

Dynamic role of “illite-like” clay minerals in temperate soils: facts and hypotheses

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Abstract Analysis of new data and reinterpretation of published information for clay minerals found in temperate climate soil profiles indicates that there is often a gradient of “illite-like” clay minerals with depth. We used the term “illite-like” because these observations are based on X-Ray Diffractogram patterns and not on layer charge measurements which allow to define properly illite. It appears that “illite-like” layers are concentrated in the upper, organic-rich portion of the soil profile both under grassland and forest vegetation. “Illite-like” layer quantity seems directly related to soil potassium status. Indeed, intensive agriculture practises without potassium fertilization reduce “illite-like” content in surface soils, whereas several years of potassic fertilization without plant growth can increase “illite-like” content. The potassic soil clay mineral, illite, is particularly important in that it can be the major source of readily available potassium for plants. Spatial and temporal dynamics of clay minerals

should be related to the potassium cycle. We propose that the frequently observed general trend of increasing exchangeable potassium in the top soil can be correlated with an increase in “illite-like” in the clays and that the decrease of potassium caused by intensive agricultural practices leads to “illite-like” layer destabilization. This vision of “illite-like” layer as a potassium reservoir refueled by plants and emptied by intensive cropping renews the concept of potassium availability and indicates a need to be discussed as well in natural ecosystems as in cultivated ecosystems.

Keywords Clay minerals · Illite · Potassium availability · Potassium cycle · Plant–soil interactions · Soil

Abbreviations

HI hydroxy-interlayered clay minerals
IS mixed layered illite-smectite clay minerals
PCI poorly crystallized illite
WCI well crystallized illite
XRD X-Ray diffractometer

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Introduction

Potassium is an important element for plant nutrition. According to Knecht and Göransson

(2004), potassium is the fifth most important element in terrestrial plant biomass, after C, O, H and N. Hinsinger (2002) considers that dry weight plant potassium content ranges from 0.5 to 5%. Potassic fertilizers, which were the first mineral fertilizers used, in the early nineteenth century (e.g. Larbaetrier 1891), are still largely used. For instance, 40 kg/ha of potassium are applied each year on average in European Union countries cultivated fields (International Fertilizer Industry Association 2004). In spite of this obvious importance, few recent studies are focused on this element. This has led Öborn et al. (2005), to state that “in recent years potassium has become a “forgotten” nutrient element”.

Three main potassium pools are commonly distinguished in soils. Primary high temperature minerals such as feldspars and micas constitute the biggest pool. Potassium contained in this pool is not directly available to plants. The smallest pool is comprised by potassium ions extractable by a 1 M NH_4OAc solution which is called the “exchangeable” potassium pool. The last pool whose size is 2 to 10 times more important than the “exchangeable” pool, is constituted by potassium ions fixed in 2:1 interlayer clay mineral and is called “non-exchangeable” potassium pool (Öborn et al. 2005). “Exchangeable” as well as “non-exchangeable” pools are known to contribute to plant nutrition (e.g. Badraoui et al. 1992; Moritsuka et al. 2004; Øgaard and Krogstad 2005).

However, 2:1 soil clay minerals do not all contain potassium. Indeed, if we consider potassium content as fixed or strongly held, i.e. not exchanged by ambient cations, the most common soil clay types with the 2:1 structure can be classified as follows: (1) illite with high potassium content, (2) mixed layered illite/smectite with variable potassium content, (3) smectite with low potassium content, (4) Hydroxy-interlayered (HI) clay minerals with very low potassium content.

Illite is generally assumed to have a rather low capacity to attract and release ambient exchangeable ions such as Ca, Mg, Na but a high potential to accumulate potassium. It is the most potassium-rich of the common soil clay minerals. Smectite normally has a low potassium content

but a high capacity to accept and release ions. It controls for a large part the amount of exchangeable ions such as Ca, Mg and to a lesser extent K necessary for plant metabolism. Mixed layered minerals (essentially variable mixtures of illite and smectite layers in the same crystallites) have of course intermediate properties depending upon the proportion of each component, illite or smectite, present. Hydroxy-interlayered (HI) are clay minerals whose layers are closed with hydroxy-aluminium. HI have very low ability to accept or release ions and they have a very low potassium content. Clay mineral potassium content is therefore strongly linked to illite layer quantity (true illite and illite layers in IS clay minerals).

