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Cadmium availability to plants in relation to major long-term changes in agronomy systems

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Abstract

Cd concentrations in food products may be controlled to some extent by reducing metal inputs in agrosystems. However, Cd is available to plants, so the management of its residual fraction in soil must be considered. Differential Cd uptake among crop species and cultivars is well known, but the long lasting effects of other agricultural practices are less clearly understood. Generally, cropping systems affect the physico-chemical properties of soil. These may produce subsequent changes in metal mobility and bioavailability. The effects of agricultural practices, e.g. crop rotation, fertilization, tillage method, and stubble treatments, were therefore examined. Attention was mostly focused on Cd concentrations in potato tubers and cereal grains that are the major plant-derived contributions to the European diet. Results from long-term field experiments at well separated locations indicate that: Cd concentration in grain is highest in wheat grown after a legume such as lupins, and lowest in wheat grown after a cereal; Cd in wheat grain and potato tubers can increase with increasing rates of nitrogen irrespective of the crop rotation; Cd in wheat grain can be influenced by Zn supply to the plant; a higher concentration of Cd is found in wheat grain in continuous wheat under direct drilling, compared to reduced till or conventional cultivation; high Cd can be measured in potato tubers growing on neutral or alkaline soils that have relatively low Cd concentration, and so the practice of adding lime to decrease Cd in tubers is questionable; the effects of stubble management and fallow in crop rotation are too inconsistent to allow conclusions to be drawn. Maximum increase in Cd concentration resulting from changes in the cropping system could be 0.04 mg kg^{-1} FW in wheat grain and 0.03 mg kg^{-1} FW in potato tubers. © 1998 Elsevier Science B.V.

Keywords: Cadmium; Crop system; Wheat grain; Potato tuber; Food quality

1. Introduction

Soil quality is a complex subject because soil has a variety of functions (Barth and L'Hermite, 1987). For rural land the most obvious are: the filtering of surface and groundwater, crop production affecting both yield and food quality, and an ecosystem function serving as a matrix for numerous living organisms and biological processes. Several abiotic and biotic processes can cause soil degradation; e.g., water and wind erosion, salinization, accumulation of chemical contaminants, physical degradation, increase in weeds and pests. All are serious problems. A report on soil quality stated that primary soil contaminants display the following: high persistence in the environment, high toxicity and bioaccumulation, relatively high mobility, and presence in significant quantities (de Haan et al., 1989). Accordingly,

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Cd is of special interest in assessments of soil quality.

To protect human health, the concentration of contaminants in food products must be controlled. In many countries, maximum permissible concentrations (MPC) for Cd have been set by national health authorities (Ewers, 1991; Tiller et al., 1997). Soil Cd concentrations in food products may be controlled slightly by reducing metal inputs in agrosystems. However, soil Cd is available to plants and the management of its residual fraction in soil must be considered. Resulting changes in soil properties (e.g., pH, cation exchange capacity, organic matter, redox potential, oxide content, and microbial biomass) because of alterations to agricultural systems may produce changes in the mobility and plant availability of chemicals such as Cd. These long lasting effects are not clearly understood because the results are frequently contradictory. This paper focuses on the interactions between major agricultural practices, i.e., crop rotation, fertilization, tillage method, and stubble treatments, and Cd availability to plants, by summarizing results from long-term field experiments. Attention is mostly restricted to Cd concentrations in potatoes and cereal grains that are the major plant-derived contributions to the European diet. Relevant data on grassland is also considered.

2. What risks?

The main inputs of trace elements to agricultural soils are: atmospheric deposition, fertilizers such as phosphates, pesticides, and animal manures (Merian, 1991; Adriano, 1992; Alloway, 1995). Minor sources of contamination such as sewage sludge, municipal solid wastes, and industrial wastes are important because of their regional or local impacts. In France, 70% of industrial facilities are located in rural areas. So, sometimes, the input of trace elements from a local source cannot be neglected.

Two case studies demonstrate the accumulation of Cd in surface soil from the increase in anthropogenic activities. Cadmium concentration in plough layer depth soils from Rothamsted Experimental Station, UK has increased by between 20–55% above the historical background level over the last 130 years (1861–1989) (Jones et al., 1991). This corresponds to an increase from 1.9 to 5.4 g Cd ha^{-1} yr^{-1} with an average of 3.2 g Cd ha^{-1} yr^{-1}; inputs on P-treated plots appeared to range from 3.1 (arable crop) to 7.2 g Cd ha^{-1} yr^{-1} (grassland). Similar increases in the concentration of Cd were also reported at the INRA Versailles Centre, France (Fig. 1; Juste and Tauzin, 1986). Input from atmospheric fallout was estimated to account for 2.7 g Cd ha^{-1} yr^{-1}. P-fertilizers increased the soil concentration by 2 to 6.8 g Cd ha^{-1} yr^{-1}. In the FYM-treated plots, cadmium increased, on average, by 3.2 g Cd ha^{-1} yr^{-1}. Concerning the large scale pollution of the troposphere of the northern hemisphere, analysis of Greenland snow cores covering the time scale 1967–1989 showed that Cd concentrations have decreased by about 2.5 fold (Görlach et al., 1991).

