Research Paper

Clay and ferrous iron stratifications in a tropical savannah valley bottom soil under irrigated rice

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ABSTRACT

High ferrous ion Fe$^{2+}$ concentration inserted into dense clay strata constitutes an important threat to the rice production in several tropical savannah valley irrigation schemes of West Africa. Many actions are currently undertaken to alleviate iron toxicity. In this study, we have investigated the presence of clay and ferrous iron stratifications within a typical flooded valley bottom called Tiefora in Burkina Faso. Taking into account the multiple slopes of the valley, two randomized soil samplings were implemented at various depths. Samples were collected as deep as 500 cm, but especially at 30, 50 and 100 cm respectively. The clay percentage was determined by grain size analysis. Ferrous iron concentrations were obtained through the reflectometric method. The stratifications of clay and ferrous ion Fe$^{2+}$ were checked using statistical hypothesis testing (ANOVA and Welch t-Test). Clay percentage within the first 100 cm top soil - 28.9% was found twice higher than in the layers underneath. Furthermore, ferrous iron was mainly located in the top 30 cm, with a mean concentration of 994 mg/L. This ferrous iron concentration is much higher than found at depths 50 and 100 cm underneath (73 mg/L), while the pH of all the three layers was almost neutral. This striking stratification suggests several means of alleviating iron toxicity. Among these means, we propose maintaining wet conditions during the growing period in the irrigated lands, combined with leaching by subsurface drainage in the fallow periods

Key words: ANOVA, Burkina Faso, iron toxicity, savannah, soil sampling, Welch t-Test.

INTRODUCTION

In the tropical savannah valley bottoms, the classic salinity build up (excess of sodium) is not the main consequence of poor drainage. The main threat is ferrous iron toxicity (an excessive accumulation of iron in the plant, taking place especially when the soil is not well aerated) which drastically reduces rice yield.

The West Africa Rice Development Association (WARDA, now called “Africa Rice”) estimated that at least 60% of the swampy cultivated inland areas of Africa are affected by varying degrees of iron toxicity (Sahrawat et al., 1996). The same association reported that in West Africa, iron toxicity causes 12 to 100% of rice yield drops, depending on its severity and the tolerance of the rice variety.

The predominance of gley soils (Schaetzl and Sharon, 2005; Ogban and Babalola, 2009) in the valley bottom in tropical savannah reduces crop yield in many irrigation schemes. This is particularly true when the soils are exposed to several cycles of flooding during the year with high groundwater tables like in Tiefora where a small 16 ha irrigation scheme was located at the heart of the tropical Savannah region of Burkina Faso.

Tiefora valley bottom rice has attracted various populations looking for livelihood. However, the rice yield remains as low as 3.0 t/ha (Sokona et al., 2010). This low yield is thought to be a direct consequence of ferrous iron toxicity (Kante, 2011).
In order to provide means for alleviating iron toxicity, various researchers brought contributions to the characterization of valley bottom redoximorphic soils (Kessler and Oosterbaan, 1974; Barron and Torrent, 1986; Ogban and Babalola, 2009). However, previous research did not provide detailed information about the soil stratification and ferrous iron distribution within the soil (Jackson and Sherman, 1953).

This potential stratification can help in building a strategy against iron toxicity. In the current research, we have hypothesized that both clay content and ferrous iron Fe$^{2+}$ concentrations are stratified in these hematite dominant (Hillel, 2004) soils, at least under certain conditions. To check these assumptions, a randomized block sampling followed by a statistical analysis was implemented in the case of the typical tropical savannah valley bottom of Tiefora.

### MATERIALS AND METHODS

#### Site location

The current location of the irrigation scheme of Tiefora has a long story. The site is geographically located at longitude 4°33’13.19” W and latitude 10°37’33.56” N, some 800 m downstream an earthen dam. The irrigation scheme was formerly intended to be constructed immediately downstream the dam, where the local population (INSD-BF, 1985) used to produce, even though rustically, a certain quantity of rice.