The mineralogical difference between illite, smectite and HI is to a large extent based on the layer charge. Illite layer have a 0.8–0.9 charge whereas smectite layer charge can range between 0.8 and 0.2. HI (hydroxyl interlayered minerals) are generally described as high charge smectite layer minerals (0.6–0.8) collapsed with hydroxyl-aluminium. Studies in diagenetic contexts showed that there is a good agreement between the theoretical definition of illite and its identification with X-Ray diffraction techniques (Meunier and Velde 2004). Basically, it is assumed that illite layers are collapsed with potassium ions and have characteristic X-ray diffraction peaks near 10 Å (d-spacing = 10 Å). The situation is more complex in soils. Indeed, several studies reported that HI minerals could collapse to 10 Å if saturated by potassium ions (e.g. Pevear et al. 1984; April et al. 1986; Egli et al. 2004). Reciprocally, illite or even mica layers could reopen in a potassium depletion context (e.g. Hinsinger et al. 1992). These studies suggest that soil clay minerals which do not correspond to the mineralogical definition of illite could be identified as illite and vice-versa. In order to avoid these theoretical problems in the present study, we will use the term “illite-like” for the 10 Å mineral identified as illite with XRD techniques.

Previous studies have shown that total soil potassium content tends to increase with depth because weathering of primary minerals is greater near the surface than at depth (Mohr and Van

Baren 1954, p124; Oh and Richter 2005). On the contrary, the “exchangeable” potassium pool tends to increase in the top of soil profiles (Mariotti 1982 and Jobbagy and Jackson 2004). Jobbagy and Jackson (2001) proposed that nutrients are “uplifted” in the soil profile through plant activity which induces this increase of “exchangeable” potassium ions on top of soil profiles. Figures 1 and 2 illustrate these two opposite trends. In spite of the potential interest for soil potassium supply, such trends have not been considered for 2:1 clay minerals. A fortiori, links between soil 2:1 clay mineral dynamics and soil potassium cycle have never been discussed.

Two opposite patterns could be expected for surface soil 2:1 clay minerals. One would be the destabilization of minerals which lose potassium by the formation of less potassic clay minerals through water–rock interaction. In this case, as physical and biological alterations are higher near the surface, one would expect that the “illite-like” quantity should increase with depth with a minimum at the plant–soil interface. On the contrary, one could consider that 2:1 clay minerals may accept potassium translocated by plants through root absorption at depth and thus get an increased potassium content. In this case, “illite-like” layer quantity should follow “exchangeable” potassium distribution with a maximum at the surface and a decrease with depth.

The aim of this paper is to link available and new data about “illite-like” minerals status in temperate ecosystems to identify and discuss

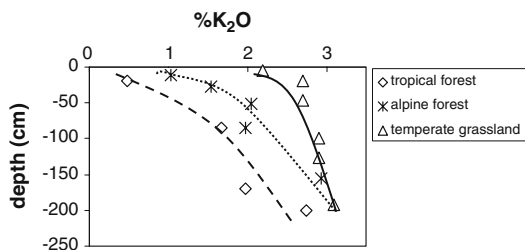


Fig. 1 Total potassium content as a function of depth in various soil profiles. Profiles of tropical forest, alpine forest and temperate grassland were established respectively thanks to data by Mohr and van Baren (1954), Egli et al. (2002) and Oh and Richter (2005). Lines are added by visual interpretation

general trends of “illite-like” minerals dynamic in soils. We will investigate the diversity of clay minerals in various situations, their variation with time (age of the ecosystem) and soil depth. We will also assess the impact of potassium constraints induced by land use on the clay minerals. Finally, we will discuss the possible mechanisms linking “illite-like” minerals to potassium and ecosystem dynamics. To our knowledge, such considerations about “illite-like” dynamics are totally new. Our review is focused on temperate ecosystems, because clay minerals are often abundant and dominated by 2:1 clay minerals in temperate soils. We have intentionally ignored kaolinite, a very common soil clay mineral, in that it has very low cation exchange capacity and no potassium. Kaolinite is also generally of minor importance in temperate soils. For instance, Velde (2001) reported that kaolinite peak represents 10–15% of the total peak surface area in diffractograms of clays sampled in the Central United States.

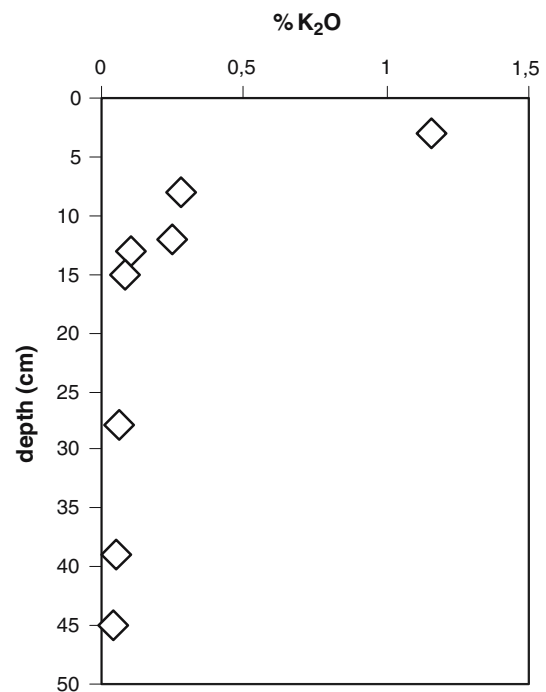


Fig. 2 Exchangeable potassium variation with depth. This figure is adapted from Mariotti (1982). The increase of exchangeable potassium near the surface conforms with Jobbagy and Jackson’s observations (2004)