Any soil protection policy must aim to protect soil for human health and as a natural resource. The need to protect consumers from chronic toxicity is the scientific motive for setting guidelines on trace element concentrations in food and feed. The threat of Cd to animals and humans has been demonstrated in several epidemiological studies (Wagner, 1993). Long-term ingestion of large amounts of Cd led to Cd accumulation in the kidney with a very long half-time period (10 to 30 years) resulting in its dysfunction (Stoeppler, 1991). Provisional tolerable weekly intake (PTWI) for adults is 400–500 μg for cadmium (Ewers, 1991). Cd is primarily of concern today because intakes are already at the highest percentage of PTWI for any toxic metal in the

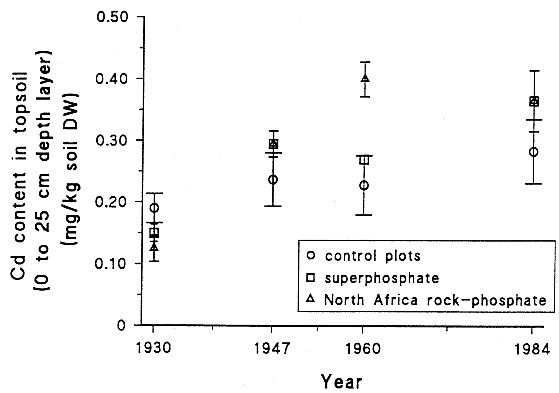

Fig. 1. Changes in Cd concentration in the plough layer of soils at INRA Versailles, France from 1930 to 1984 (Juste and Tauzin, 1986).

Table 1
Concentration of Cd in plant-derived produces and Cd exposure to human through French dietary intake

Cd content in marketed plant produces (μg kg^{-1})	Mean	Min	Max	sd
Leafy vegetables	27	2	215	6
Row vegetables	14	2	26	4
Potato tubers	23	2	72	4
Other vegetables	32	2	696	14
Fruits	4	1	10	1
Cereals	7	1	20	2

Dietary Cd to the general population in France	1978	1992
Daily intake (μg):		
Foods	28.0	18
Drinks	3.6	5
Total	31.6	23
Weekly intake (WI) (μg):		161
Provisional tolerable: weekly intake (PTWI) (μg)		420
WI vs. PTWI (%)		38

Direction Générale de la Santé, 1995.

average European diet (Table 1) (de Haan et al., 1989; Stoeppler, 1991). Concentration of Cd in pastures and feed (including feed additives), which indirectly influence human intake via meat and especially offal, and also in potato tubers and cereal grains, which are the major plant-derived elements of the European diet, and leafy vegetables, must be investigated.

Table 2 lists cadmium concentrations in whole wheat grain from several developed countries. Median concentrations of Cd in potato tubers in national surveys are about 0.03 mg kg^{-1} FW (Tiller et al., 1997). Values reported by Weigert (1991) are similar: 0.03 to 0.05 mg kg^{-1} FW. Potato tubers can represent 50% of mean adult dietary Cd intake in some countries such as Australia where 25% of marketed potatoes exceed the limit of 0.05 mg kg^{-1} FW (McLaughlin et al., 1994). Guideline values for Cd have been set in several European countries for feed and foodstuff. In Germany, guideline values for Cd are 0.1 mg kg^{-1} FW in potato tubers and in whole wheat grain (Ewers, 1991). In France, the MPC value for Cd was set at 1 mg kg^{-1} (at 88% DM) for animal feed.

Trends in the Cd content of herbage collected over the last 130 years from the Park Grass experiment at Rothamsted, UK indicated that recent (1960–1989) samples from the low pH soil contained between 182–231 μg Cd kg^{-1} DW, on average 70% higher than pre-1900 samples (102–152 mg Cd kg^{-1} DW) (Jones et al., 1991). The increase in soil Cd may partly account for Cd increase in herbage. However, direct inputs of atmospherically-derived Cd onto herbage are probably significant: e.g., between 20 and 60% of grassland foliar Cd at a rural site in Denmark (Hovmand et al., 1983); small particles often enter via the stomata where they dissolve and transport metal throughout the plant. Consequently, the intake of Cd by grazing livestock, and hence levels in offal, increases.

Risk assessment is difficult to perform because in soil dose-crop response relationships are complex. Soil has a buffering capacity, e.g. the effect of a contaminant can be delayed when metals bind to soil constituents or are chemically converted into inactive or insoluble compounds. In addition, soil is heteroge-

Table 2
Cd concentrations in wheat grain (mg kg^{-1} of dry matter) from field experiments in several developed countries

	France	USA			Australia	UK	FRG	Other data
References[a]		[1]	[4]	[5]	[2]	[3]	[6]	[7]
Min	0.015		0.08		0.013	0.004	0.04	0.045
Max	0.146		0.15		0.119	0.31	0.45	0.20
Mean	0.058	0.016		0.051		0.038		0.045–0.08
Guide value in FRG							0.12	
Guide value in Australia					0.059			

[a][1] Kubota et al. (1992), [2] Oliver et al. (1993), [3] Chaudri et al. (1995), [4] Zook et al. (1970), [5] Wolnik et al. (1983), [6] Delschen and Werner (1989), [7] Tiller et al. (1997).