The original idea was to integrate into the scheme the lands where rice was already grown by the population (SOTETHA, 1963). However, it appeared that not only those lands downstream of the dam were composed of isolated pieces of soils with no water layer interconnection, but also, the soils were not so suitable for rice production (ONBAH, 1987). After soil and topographic survey, the irrigation scheme was finally constructed at the current site, where soils were more clayey and subject to flooding.

#### Soil sampling and measurements

The sampling was performed in view of finding the relationships among four variables: the depth in the soil, percentage of clay in the soil, ferrous iron Fe$^{2+}$ concentrations and the pH.

The V-shape of the Tiefora valley bottom suggested making a randomized block sampling (Spiegel et al., 2001; Boslaugh and Watters, 2008). Within a cross section, three conditions of slope exist: left bank (LB), valley axis (VA) and right bank (RB) (Figure 1). These slopes are suspected to impact on the clay deposition in the valley.

In addition, the longitudinal slope is also suspected to have impact on clay deposition in the soil profile. Hence, the valley was longitudinally divided into an upstream region (UR), a middle region (MR) and downstream region (DR). The blocks were thus defined within the cross section, each one related to a homogeneous slope region. These blocks are LB, VA and RB (Figure 1). In order to integrate the longitudinal effect, one replicate was done in each of the 3 regions UR, MR and DR. Therefore, the valley was divided into nine sub-regions and a soil extraction site was selected randomly from each one. This way, the confounding effects on clay deposition of the longitudinal and lateral slopes were assumed neutralized since each sloping condition is equally represented in the final sample of soil extracts.

Two series of soil extraction were conducted in the flooded soil. In the first series, taking into consideration the fact that rice root maximum depth is 100 cm (Allen et al., 1998), three depths were targeted: 30, 50 and 100 cm respectively. Therefore, nine boreholes were perforated using a boring auger and a soil extract taken from each of the three depths. This led to 27 soil extracts.

The second series of operations bored also nine holes in the randomly selected sites. However, the depths were not limited to 100 cm since the purpose was to investigate on soil stratification. While boring, an extract was taken when a change in colour or texture was observed. Finally, the borehole execution was ended each time a fine sand layer forming a stratum of water inflow was found. The second series led to the gathering of some 51 soil extracts.

These two sets of soil extracts (27 + 51) were used for two different purposes. The 27 soil extracts were used to investigate clay percentage and ferrous iron concentration in the soil root zone. As for the 51 soil extracts, they were utilized to look further for clay percentage stratification in depth, up to 5 m when nothing was revealed in the 100 cm top soil.

With the 27 extracts, the ferrous iron concentrations were measured using a reflectometer with Fe$^{2+}$ reflectoquant strips (Persson, 1997). The strips used with this device measured concentrations within the two ranges (0.5 and 20 mg/L) and (20, 200 mg/L) in the soil solution. Dilutions were made any time the observed concentrations in ferrous ions were out of these ranges. The soil solution was obtained through dilutions with factor 5 from the saturated soil extract (Murray, 1994). For both groups of soil extracts, the clay proportions were obtained by grain size and sedimentometry analyses according to the ASTM norm (American Society for Testing and Materials).

#### Statistical analyses

It is anticipated that stratifications according to the depth will occur with clay percentage and ferrous iron concentrations. Therefore, ANOVA test (Stephens, 2004) was performed with the software Minitab to look for significant differences in means within the populations underlying the various soil extracts. The three conditions of
applicability of ANOVA: the normality of the underlying populations, equity of variances and the equity of the number of samples were checked before implementation (Boslaugh and Watters, 2008). These conditions were met with the 51 extracts of soils. However, the important difference in variances did not permit the application of ANOVA to the 27 other soil extracts. Consequently, the Welch t-Test that does not require the equality two sample variances (Welch, 1947) was applied to look for stratifications in ferrous iron concentrations.