New techniques allow new insight in soil clay minerals study

Clay minerals identification

The major if not exclusive method used to identify clay minerals in complex soil assemblages is by X-ray diffraction methods using oriented particle samples. Significant recent progress in the interpretation of diffractograms (Lanson 1997) can be used to numerically analyse complex band groups which are omnipresent in the X-ray diffraction diffractograms of soils. Curve decomposition methods allow one to distinguish the different major clay mineral phases present with precision and to follow, numerically, the changes which occur under different conditions as a function of time. Given this method and the fact that the quality of X-ray diffraction equipment has also made great advances in the last three decades, we can now study un-treated soil clay samples. This was not the case when ML Jackson established the standard methods of chemical treatment for preparing and identifying clay minerals in the 1950's (see Jackson 1964). At that time extraction of organic material, iron and aluminium hydroxyoxides was recommended, a method still in use in most soil clay laboratories. However, it has been shown that chemical treatment is no longer necessary. In particular, it has been evidenced that the destruction of organic matter can significantly change the clay mineralogy of prairie type soil clay materials (Velde 2001). We can now observe the clay minerals actually present and active in the soil, with their current properties, those acting in the context of plant–soil interactions.

Using the observations of Moore and Reynolds (1997), Righi et al. (1995) and Velde (2001), we use the following clay mineral identification procedure:

The samples, Sr-saturated in an air-dried state, which have a 15.2 Å interlayer spacing are smectites (two water layers surrounding the Sr cation) and those with a 10 to 10.3 Å layer spacing are illite. Hydroxy-interlayered (HI) minerals (soil vermiculite) and chlorite show 14.2–14.4 Å spacings under these conditions. Chlorite has a narrow peak (near 0.3° two theta at peak half

height using Cu radiation), while HI minerals (soil vermiculite) have a peak of near 0.8° width at half height or greater. Mixed layer minerals, when predominantly smectitic, are here designated as S/I, and when predominantly illite are here designated as I/S. Their peak position is generally a function of the proportion of each component, illite or smectite. These phases show peak widths of 1.5–2° two theta using Cu radiation. Most of these clays show a disordered stacking sequence (see Moore and Reynolds 1997) in mature soils.

Illite can be considered as two components in X-ray diffraction diagrams, poorly crystallized illite (PCI) and well crystallized illite (WCI). PCI have a higher peak width than WCI (about 0.8 vs. 0.4 2° two theta using Cu radiation). PCI have 10.3–10.5 Å spacings whereas WCI have a spacing near 10 Å. Both types are potassic. They are considered here to be part of the same mineral group (for details, see Meunier and Velde 2004).

The mismatch between clay mineral definitions and their identification in soils was discussed in the introduction. Figure 3 illustrates this issue. It presents XRD patterns of a clay fraction extracted from a French farmed soil under various treatments (untreated, 1 M KCl treated and washed 5 times with deionized water and 1 M KCl treated, then 1 M SrCl₂ treated and washed 5 times). These treatments are standard laboratory operations and would not be expected to modify the 2:1 structure of the clays. In the KCl treatment illite peaks increase. The subsequent treatment with Sr²⁺ reveals that a part of the layers closed after potassium addition did not reopen through Sr²⁺ addition. Illite content (PCI + WCI) changes from 30% to 50% with K saturation but remains at 42% after subsequent Sr saturation. This suggests that the newly fixed potassium is strongly fixed in 10 Å layers. This laboratory experiment emphasizes the ambiguity in soils between the theoretical definition of illite and its identification by simple X-ray diffraction. In this paper, we will call the clay populations identified as PCI or WCI, “illite-like” minerals. No layer charge is therefore assumed for “illite-like” clay minerals.