neous and produces different responses depending on soil type and parent material. Moreover, different species of plants are more or less sensitive to trace element accumulation in soil (Fig. 2). Vegetables such as spinach and lettuce accumulate more Cd than French beans, whereas maize is less affected (Wagner, 1993; Alloway, 1995). For sewage sludge treated soil in the EU member states, soil Cd concentration guide values vary between 1–3 mg kg^{-1} soil DW in the topsoil (McGrath et al., 1994). This can however be misinterpreted as permission to pollute the soil up to this value. So, input of Cd per year is also sometimes restricted. In Sweden, the limit for addition in sewage sludge is 2 g Cd ha^{-1} yr^{-1} (McGrath et al., 1994). In comparison, the EU guide value for sludge-borne Cd input was set at 150 g Cd ha^{-1} yr^{-1}, and the sludge directive in France led to a 60 g Cd ha^{-1} yr^{-1} as a maximum. The guideline for extractable Cd with aqueous $NaNO_3$ was set at 0.03 mg kg^{-1} soil DW in Switzerland (Ewers, 1991). Tiller et al. (1997) noted that regulation of food quality has led to metal contamination controls in agriculture. Australia has one of the lowest Cd limits for wheat grain (0.05 mg kg^{-1} FW).

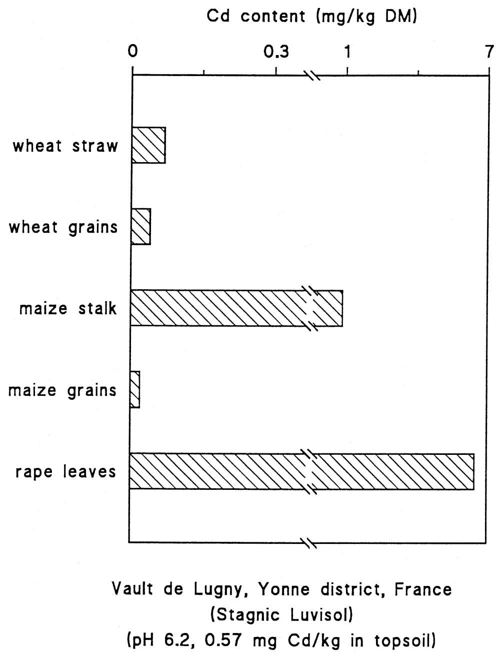

Fig. 2. Cd concentration depending on plant species and plant parts collected, in the same year, at a French experimental site (Vault de Lugny).

Because of its potential for leaching through soils, Cd can also affect water quality (surface and groundwater) (de Haan et al., 1989), but this point will not be further considered here.

3. Impact of changes in agricultural systems on Cd content in edible plant parts

The importance of soil factors such as pH, soil texture, organic matter, type of soil colloids, and plant factors such as species, cultivar, and rhizosphere on the transfer of cadmium from soil to crop is well recognized (Jackson and Alloway, 1992; Alloway, 1995; Tiller et al., 1997). Changes in agricultural systems may significantly affect the buffering of a contaminant by soil. Cd adsorption by clay, iron and manganese oxides, and organic matter decreases with decreasing pH (Alloway, 1995). One would therefore expect that any processes that modify the buffering capacity of soil, especially decreasing soil pH, would increase the Cd availability to plants. Many studies of these factors have been carried out in controlled conditions, but field experiments often prove more realistic.

3.1. Fertilizers and manure

3.1.1. Nitrogen level

In pot experiments, nitrogen fertilization based on ammonium supply has been shown to decrease soil pH in the rhizosphere (Marschner and Römheld, 1983). In the field, nitrification occurred rapidly, but this would still cause localised acidification, even though changes in soil pH are not easy to investigate because of soil variability. The significance of changes in Cd concentration in edible plant parts, and especially in cereal grain in relation to nitrogen fertilization, is also difficult to evaluate because N supply generally affects plant yield: an important confounding factor. In winter wheat, increasing amounts of nitrogen increased yield as well as Zn and Cu concentrations in grain (McGrath, 1985). In contrast, Jones and Johnston (1989) found no obvious relationship between increasing wheat grain yield and grain Cd concentration. The application of N fertilizer to Swiss Chard growing in a sludge treated soil containing 5 mg Cd kg^{-1} DW had the effect of increasing the yield and thus the uptake of Cd by 50% (de Villarroel et al., 1993).

In one field experiment, Oliver et al. (1993) found that the Cd concentration in wheat grain increased with increasing rates of nitrogen irrespective of the crop rotation. The highest additional Cd translocated into wheat grain was about 0.04 mg kg^{-1} FW. However, the same authors reported in another experiment that twice as much N applied as urea had no significant effect on the Cd concentration in wheat grain. Thus, one must be careful in extrapolation because such data have been obtained for relatively low N rates (i.e., 0 to 80 kg ha^{-1}) and the effect of higher N fertilization (> 200 kg ha^{-1}) which is practised in some northern European states needs further study. Extensification, in contrast, may result in nitrogen stress. Whether nitrogen stress during the post-flowering period intensifies leaf senescence, and thus modifies metal translocation to cereal grain is apparently not clear. Cd accumulation in flax seed was little affected by post-flowering N stress (Moraghan, 1993).

N fertilization may interact with other inputs, especially organic matter such as compost and sewage sludge. Potatoes were annually cropped on a sandy soil in a long-term experiment at the INRA Couhins experimental farm, near Bordeaux: the highest rate of ammonium nitrate (400 kg ha^{-1} yr^{-1}) led to an increase in the concentrations of Zn, Cu and Mn in tubers by 72%, 49%, and 114% respectively compared to the lowest one. However, for Cd, the difference between the lowest and the highest nitrogen levels was significant only when sludge application (10 t DM ha^{-1} 2 yr^{-1}) was combined with intensive N fertilization (Fig. 3). The Cd concentration in tubers did not increase in sludge-treated soil with no N fertilization compared to control soil.