RESULTS AND DISCUSSION

Clay stratification occurrence

One-way ANOVA test was applied with the 51 soils extracts despite the differences in the number of observations (Table 1) according to the depths. In fact, this test is known to be more sensitive to non-normality of the populations and inequality of the variances than to the differences in number of observations (Table 1) (Montgomery and Runger, 2011).

In normal conditions, the materials in a tropical savannah valley bottom are mainly composed of colluvial and alluvial depositions in the form of strata (Foth, 1990). However, in the case of Tiefora, the land has been under irrigation over more than 50 years and one would expect that agricultural modelling of the soil during rice production would destroy any stratification, at least in areas close to the top soil. Therefore, our null hypothesis is that there is no stratification in the soil, and the alternative hypothesis is that there exists certain stratification in terms of clay percentage. ANOVA was applied to test these hypotheses at 5% of significance level. In addition, a Fisher test about strata differentiation was also applied.

The results showed that clay content in the soil reduces steadily but definitely with the depth (Figure 2). Because of the small p-value (1.5%), we reject the null hypothesis that all depths are equivalent in terms of clay content and that there is no stratification (Table 2). The picture given by the soil according to the strata ID (3rd and 4th column in Table 3) is that the clay percentage is significantly higher in the first 100 cm than at any other depth underneath. However, in the layer 200 to 300 cm, the mean clay percentage was lower than in the top 100 cm and shared some similarities with that of 100 cm (sharing of letter A with this layer, Figure 2 and Table 3).

Clay content drop with the depth in the soil may explain why metallic ions (such as ferrous ion Fe^{2+}) and other chemicals tend to concentrate more near the soil surface (Herzsprung et al., 1998). In fact, since clay and humus (also found near the surface of soil) are one of the most chemically active components of agricultural soils, most of the cations and anions will stick near the top soil (Foth, 1990). However, if the soil is quite permeable, for example, not composed of heavy clay, seasonal fluctuating ground water table may bring the ions deeper in the soil during dry periods (Peel et al., 2007). Here, there would be one exception: if the valley is also irrigated during the dry
Table 1. Clay percentage of the soil extracts taken in the valley bottom.

<table>
<thead>
<tr>
<th>Depths (cm)</th>
<th>N observations</th>
<th>Mean % clay</th>
<th>Std. dev</th>
<th>Variance</th>
<th>Minimum</th>
<th>Maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td>00-100</td>
<td>25*</td>
<td>28.9</td>
<td>12.3</td>
<td>150.7</td>
<td>3.6</td>
<td>56.4</td>
</tr>
<tr>
<td>100-200</td>
<td>9</td>
<td>19.6</td>
<td>11.4</td>
<td>129.2</td>
<td>1.1</td>
<td>36.6</td>
</tr>
<tr>
<td>200-300</td>
<td>5</td>
<td>18.18</td>
<td>10.4</td>
<td>108.3</td>
<td>3.1</td>
<td>31.0</td>
</tr>
<tr>
<td>300-400</td>
<td>4</td>
<td>15.8</td>
<td>11.6</td>
<td>133.8</td>
<td>4.1</td>
<td>26.9</td>
</tr>
<tr>
<td>400-500</td>
<td>6</td>
<td>13.8</td>
<td>07.0</td>
<td>48.5</td>
<td>6.0</td>
<td>23.1</td>
</tr>
</tbody>
</table>

*Without 2 outliers.

Figure 2. Clay percentage dispersion and decrease with the soil depth.

Table 2. One-way ANOVA results – significant difference in clay % within the soil layers.

<table>
<thead>
<tr>
<th>Source</th>
<th>DF</th>
<th>Sum of squares (SS)</th>
<th>Mean squares (MS)</th>
<th>F of Fisher</th>
<th>P-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Depths class (cm)</td>
<td>4</td>
<td>1805</td>
<td>451</td>
<td>3.47</td>
<td>0.015*</td>
</tr>
<tr>
<td>Error</td>
<td>44</td>
<td>5726</td>
<td>130</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>48</td>
<td>7531</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* Significant at α = 0.05

period (for rice growing). In that case, the exchangeable ions may remain in the top soils. This hypothesis was checked for ferrous iron as in the case of Tiefora subsequently examined.