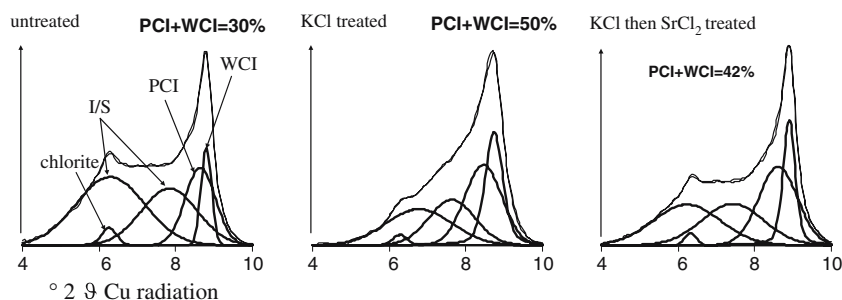


Fig. 3 XRD patterns of untreated, 1 M KCl treated and 1 M KCl then 1 M SrCl_2 treated clays extracted from a French grassland soil (Baie de l'Aiguillon, department de la Vienne, France). KCl treated sample have a greater “illite-like” content. It is also noticeable that I/S peaks of the KCl treated clays have a greater position, which means

that they have a higher “illite-like” layer content. “Illite-like” content in the KCl then SrCl_2 treated clays is intermediate between untreated and KCl treated clays. It illustrates the observation that XRD of 2:1 clay minerals could vary with their potassium content even if their layer charge do not change

Clay minerals quantification

It is possible to identify the clay mineral phases quantitatively by using background subtraction and curve decomposition routines (Lanson 1997). Simulations of diffractograms, following the methods outlined by Moore and Reynolds (1997) allow one to estimate the proportions of illite and smectite present in each phase and to estimate the relative proportions of each component from peak areas determined by decomposition methods. Although these estimations are not totally rigorous in all cases, they can be used with great effect on a comparative basis when clay mineral assemblages are similar. This is the basis for the examples presented here.

“illite-like” gradient in the clay fractions of temperate soils

Results from studies reporting “illite-like” minerals distribution in soil profiles are shown in Table 1. It is noticeable that only few data on the subject are available. Nonetheless, the geographical distribution of the data is interesting. Indeed, studies from North America, Western Europe and Asia show the same trend: “illite-like” mineral quantities increase near the surface in clay fractions. It is the case both under grassland and deciduous forest.

Figure 4 shows unpublished X-ray diffractograms (de Mecquenem and Barré) of clay

fractions from soils under oak forest and grassland sampled in the Foljuif Ecological station, near Paris (France). These results are consistent with the trend derived from Table 1. The dataset contains XRD patterns of clay fractions from 11 soil cores sampled along a grassland/forest transect. Figure 4 shows two diffractograms of topsoil (–2.5 cm) clays in the micaceous clay minerals range and two diffractograms of clay fractions from soils sampled at a 45 cm depth. These XRD patterns, recorded on similar size fractions (<2 μm), suggest clearly that “illite-like” quantity is higher near the surface under grassland as well as under oak forest. On the contrary the HI mineral peaks increase with depth in both cases. The X-coordinates of the gravity centers of the diffractograms could be considered as integrative indicators of the observed modifications. Indeed, an increase of “illite-like” layer quantity should decrease the X-coordinate value of the gravity center whereas an increase of smectitic or HI layers should increase this value. The measurement of the center of gravity X-coordinates allows a numeric comparison of the diffractograms with depth. First, we tested with the SAS ANOVA procedure if the vegetation type, depths and the interaction between vegetation type and depth have an effect on diffractogram centers of gravity. As no effect of vegetation ($P = 0.92$) and no effect of the interaction ($P = 0.85$) were observed, we considered that the 11 cores were 11 replicates and we studied the evolution of centers of gravity with depth with the SAS ANOVA

Table 1 Summary of published references dealing with clay mineralogy in temperate soil profiles. “+” signifies that higher quantities of “illite-like” are noticeable on the top of the soil profiles. “0” signifies that “illite-like” quantity stays constant along the soil profile

Authors (year)	Area	vegetation	illite increase
Nettleton et al. (1973)	California	grassland	+
Mahjoory (1975)	Iran	grassland	+
Spiers et al. (1984)	Nebraska	grassland	+
Badraoui et al. (1987)	Minnesota	grassland	+
Kuzila and Lewis (1993)	Alberta	grassland	+
Boettinger and Southard (1995)	California	grassland	+
Tice et al. (1996)	California	oak forest	+
Bain and Griffen (2002)	Scotland	grassland	0
Velde et al. (2003)	France	grassland	+

procedure. Mean separation was done using the least significant difference test (LSD test) (Fig. 5). Results of the statistical analysis show that the depth has a significant effect on X-coordinates of the centers of gravity of the diffractograms ($P = 0.005$). The LSD test reveals that X-coordinates of gravity centers of clays sampled at 2.5 cm are lower than those of clays sampled at 15, 35 and 45 cm. The X-coordinates of centers of gravity of clays sampled at 7.5 cm are significantly lower than those sampled at 15 and 35 cm. The concomitant increase of the HI peak and decrease of the “illite-like” peak with depth induced an

increase with depth of the X-coordinate values of the center of gravity of the diffractograms. These results and those summarized in the Table 1 indicate that “illite-like” minerals quantity is higher in the humic horizon than below it.