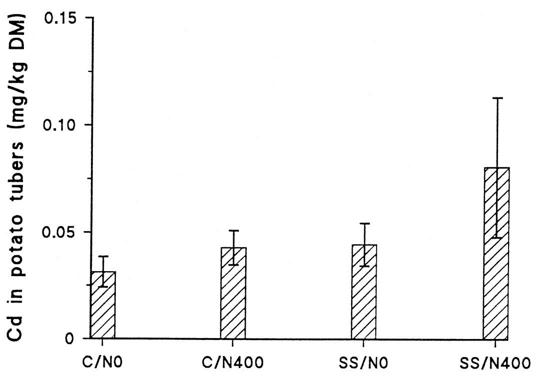

Fig. 3. Cd concentration in potato tubers grown in a sandy soil (INRA Couhins, Bordeaux, France) in relation to the rate of N (ammonium nitrate) supply and the application of sewage sludge. (C/N_0: untreated plots; C/N_{400}: 400 kg N ha^{-1}; SS/N_0: 10 Mg sewage sludge ha^{-1}(2 yr$)^{-1}$; SS/N_{400}: 10 Mg sewage sludge ha^{-1} 2 yr^{-1} and 400 kg N ha^{-1}).

3.1.2. NPK *vs.* Farmyard Manure (FyM)

Changes in soil Cd concentrations and Cd in cereal grain have been monitored in the continuous Rothamsted Classical Experiments (Jones and Johnston, 1989; Jones et al., 1991; Johnston and Jones, 1992) in relation to generally adopted farming practices such as FYM and NPK inputs. The yield of wheat on Broadbalk showed considerable differences over the period of the experiment (1877–1984), especially because of the increased yield potential of new varieties, the control of pathogens and climatic factors; however, no obvious relationship was found between increasing grain yield and grain Cd concentration. The FYM and NPK fertilizer treatments gave similar yields in each period, were subject to the same atmospheric deposition, and FYM and superphosphate were applied at the same rate throughout the 100-year period. For all crops since 1877–1881, concentrations in grain and offtake have been consistently greater from the NPK-fertilised plot than from the FYM-treated soil; moreover both differences have increased with time (Jones and Johnston, 1989). For the years 1979–1984, concentrations in wheat grain ranged from 0.016 to 0.05 mg Cd kg^{-1} for the FYM-treated plots, and from 0.063 to 0.09 mg Cd kg^{-1} for the NPK-fertilised plot. These changes were not consistent with the changes in the amount of total Cd in soil, which are larger in FYM-treated soil than in one receiving NPK fertilizers (Jones et al., 1987). No change was found in the organic matter content of the NPK-treated soil while that on the FYM-treated soil has gradually increased during the last 100 years by 2.5 fold. These data suggest that soil organic matter rather than soil pH is a more important determinant of Cd retention in soil. The explanation for the lowest Cd concentration in wheat grain occurring on FYM-treated plots may be also that soils receiving annual applications of FYM now have higher concentrations of Zn in the plough layer (142 mg Zn kg^{-1} soil DW) compared to that in the unmanured plots (83 mg Zn kg^{-1} soil DW) (see below).

A similar experiment is managed at the INRA experimental farm at Couhins. The plots were established in 1974 on an acid sandy soil (Arenic Udifluvent, pH 5.5). Fertilization of the NPK-fertilised or FYM-treated plots was adjusted to the same level (i.e., 200 kg N as ammonium nitrate, 250 kg P as superphosphate, 166 kg of K, and 50 kg of Mg ha^{-1}) assuming that 50% of the N added with FYM is mineralized during the same year. All field plots have been annually cropped with maize (Weissenhorn et al., 1995). Usually, only parts of plants have been removed for element analysis and grains for yield determination, crop residues being chopped and ploughed in every year at the end of winter. For the years 1976–1992, concentrations in maize ear leaf ranged from 0.5 to 0.2 mg Cd kg^{-1} for the FYM-treated soil, and from 0.5 to 1.05 mg Cd kg^{-1} for the NPK-fertilised soil. Since 1986, Cd concentrations in maize ear leaf and offtake have been consistently greater from the NPK-fertilised plot than from the FYM-treated soil (Fig. 4). In contrast, Cd concentrations in maize grain were similar in both treatments and ranged from 40 to 60 mg kg^{-1} DM apparently depending on the annual climatic conditions. As at Broadbalk, the amount of total Cd in soil at Couhins is larger in FYM-treated soil (0.48 mg Cd kg^{-1} DW) than in that receiving NPK fertilizers (0.33 mg kg^{-1} DW). However, soil organic matter and soil pH are higher in the FYM-treated plots than in the NPK-fertilised ones (i.e., 3.5% and 2.1% organic matter, and pH 6.4 and 5.4, respectively), thus these parameters appear important determinants of Cd retention in soil. In addition, the Zn content was twice as high in FYM-treated plots than in NPK-fertilised ones.

