in the Sahel. According to the parametric evaluation, most suitable dominant soil units are found in the Chad basin, in the inner Niger delta and along some of the Niger tributaries. A shortcoming of the FCC-based parametric method is that implicit information obvious to the expert, e.g. likely location in the landscape, is not accounted for.

The case study of the Senegal Valley revealed the variability within a unit ranked as marginally suitable (S3) based on the DSUs of the small scale map (1/5 000 000). The more detailed evaluation (original map scale 1/50 000) revealed that out of the 11.8 thousand ha of the study area, 27% was classified as highly suitable (S1), 45% as moderately suitable (S2) and 21% as marginally suitable (S3). Soils types falling within the same suitability class may need different water management practices. Soils located on the low levees are usually highly or moderately suitable. They require less extensive drainage systems but may create water logging and salinity problems in the depressions. Soils located in the back-swamps are in general highly suitable, but require higher investment cost for drainage and flood protection. They may, however, lead to more sustainable production systems when drainage water can be disposed of.

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