A detailed examination of clays from a time sequence of diked and used for pasture sediments (1868, 1575, 1068; carte géologique de la France, 1/50000, Rue, XXI-6, BRGM edition) in the baie de Somme area (baie d’Authie, France) reported initially by Velde et al. (2003) allows another analysis of the increase of “illite-like” layers in the upper, root zone. The sedimentary material is

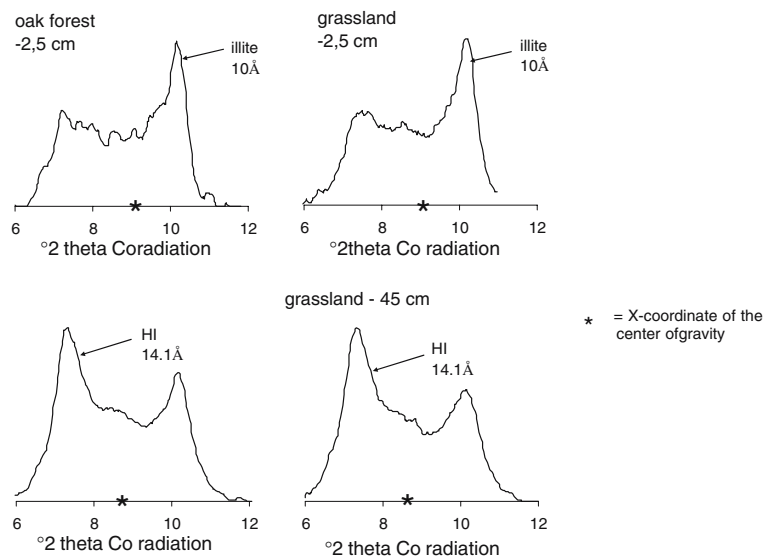


Fig. 4 XRD of clay fractions of grassland and forest soils sampled at the Foljuif’s ecological station (Seine-et-Marne, France). The “illite-like” peaks are more important at a 2.5 cm depth than at 45 cm. On the contrary, HI peaks are increasing with depth. These two trends are noticeable as well in the grassland soil as in the forest soil.

The X-coordinate of the centers of gravity were calculating in $^{\circ}2 \theta$ Co radiation and then converted in Å. Their values for –2.5 cm oak forest, –45 cm oak forest, –2.5 cm grassland and –45 cm grassland are respectively 8.84, 8.56, 8.90 and 8.42 $^{\circ}2 \theta$ Co radiation which correspond to 11.61, 11.99, 11.54 and 12.20 Å

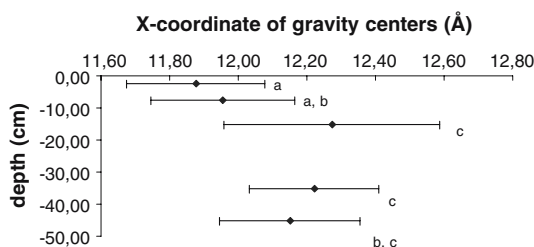


Fig. 5 Variation with depth of X-coordinates of X-ray diffractograms gravity centers of clay fractions of forest and grassland soils sampled at the Foljuif's ecological station (Seine et Marne, France). X-coordinate values increase with depth due to the decrease of “illite-like” layer quantities and the increase of HI peak areas. Please note that X-coordinate values are expressed in Angstrom and not in 2 theta degrees

composed of sand and clays that are derived largely from top soils from various parts of the Seine basin. The three profiles presented show a variation with time from initial, plant - free material to that of the established grazed prairie. Proportions of “illite-like” layers in the clay assemblage occurring as WCI + PCI or illite layers in the mixed layer phases (I/S and S/I) were calculated and plotted against depth (Fig. 6a, b).

The “illite-like” minerals (WCI + PCI) and “illite-like” layers in the mixed layer minerals show nearly the same trends in the two oldest soils: an increase of “illite-like” minerals (PCI + WCI) and “illite-like” layers in mixed layered clay minerals in the humic zone of the profile and a general decrease in the lower portion of the profile. This trend is not observable in the youngest soil (1868). Differences between values in the humic zone and the zone below are greater in the oldest poldered sediments. Indeed, PCI + WCI increases respectively from 13 to 17% peak area (the two means are significantly different, $P = 0.03$ for a t -test performed with SAS) below the humic zone and within it in the 1575 core and from 13 to 21% ($P = 0.02$) in the 1091 core. Averages of “illite-like” layers in the mixed layered minerals (S/I and I/S) increase respectively from 9 to 14% ($P = 0.018$) and 12 to 24% ($P = 0.002$) in going from the lower to upper portions of the profile. These data suggest that the “illite-like” content, as a phase or as part of the interlayer mineral complexes near the surface, increases with time.