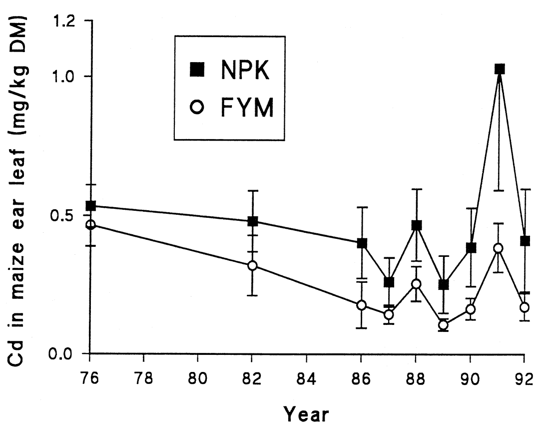

Fig. 4. Changes in Cd concentration in the ear leaf of maize plants cultivated in NPK-fertilised and FYM-treated plots at the INRA Couhins experimental farm, Bordeaux, France.

3.1.3. Phosphatic fertilizers

Since the 1970s many researchers have investigated Cd accumulation in soils caused by phosphate fertilizers and looked for effects in arable crops and pasture herbage (Johnston and Jones, 1992). Many authors concluded that Cd concentration in wheat was not significantly changed by phosphate fertilization. Mulla et al. (1980) showed that Cd was mainly accumulated in the topsoil in a citrus grove highly fertilized with triple superphosphate for 36 years, and that barley subsequently grown in the field contained no additional Cd. Relative excesses of P can reduce the uptake of Cd by plants (Alloway, 1995). The concentration of Cd in the fertilizer, the amount applied, soil type, and crop species are all important factors. Differences in the bioavailability of Cd in various forms of P fertiliser have been found in pot experiments; however, this result is often not obtained in field trials because of the residual Cd from earlier fertiliser applications.

Field experiments in Australia on three sites demonstrated that (i) applications of different fertilizer types, each with contrasting Cd content, did not influence tuber Cd in the current potato crop; (ii) soil Cd content from past fertilization and site characteristics dominated Cd uptake; and (iii) no relation was found between Cd introduced into the soil by phosphate and Cd in potato tubers (McLaughlin et al., 1994; Tiller et al., 1997). Fertilizer Cd content had no effect on Cd uptake by tubers even though Cd content in fertilizers differed by over 100 mg kg^{-1} (Sparrow et al., 1993). Increasing the rate of P application enhanced Cd uptake probably through an increase in root growth and access to residual Cd in the soil, and therefore introduction of low Cd fertilizers will have little immediate impact on Cd levels in potato tubers (Tiller et al., 1997).

In the case of pasture, P fertilizer as well as soil and grazing management are particularly significant for Cd intake by animals. In Australian and New Zealand experiments, the concentration of Cd in the dominant pasture plants responded linearly with applied phosphorus (Tiller et al., 1997). Cd concentrations were often higher in leguminous species and the Cd content of clover plants was closely related to the fertilizer Cd content. At Rothamsted, UK, Cd in herbage from the Park Grass Experiment was measured within three treatments: unmanured, P only, and NPK-fertilised soils. The increase in Cd concentration over time was larger on P-treated soils and was related to the additional retention of Cd added in the superphosphate in these acid grassland soils that contained 5% organic matter (Johnston and Jones, 1992).

It is difficult to generalize concerning changes in fertilizer inputs. In France, the amount of N and K fertilizers sold during the 1993–1994 period increased slightly by 3.1% and 2.1% respectively, but P remained constant. On average, the amount of fertilizer applied (in kg ha^{-1}) was 87 for N, 40 for P and 54 for K. At this P rate, superphosphate containing 10 mg Cd kg^{-1} would add 12.6 g Cd ha^{-1}. In comparison, Jones and Johnston (1992) estimated that atmospheric deposition ranged from 1.9 to 5.4 g Cd ha^{-1} in a semi-rural area. N fertilization levelled off at around 90 kg N ha^{-1} yr^{-1} since 1985–1986, whereas the P and K fertilization has decreased since 1988–1989 (Fig. 5). Fertilization depends however on the kind of production and the district: in 1993–1994, the N fertilization ranged from 18 kg N ha^{-1} (Corse or Limousin districts) up to 153 kg N ha^{-1} (Ile de France district); five major districts exceed the mean value for N fertilization by more than 30% (value > 113 kg N ha^{-1}). Experiments investigating these large differences are therefore needed.

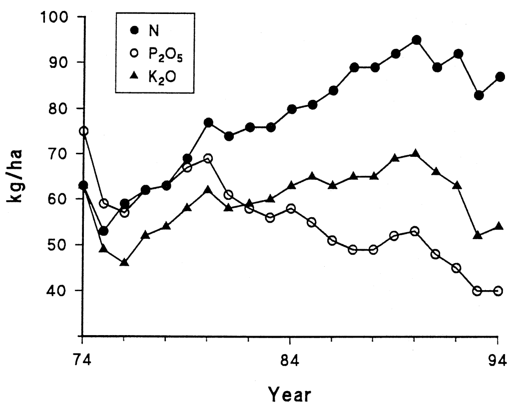

Fig. 5. Changes in usage of total N, P, and K fertilizers sold in France (Source: SNIE).