Ferrous iron concentration is stratified in the root zone

One of the most reliable way to test the hypothesis of ferrous iron stratification in the 100 cm top soil was to apply the two samples Welch t-Test (Welch, 1947), which does not require any assumption of sample equality of variances. The one-way ANOVA could not be performed because of the great difference within the variances (Table 4 and Figure 3). In fact, both the Bartlett’s and the Levene’s tests of equality of variances (Carroll and Schneider, 1985) performed at 5% of significance level led to the rejection of their equalities. Therefore, Welch t-Test was performed at 5% of significance level. The null hypothesis was that the 3 soil depths were equal in terms of mean ferrous iron concentrations (no stratification). The test led to the rejection of this null hypothesis in favour of the stratification with a p-value = 0.0% (Tables 4 and 5).

In fact, it seems that either high or low ferrous iron concentration can be associated with low or neutral pH level in the soil. High ferrous iron content in
Table 3. Fisher method - the mean clay% are significantly different for at least two depths

<table>
<thead>
<tr>
<th>Depths class (cm)</th>
<th>Number of observations</th>
<th>Mean of clay percentage</th>
<th>Soil stratum ID(a)</th>
</tr>
</thead>
<tbody>
<tr>
<td>00-100</td>
<td>25</td>
<td>28.92</td>
<td>A</td>
</tr>
<tr>
<td>100-200</td>
<td>9</td>
<td>19.60</td>
<td>B</td>
</tr>
<tr>
<td>200-300</td>
<td>5</td>
<td>18.08</td>
<td>AB</td>
</tr>
<tr>
<td>300-400</td>
<td>4</td>
<td>15.85</td>
<td>B</td>
</tr>
<tr>
<td>400-500</td>
<td>6</td>
<td>13.85</td>
<td>B</td>
</tr>
</tbody>
</table>

(a) Means that do not share a letter are significantly different

Table 4. Ferrous iron concentration in the soil extracts taken at three depths.

<table>
<thead>
<tr>
<th>Depth (cm)</th>
<th>N observations</th>
<th>N* missing</th>
<th>Mean Fe²⁺ (mg/L)</th>
<th>Std. deviation</th>
<th>Variance</th>
<th>Minimum</th>
<th>Median</th>
<th>Maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td>30</td>
<td>8</td>
<td>1</td>
<td>994.1</td>
<td>215.3</td>
<td>46363.3</td>
<td>615</td>
<td>1025</td>
<td>1200</td>
</tr>
<tr>
<td>50</td>
<td>9</td>
<td>0</td>
<td>74.5</td>
<td>10.9</td>
<td>119.5</td>
<td>55</td>
<td>80</td>
<td>85</td>
</tr>
<tr>
<td>100</td>
<td>9</td>
<td>0</td>
<td>72.3</td>
<td>18.1</td>
<td>328.0</td>
<td>43</td>
<td>73</td>
<td>98</td>
</tr>
</tbody>
</table>

Table 5. Welch two samples t-test for Fe²⁺ at 3 depths.

<table>
<thead>
<tr>
<th>Couple of depths (cm)</th>
<th>Difference of means (mg/L)</th>
<th>95% Confidence interval</th>
<th>t-Test of difference</th>
<th>Deg. of freedom</th>
<th>p-Value</th>
<th>Depth (cm)</th>
<th>Iron stratum **</th>
</tr>
</thead>
<tbody>
<tr>
<td>30 vs. 50</td>
<td>919.6</td>
<td>(739;1100)</td>
<td>12.07</td>
<td>7</td>
<td>0.000*</td>
<td>30</td>
<td>A</td>
</tr>
<tr>
<td>30 vs. 100</td>
<td>892.4</td>
<td>(682;1103)</td>
<td>10.04</td>
<td>7</td>
<td>0.000*</td>
<td>50</td>
<td>BC</td>
</tr>
<tr>
<td>50 vs. 100</td>
<td>2.22</td>
<td>(-13;17)</td>
<td>0.32</td>
<td>13</td>
<td>0.758</td>
<td>100</td>
<td>CB</td>
</tr>
</tbody>
</table>

* Significant at α = 0.05 and ** strata that do not share a common letter are significantly different.