Is “illite-like” clay minerals content driven by potassium dynamic?

In the first part of the above section, it was established that there is an “illite-like” minerals gradient in temperate soils and that this gradient increases with time. We will see in this second section what could induce “illite-like” minerals content modifications in the upper organic zone of soil profiles. As potassium ions are fixed between “illite-like” layers, it seems reasonable to investigate the impacts of potassium addition or removal on the soil clay mineralogy.

Results published by Pernes-Debuyser et al. (2003), on the INRA 42 plots experiment (Versailles, France), provide a good insight of 2:1 clay minerals modifications after potassium addition. Indeed, the authors compare clay mineralogy of topsoils (0–5 cm) that have received KCl or manure amendment for about 70 years with clay mineralogy of control soils and initial clay mineralogy. The authors observed that both in manure and KCl treatments the exchangeable potassium pool was ten times higher than in the control. Plant growth was allowed neither on treated soils nor on control soils. Table 2 presents the contributions of “illite-like” peak areas to the total diffractogram areas. It shows that “illite-like” peak areas double after 70 years of manure or KCl treatment compared to the initial and control soil clay mineralogy. This suggests that 2:1 clay minerals fixed partly potassium contained in manure or KCl which led to “illite-layer” layer quantity increase.

Field experiments on parcels continuously cultivated without potassium amendment give information on clay mineralogy reaction to potassium depletion induced by crop harvest. Velde and Peck (2002) compared clay mineralogy of soils sampled in 1913 (soil samples have been kept from this period) to those collected after 42 and 83 years of continuous corn cropping. Figure 7 shows these XRD patterns. A strong decrease of “illite-like” layers with time is observable in each clay minerals population. The WCI illite peak intensity is decreasing with time. The PCI peak did not really change until 1955. After that the PCI illite peak shifts to a lower 2 theta angle value which means that its

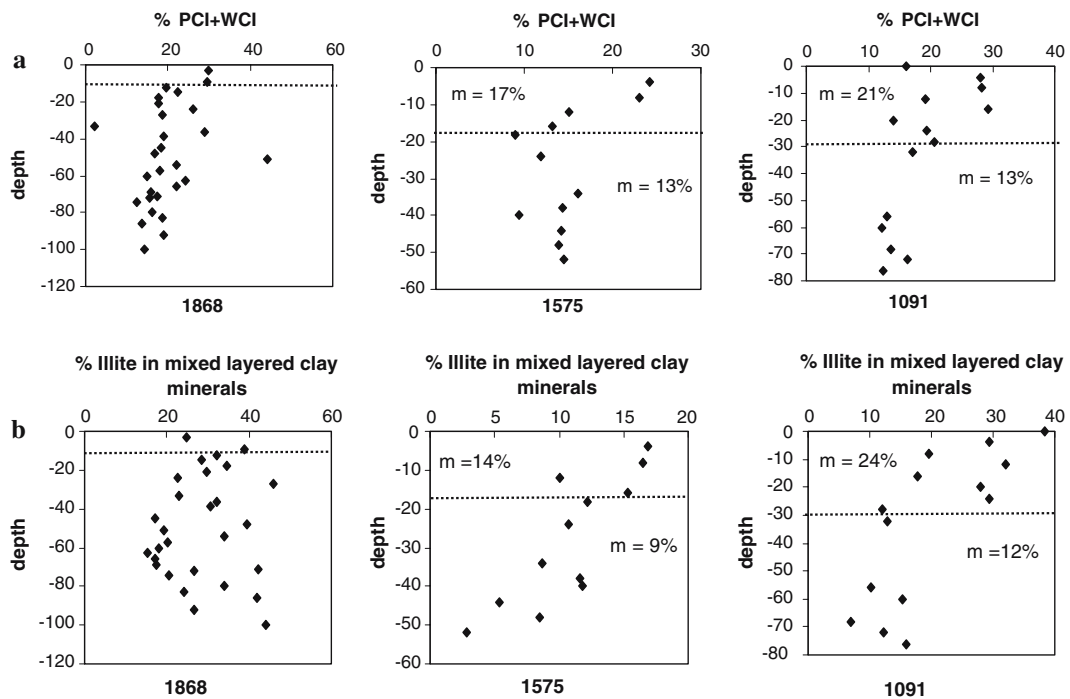


Fig. 6 Variation of continental sediments (dominated by prairie or agricultural soil clay minerals) under natural grazed prairie as a function of time, from fields diked in 1868, 1575 and 1058 (reported by Velde et al. 2003) baie d’Authie, Département de la Somme, France. Dotted line indicates the humic zone boundary developed by the prairie grass regime. (a) The initial sediment clays change

by an increase in “illite-like” (PCI + WCI) in the upper humic horizon of the sediments for the two oldest polderised sediments. (b) The increases of “illite-like” layers in the mixed layered clay minerals in the humic zone are obvious for the 1575 and 1091 cores. No enrichment is observed for the 1868 core