3.1.4. Zinc fertilization

Interaction between Cd and Zn has long been recognized, but effects may be additive, antagonistic or non-existent (Wagner, 1993; Alloway, 1995; Tiller et al., 1997). A negative relationship was the most frequently observed effect. The Cd–Zn interaction was investigated under farm-relevant conditions on Australian soils contaminated by residual Cd originating from fertilization (soil Cd content < 1 mg kg^{-1} DW) (Oliver et al., 1994a). These Xeralfs soils ranged in texture from sand to sandy clay loam and in pH (water) from 5 to 8, and were characterized by being marginally zinc deficient. Applications of low rates of Zn fertilizer, up to 5 kg Zn ha^{-1} in sulfate form, were found to decrease the Cd concentration in wheat grain by up to 50%, but these effects decreased with time since the zinc application. To be significant, the effect of residual zinc application needs a much higher rate, beyond 10 kg Zn ha^{-1}. This was interpreted as reflecting decreasing availability of the applied zinc because of time dependent soil reactions. In most cases, decreased Cd concentration in grain could not be attributed to growth dilution. Loss of root membrane integrity or release of phytosiderophores by wheat roots under conditions of nutrient deficiency were speculated to be involved (Tiller et al., 1997).

Field experiments in Australia at locations with different potato tuber Cd status and soils not Zn deficient showed that Zn application at rates up to 100 kg ha^{-1} did decrease tuber Cd level, but by less than 20% (Tiller et al., 1997); for herbage, application of very high rates of Zn sulfate (up to 64 kg ha^{-1}) did not appreciably decrease Cd concentrations in subterranean clover harvested in the following years.

The effect of soil acidification on Cd–Zn interaction in plants is questionable. Zn mobility would be expected to increase as soil pH decreases, making Cd uptake and translocation in the plant decrease. However, some agricultural materials such as superphosphate have a higher Cd than Zn content. Long-term changes in Cd:Zn ratio in the topsoil may therefore be plausible and may counter-balance soil acidification.

3.2. Liming practices

Consequences of soil acidification from ammonium-based fertilizers, acid deposition, and crop removals for hundred of years on metal mobilization and their plant uptake by plants have been reviewed elsewhere (Goulding and Blake, 1997).

Liming is frequently used to control soil pH and Cd uptake. Christensen (1984) showed that the Cd adsorptive capacity of soils increased by a factor of three for each increase of one pH unit between pH 4.0 to 7.7. Increasing soil pH value from 5.7 to 7.6 using basic slags in (truncated) Chromic Luvisols over jurassic limestones decreased Cd in wheat grain from 0.14 to 0.05 mg Cd kg^{-1} DW (Mench et al., 1997). The benefits of liming on grain cadmium in field experiments are much more complex and some field experiments carried out in Sweden, Finland, and Australia showed inconsistent responses of grain cadmium to liming (Oliver et al., 1994b; Tiller et al., 1997). Authors outlined the high affinity of the soil for Cd over the whole pH range studied (4.0–6.0) and/or the marked seasonal differences in the response slopes of the concentration of Cd in wheat and barley grain versus soil pH relationships at a particular site. Root distribution in relation to soil moisture status can be a keypoint. If the effect of liming does not readily extend into the subsoil and if adequate moisture is not maintained in the plough layer, cereal roots will be more active in the lower layers, leading to a reduced or no pH response. In contrast, if adequate moisture is maintained, cereal roots will remain in the topsoil, thus maximizing the Cd uptake as well as the influence of liming on soil pH. Tiller et al. (1997) reported that the growing seasons in which grain concentrations do not respond to pH change provide grain with the lowest Cd concentrations.

For vegetables grown on sewage sludge treated soils, the application of lime was shown to reduce the bioavailability of Cd to cabbage (by 43%) and lettuce (by 41%) but not to potato tubers (Jackson and Alloway, 1991). Similar trends for potato tubers can be found in field experiments in Tasmania and Australia (Tiller et al., 1997). Despite large rates of lime applications, changes in soil pH were often only one unit or less because of the buffering capacity of soil. The highest Cd concentration in tubers was found in neutral or alkaline soils which had relatively low Cd concentrations (Tiller et al., 1997). In an experiment at Versailles, calcium carbonate (1 mg ha^{-1} yr^{-1}) or basic slag (158 kg ha^{-1} yr^{-1}) were applied to a loamy soil from 1929 to the present. Although the soil pH increased from 6.4 to 7.9 and 7.6 respectively, and the Cd content in soil was constant, the Cd–HCl 0.1 M extractable fraction increased from 40 to 46% with $CaCO_3$ and from 43% to 61% with basic slag, compared to total Cd in soil (Juste and Tauzin, 1986). These results indicate that recommending liming to reduce Cd availability is questionable. Moreover, in saline soils, the effectiveness of limestones in decreasing crop Cd concentration may be markedly reduced.

Herbage from the Park Grass experiment, Rothamsted, UK was collected from two plots of different soil pH, 5.3 and 7.1, and bulked for five years intervals for the years 1861 to 1989. Concentrations of Cd in herbage from the limed soil were lower than those from the unlimed control (Jones et al., 1991): concentrations since liming began in 1903 have varied between 72 and 191 mg Cd kg^{-1} DW, whereas in the unlimed control they increased from 102–152 mg Cd kg^{-1} DW to more than 200 mg Cd kg^{-1} DW. In southern Australia, liming was investigated in a series of field trials on acidic pasture soils. Significant negative responses of cadmium levels to liming were found especially in subterranean clover, but not sufficient to appreciably decrease the Cd intake of grazing animals or to justify the expense of liming (Tiller et al., 1997).