Figure 3. Ferrous iron concentration dispersion with the soil depth.

Flooded rice soils has often been found in association with low pH of less than 5 after the oxidation of pyrite (Moormann and Breemen, 1978; Suryadi, 1996). In the case of Tiefora, all the three layers have a slight but equal acidity of 6.5, and one could expect less ferrous ion Fe²⁺ in all of them.
That means that the high ferrous iron concentration (994 mg/L; Table 4) in the depth 30 cm was rather unexpected since associated with only a slight acid pH of 6.5. At the same time, a comparatively very low ferrous iron concentration was found at 50 to 100 cm for the same pH value. Therefore, it seems that high Fe^{2+} concentration can occur in either acidic or neutral conditions even though, the more acid the medium, the more soluble – and then, potentially toxic for the rice is Fe^{2+} (Suryadi, 1996).

This ferrous iron distribution of top soil 100 cm presents some similarities with other cation distributions. The huge iron concentration in the 30 cm top soil surprisingly contrasts with the horizons underneath (Figure 3). From an average of 994 mg/L, it drops to 74 mg/L at the depth of 50 cm, and then, slightly rises to 72 mg/L (Table 4), all this occurring in the clay dominant section of the soil.

Such a drastic change is difficult to explain by the intake of iron by the rice roots that remained after harvest in the soil. It seems reasonable to think that this concentration in the top 30 cm is due not to oxidation which would have been conducted to Fe^{3+} compounds (Dent, 1986), by evaporation following capillary rise in the clay layer.

Therefore, these phenomena would have similar effect to the one occurring in soils affected by sodium salinity (Bajwa et al., 1986) in which white sodium chloride (NaCl) is visible during dry period on the surface of the soil. In fact, in Tiefora, a thick layer of ferric iron Fe^{3+} (the oxidized form) is also visible with its vivid red colour in rice nursery areas when no ponding water remains.

Ferrous iron alleviation techniques will have to take into account this stratification in the valley. It is noteworthy that within this non-stratified clayey of 30 cm top soil, even though, the variation is important (variance = 46360 mg^2/L^2), the ferrous iron concentration is very high everywhere in the flooded and oxygen depleted valley bottom (mean = 994 mg/L). There is no single location where the phenomenon is not present. This is also in favour of the explanation that water evaporated leaving behind the ferrous iron.

Sub-surface drainage (leaching) with open channels (Schultz, 1988), or buried pipes implemented in the 100 cm to layer may help to oxygenate the root zone and transform soluble ferrous iron into solid ferric iron that are less toxic to rice.

**Conclusions**

The stratification of clay and ferrous iron concentration can help to develop a strategy to alleviate iron toxicity in tropical savannah soils under irrigated rice. In our case study, the results show that clay content is significantly higher in the 100 cm top soil, with a mean of 28.9% (standard deviation of 12.3%) that dropped to 13.8% at 400 cm of depth. We have found that ferrous iron was mainly concentrated within the top 30 cm of the clay, reaching 994 mg/L (standard deviation of 215). The iron concentration drops much more quickly than the clay since already at 50 cm depth, the value is only 74.5 mg/L (standard deviation of 10.9).

Moreover, this high iron concentration is observed within the top 30 cm of soil all over the flooded valley bottom, supporting the idea that it was left behind after capillary rise and evaporation. These extreme stratification and concentration in the top soil provide a way to alleviate iron toxicity. It is proposed to maintain permanent wet conditions during the growing period in such irrigated land, in combination with leaching (subsurface drainage) in the fallow periods that may help in removing the excess of ferrous iron or preventing its occurrence.

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