“illite-like” layer quantity decreased. The same phenomenon is observable for I/S populations. Its peak position increased continuously with time from 13.5 Å to 14.3 Å which corresponds to an “illite-like” layer quantity decrease. Tributh et al. (1987) report a similar, though non-quantified, effect in another field experiment of plant cropping without potassium application. In Velde and

Peck observations, one can notice that clay minerals modification intensities follow corn yields. Indeed, modifications are much stronger between 1955 and 1996 than between 1913 and 1955, while corn production increased from 1000 to 1500 kg/ha between 1913 and 1955, and from 1500 to 3200 kg/ha between 1955 and 1996.

Table 2 “Illite-like” peak area contribution to total area of the spectrum. Peak areas were calculated based on the diffractograms published by Pernes-Debuyser et al. (2003). Manure and KCl addition without plant growth led to a clear increase of “illite-like” among clay minerals of the 42 plots experiment

Treatment	WCI (%)	PCI (%)	PCI + WCI (%)
Reference 1929	1.3	3.3	4.6
Control 1999	1.8	2.4	4.2
KCl 1999	3.3	6.1	9.4
Manure 1999	1.9	5.7	7.6

The nutrient uplift, an explanation for the “illite-like” gradient in soils

Data presented above show that there is frequently an “illite-like” minerals gradient along the soil profile and that this gradient increases with time. Versailles experiments suggest that addition of potassium in soils may promote “illite-like” layer formation. Let us see what could be the driving force of the potassium increase in humic horizons inducing these “illite-like” gradients.

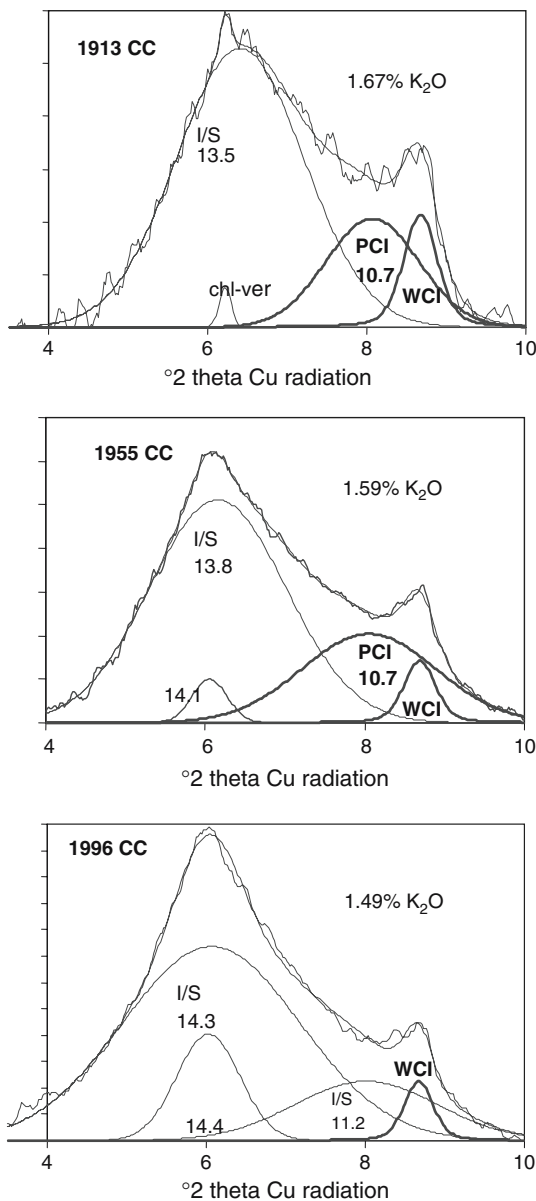


Fig. 7 Treated clay mineral diffractograms showing the change in illite (PCI + WCI) under continuous corn and non-fertilized cropping. The “illite-like” (PCI + WCI) content decreases sharply in the latter period of the experiment when very high corn yields were achieved using hybrids. “Illite-like” changes from 30 to 4% peak area on the diagrams. In the 1996 sample poorly crystallized illite (PCI) has shifted to a mixed layer mineral rich in illite (I/S)