3.3. Crop rotation and fallowing land practice

Studies of crop rotation generally compared treatments such as continuous cultivation, and a 2-year rotation cereal/legume, cereal/volunteer pasture and plant/fallow. Two experiments at well separated locations indicated that the Cd concentrations in grain were highest in wheat grown after lupins, and lowest in wheat grown after cereal (Oliver et al., 1993). Other treatments were not found to be significant. An effect of crop rotation on soil pH (range from 5.3 to 6.3) was reported in one experiment, but in two others no effect was found. Localized rhizosphere pH effects are possible, especially below the plough layer, because lupins are known to release citric acid which may increase Cd availability. Roots of a subsequent wheat crop may also colonize the root channels derived from the previous lupin crop (Tiller et al., 1997).

The effect of long-term cropping systems on adsorption of Cd was studied for soils obtained from two sites at Sutherland, in Iowa, USA (Basta and Tabatabai, 1992). Treatments with ammonium-forming fertilizers decreased the Cd adsorption maxima under continuous maize at both sites, while in general maize–soybean–maize–soybean and maize–oats–meadow–meadow cropping systems with or without N (ammoniacal fertiliser) treatments did not affect the metal adsorption maxima of soils.

Because of EU governmental programmes, fallowing land (set aside, with or without rotation) was reintroduced into European agricultural systems. Its long lasting effect on the buffering capacity of soil is not clear, and metal mobility and plant uptake may be modified. In sandy soils located in Southwest France, it was found that cultivated fallow induced a decrease in organic matter because little carbon inputs occurred and the water content in soil was higher than in cropped soil which resulted in an increase of the organic matter mineralization by soil microorganisms (see Section 3.5) (Plénet et al., 1993)

Results dealing with fallowing land practice and Cd availability to edible plant parts are very rare at the field scale. Some preliminary results for Cd mobility were obtained at the INRA Couhins experimental farm on plots with cadmium nitrate applied in a loamy-sandy soil. Cd concentrations in the plough layer ranged from 0.4 to 40 mg Cd kg^{-1} DW. Maize was cultivated twice and then subsequently fallowing was practiced on half of the plots and ryegrass cultivated on the others. After 3 years, changes in EDTA extractable Cd concentration were found to be insignificant between the two treatments, while a difference was found for Cd bound to Fe and Mn hydrous oxides (Linères, unpublished data). In a pot experiment, the effect of fallowing land and crop rotation was investigated using maize and tobacco which is a widely known leaf Cd-accumulator (Table 3). Whatever the previous crop, and the source or level of soil Cd, changes in Cd concentrations in the

Table 3
Mean cadmium concentration (mg kg^{-1} DM) in maize and tobacco shoots following crop or fallow in the subsequent year

Soil		A	B	C	D
Cd source		sludge	sludge	geochemical	Cd nitrate
Cd content in soil (mg kg^{-1} soil DW)		5.3	20	0.14	10.7
Subsequent crop	Previous treatment				
Maize					
	Fallow	25 c	80 c	3.1 b	43 c
	Maize	36 c	95 c	2.0 b	39 c
	Tobacco	30 c	76 c	2.0 b	44 c
Tobacco					
	Fallow	126 a	318 a	6.5 a	88 a
	Maize	84 b	203 b	3.5 b	61 b
	Tobacco	75 b	210 b	3.9 b	69 b

Within a column, mean values followed by the same letter are not statistically different ($P < 0.05$, Newmann–Keuls test) (Source: Mench et al., 1993).

shoots of subsequent plant species were insignificant. In contrast, Cd concentration in the tobacco shoots increased following a 1 yr-fallow for all soils and Cd levels.

3.4. Tillage practices

The effect of tillage practices, i.e., conventional cultivation, reduced till, direct drill, on Cd concentration in wheat grain were generally too inconsistent to allow conclusions to be drawn. However, higher Cd concentrations were found in wheat grain ($>30\%$) grown was found in a continuous wheat rotation under direct drilling, compared to reduced till or conventional cultivation (Tiller et al., 1997). This may be due to the restriction of root growth to the upper soil horizons where nutrients and anthropic metals such as Cd are mainly located.

Another process must be considered for cultivation effects. Cereal roots in the case of direct drill could explore the pores created by the previous crop. In the case of lupin, it has been found that roots acidified their rhizosphere and released citric acid under P deficiency (see above). Possible zones of soil acidification would be retained under direct drill and could preferentially be colonized by wheat roots.

3.5. Stubble management

In recent decades, there have been marked changes in organic residue management. Wheat straw is mostly taken off or sometimes burnt in France for example, whereas FYM is often not available in rural areas with intensive arable agriculture. This could have an effect on the organic matter content of the soil and its buffering capacity. In two long-term experiments located on loamy sandy soils in South West France, changes in organic carbon status were measured over a 22- and 25-year period respectively. Whatever the treatment applied, i.e., continuous maize crop with stalks returned to the soil or removed, soil carbon concentration in the plough layer decreased from 8.3 to 6.9 g kg^{-1} over 22-year and from 15.5 to 9.65 g kg^{-1} over 25-year (Plénet et al., 1993). In contrast, introducing a cultivated fallow resulted in a marked decay of organic matter, averaging 7 t organic C ha^{-1} during a 10-year period. Whether oxidation of organic matter enhances Cd in foodstuffs is not certain, organic matter content is however an important factor limiting Cd uptake in grassland (Johnston and Jones, 1992). In an Australian experiment, stubble treatments (e.g., stubble burning, incorporation into the soil, mulching) had no significant effect on grain Cd concentration for the following wheat crop (Tiller et al., 1997).