The increase of “illite-like” layers near the surface is consistent with the “nutrient uplift hypothesis” expressed by Jobbagy and Jackson (2001) where some elements are selectively

moved up to the top soil by plant growth. This hypothesis proposes that “as long as nutrient uptake by plants takes place at greater depth than nutrient return to soil (as litter decay), a net uplift should be expected as a result of cycling”. Interstratified I/S clay minerals have a strong ability to fix potassium and doing so, increase their “illite-like” layer content (Fig. 3). Thus, potassium uplifted by plants may interact with interstratified illite-smectite clay minerals in top soils which should promote the formation of “illite-like” layer. This mechanism could explain the formation of “illite-like” layer in top soils and the gradual increase with time of “illite-like” layers as observed in the Baie d’Authie poldered sediments. Moreover, potassium trapped in clay layers becomes partly non-exchangeable. It means that nutrient uplift measured by Jobbagy and Jackson which takes into account only exchangeable ions most likely underestimates the potassium uplift in soils when “illite-like” clay minerals are produced.

One should note that organic matter also increase near the surface. Organic matter has the ability to complex Aluminum ions and doing this, could prevent HI layer formation. In this case, organic matter would increase interlayer sites available to potassium. Organic matter could therefore indirectly favor “illite-like” layer formation.

A potassium reservoir, a new view of illitic clay minerals

For ecosystem dynamics, the “illite-like” layers increase in the humic horizon would be of little interest if plants cannot use this accumulated potassium. However, many studies showed that interlayer potassium is used by plants (e.g. Shaik et al. 1994, Springob and Richter 1998). Velde and Peck (2002) showed XRD diffractograms evidencing that potassium depletion parallels “illite-like” layer destabilization which allow us to propose a new vision of the illitic clay minerals in soils. We propose that illitic clay minerals are a reservoir which is refueled by potassium translocation and emptied by plant uptake. According to the “nutrient uplift” theory (Jobbagy and

Jackson 2001) plants tend to increase available potassium near the surface. We propose that this potassium is partly fixed in 2:1 interlayers. This fixation may prevent potassium leaching and concentrate potassium near the surface. As it is considered that the majority of the roots of temperate vegetation (Schenk and Jackson 2002) are in the top 20 cm, the reservoir is fuller in the root zone than below. If the balance between potassium translocation and plant uptake is positive, as in the baie d'Authie, a gradual increase of “illite-like” layers near the surface should be expected. If the balance is negative, as we saw in cropping systems without potassium fertilization, “illite-like” layers soil content should decrease.

The conceptual model of “illite-like” layers as a potassium reservoir which is refueled by nutrient uplift and depleted by cropping may also explain historical facts. Indeed, cycles of fallow or moderate grazing (as in the baie d'Authie) and cropping periods should lead to a balance between potassium uplift and potassium exportation. The abandonment of such traditional agricultural practices recommended for centuries (de Serres 1620) due to the conversion of animal powered farming to mechanical methods in the 1950's induced a high requirement in potassium fertilization. Sustainable agricultural methods must take into account the “illite-like” potassium reservoir.

This view of illitic clay minerals as a potassium reservoir can also have important application in natural ecosystems. If it seems obvious that “illite-like” quantity is increasing in the humic horizon and that potassium contained in these “illite-like” layers is available for some plants, the fact that all plants can take this potassium is unclear. Field and greenhouse experiments suggest that *Taraxacum officinale* is a poorer competitor for potassium than common grass such as *Agrostis tenuis*, *Festuca rubra*, *Poa pratensis*, *Alopecurus pratensis* and *Dactylis glomerata* (Tilman et al. 1999). A lower ability to take up potassium from “illite-like” clay minerals could be an explanation of this lower ability to compete for potassium. It has been established (e.g. Vitousek et al. 1997) that human activities are increasing the availability of nitrogen over large region of earth. Because of this modification of the nitrogen cycle,

some N-limited ecosystems should shift to a K-limitation. This limitation has already been illustrated for bog vegetation (Hoosbeek et al. 2002; Bragazza et al. 2004). In this context, plants which are able to destabilize “illite-like” layers to take potassium would necessarily be favored. In these cases, 2:1 clay minerals would act as an inter-specific competition factor.

Conclusion

Illitic clay minerals, as exchangeable potassium and potassic primary minerals show rapid variations in space and time. This dynamic can be monitored by XRD study, which allows one to consider the non-exchangeable potassium pool not as an inactive black box but as a labile reservoir. This new point of view on the potassium cycle raises many questions: What are the mechanisms of “illite-like” layer formation and destabilization? Are “illite-layer” destabilization only a chemical process or does it involve soil microorganisms as Sheng (2005) suggests? Are all plants equally efficient to remove potassium from illite interlayer? And if not, what are the consequences for plant competition and plant community dynamics?

All these important questions are still widely open and suggest that further research on the topic is urgently needed. Such contributions should contribute to a renewal of interest in the potassium cycle, which should be of great use to the fields of biogeochemistry, ecology and agronomy.

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