3.6. Irrigation and soil salinity

A field survey in Australia concluded that soil salinity and especially soil (water) extractable Cl were linked with Cd concentrations in potato tubers (McLaughlin et al., 1994). Chloride in the irrigation water can also be an important factor, which can be greater than the influence of soil pH and soil Cd content (Tiller et al., 1997).

3.7. Plant breeding and plant species management

In the Classical Rothamsted Experiments, no obvious relationship was found between Cd content in grain and yield although changes in cultivars occurred over the 130-year period (Johnston and Jones, 1992). Andersson and Pettersson (1981), Tiller et al. (1997) and Chaudri et al. (1995) reported that soil and site factors had greater impact on grain Cd concentrations than varietal differences. However, at sites with higher Cd in grain, the newly released wheat cultivars have higher Cd concentration than the oldest ones: the range was approximately two-fold (Tiller et al., 1997). Protein content is an important criterion for selection, but the increase in SH groups might be involved in the higher translocation of Cd from leaves into grain. Cd concentration is generally higher in grain of *Triticum durum* than in that of *T. aestivum*. Analysis of Cd in potato cultivars was done by McLaughlin et al. (1995): the range in values was from 0.03 to 0.06 mg kg^{-1} FW.

The effect of plant genotype is well known, and in pasture species marked differences in Cd uptake occur. Generally, Compositae and Brassiccae contain high Cd levels in shoots (Stoeppler, 1991; Wagner, 1993). Tiller et al. (1997) reported that capeweed (*Arctotheca calendula*) contained 10 and 40 times the Cd concentrations in subterranean clover and ryegrass, respectively. So, changes in plant species available to grazing animals via farm management can have an impact on Cd uptake.

Present understanding of Cd uptake and accumulation processes that are important in agriculture production are quite limited. Most studies to date have used high-level Cd exposure to elicit responses, far above those encountered in agricultural production. Recent investigations have raised the possibility for altering Cd accumulation in crop plants and in particular in edible parts. Attempts to manipulate plants to reduce the cadmium content of crop were reviewed by Wagner (1993).

4. Conclusions

Studies in Germany and in the United Kingdom on grain samples from earlier years reveal no increase in the cadmium concentration, neither during the recent period (Chaudri et al., 1995) nor when very old wheat samples were compared with those of recent years (Jones and Johnston, 1989; Weigert, 1991). However, some agricultural products already have Cd concentrations over MPC in foods established in several states (Jackson and Alloway, 1992; Chaudri et al., 1995). To protect the food chain in the long-term, decreased inputs must be practised. Using fertilizers of lower Cd concentration, reducing Cd in atmospheric emissions and in recycled wastes products such as sewage sludge will protect soil quality. Moreover, this strategy is not sufficient for quality of food produced on soils already at risk. Clearly, changes in agronomic practises must be combined with a decrease in metal inputs. Long-term experiments in the UK and Australia outlined that fertilizers, crop rotation and cultivar, liming, cultivation, and irrigation have the potential to increase or reduce uptake of cadmium by crops. Indeed, a major challenge remains to identify agricultural regions in which edible plant parts such as wheat grain, potato tuber and leafy vegetables approach or exceed the maximum permissible concentration for metals such as Cd established by national authorities or by commercial requirement (Oliver et al., 1994a).

Predicting the effect of long-term changes in production systems on human exposure is a challenge. Here, a simple calculation is proposed. The maximum additional Cd concentration for wheat grain because of changes in crop rotation reported by Tiller et al. (1997) was in the range of 0.04 mg kg^{-1} FW (0.045 on DM basis). Additional Cd content in potato tubers often is 0.03 mg kg^{-1} FW. Now, Jackson and Alloway (1992) reported that the amount of cereals intake per day in Europe was 250 g DM, and that Cd content in flour can decrease no more than 50% compared to whole grain. The amount of potato tuber intake per year ranges on average from 60 to 140 kg FW in France. Consequently, the additional contribution of cereal grains and potato tubers would be in the range of 5.6 mg Cd day^{-1}, and 4–11.5 mg Cd day^{-1}. Total daily dietary intake for Cd was estimated at about 23 mg Cd day^{-1} in France (Table 1); in comparison, the increase in Cd in cereals and potato tubers alone may lead to an increase in the range of 41% to 74% of the Cd dietary intake (i.e., to 32–40 mg Cd day^{-1}).

In conclusion, one would emphasise the value of having a number of long-term field experiments taking account of various soil types and climatic conditions. These can be used in particular for predicting the effect of changes in rural land use and agricultural practices on foodstuff and feed quality. The reversibility of changes in agronomy must also be investigated; data is lacking on long-term effects and reversibility of fallowing land practice (i.e., set-aside) or intensive/extensive N fertilization with continuous cropping. More data are also needed regarding leafy vegetables, especially in urban areas, and fodder. Last but not least, numerous studies have focused on Cd but data for other trace elements which are plant-available, mobile and persistent in ecosystems, and potentially toxic or phytotoxic, e.g., Ni, Tl, and Zn, are more rare. Clearly for trace elements as well as other pollutants, reliable guidelines for the manipulation of agronomic practices must be provided, especially because any relationship between increasing contaminant content in soil and crop concentration may be masked by numerous factors.

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