The Role of Soil Biontic Processes in the Search of Quantitative Indexes of Soil Quality.

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ABSTRACT

Monitoring soil quality involves measurements of soil properties over periods of several years. This article examines the potential role of chemical SOM composition and of soil biontic processes as faster indexes of soil quality.

Soil quality was quantified on the basis of individual soil attributes and time. Chemical characterization of soil organic matter by solid ^{13}C-NMR and Py-FIMS showed that a degraded Gleysol cropped to corn during 25 years suffered C losses from all chemical functional groups. Surprisingly, aromatic-C was lost at proportional higher rates than aliphatic-C. These results indicate that chemical composition of SOM determined by quantitative non-destructive methods can be used as quality indexes in agricultural soils.

Biontic processes reflect changes in soil quality over shorter periods than total or type of SOM. Microbial specific respiration (qCO_2) is a soil attribute that consistently reflected differences in soil quality. It was hypothesized that qCO_2, the microbial adenylate energy charge and anabolic reduction charge may permit to asses soil quality over monitoring periods of weeks to <5y.

Soil As A Multilevel Organization

Soils can be represented as hierarchical systems consisting of different levels of energy and trophic interaction among biotic components (Figure 1). Since the start of evolution, autotrophic organisms have served as the basis for this multilevel structure. Autotrophs generate their tissue C and N from inorganic sources like Na_2CO_3, CO_2, NH_3 and N_2. They derive their energy source (ATP) from light absorption and the oxidation of inorganic substrates. Autotrophs contributed significantly to the initial accretion of soil organic matter in aquatic and terrestrial systems.

Heterotrophic decomposers occupy the second level of the organization. Under aerobic conditions, heterotrophs play an important role in decomposing soil organic matter. These organisms derive their energy (ATP) and carbon sources from the oxidation of soil organic molecules. Soil fauna represents a higher level of cell metabolic organization. Grazers feed on the primary biomass produced at the two lowest levels of the pyramid (Clarholm, 1984).

Temperature, precipitation and wind are external abiotic agents regulating biotic activities within this multilevel organization. The biotic and abiotic interactions control organic matter transformation and the release of nutrients to plants (NH_4^+, NO_3^-, SO_4^{-2}) and gases (CO_2, CH_4, N_2O, H_2S, PH_4) to the atmosphere.

The inner circle of Figure 1 represents the physical boundaries of soil aggregates. In soil systems, most biotic-abiotic interactions and energy transfer processes take place within the boundaries or at the surface of soil aggregates (Tisdall and Oades, 1982; Elliot, 1986). The chemical recalcitrance and physical protection of organic matter are defined and controlled by processes carried out at this level. Biochemical transformation of soil organic matter (SOM) and chemical polymerization reactions take place within the webb of soil organic molecules and between organic molecules and clay surfaces (Schnitzer, 1991).

Man, at the top of the pyramid, alters the system by introducing disturbances through the introduction of agronomic practices. Implementation of specific crop rotations or the application of fertilizers, manure or chemical pesticides may not only affect SOM transformations, but also the quality of soil, water, air, food and crop productivity (Campbell et al., 1991; Chu et al., 1990 and Zentner et al., 1987).

The interaction of man with the abiotic and biotic components in the hierachical system controls soil quality. The relative contributions of physical, chemical and biological properties to soil quality have not been

quantified. Within this context, the objective of this article is to analyze the potential role of chemical, biological and biochemical soil attributes as indexes of soil quality.

Soil Quality and Attribute Quantities

Soil quality is the ability of a soil to accept, store and recycle nutrients, water and energy (Anderson and Gregorich, 1984). It is preferable to define soil quality on the basis of inherent soil properties instead of productivity. Productivity is determined by the efficiency in the use and management of resource inputs (Larson and Pierce, 1991). Monitoring changes of soil quality requires measurements of soil attributes over time and space. These measurements can then be compared to attributes of a standard reference soil pedon. Individual soil attributes (q_a) are defined by intrinsic chemical, physical or biochemical soil properties. Chemical attributes may be represented by pH, organic-C,N,P, S, redox potential, electrical conductivity and sodicity. Bulk density, compaction, thickness of A horizons, water retention, water stable aggregates, sand, silt and clay represent some phsical attributes. A minimum set of nine soil attributes have been proposed to monitor changes in soil quality (Larson and Pierce, 1991).

Biochemical properties may include the total soil biomass, active soil biomass, available energy of active microbial biomass, taxa of soil organisms, intra- and extra-cellular enzyme activities, and adaptation capacity of microbial biomass to environmental stress (Tiedje, 1990). Microbial processes are fast and may reflect rapid changes in soil quality. The assessment of soil quality over short periods is complicated by the fact that trend changes may be of the same magnitude as random or periodical changes.

Soil quality (Qs) may be defined in terms of individual attribute qualities (Qa) in dimensions of time and space:

$$Qs=f[Qa(t,s)] \qquad (1)$$

where t=time and s=space.

Noteworthy, the quantitative function defining Qs in term of a group of Qa has yet to be defined. For the effects of simplicity, the following discussion deals with soil quality in terms of single soil attributes and time.

Monitoring changes in soil quality involves the quantification of the rate of change of a given soil property according to:

$$\frac{dQa}{dt} = ABS\sum_{j=0}^{t} \frac{(qa)tj - (qa)tj+1}{tj+1 - tj} \qquad (2)$$

where t_j=time of first observation and ABS is the absolute rate of change.

Soil quality can also be defined in terms of a reference standard. Knowing the individual attributes in a standard reference allows the variables to be normalized so that dQa becomes small. From a chemical, biological and biochemical viewpoint, this standard reference may be represented by: the total soil organic-C, microbial biomass and respiration at the time when a cropping system is first implemented (Larson and Pierce, 1991). The state of change in soil quality for a particular soil attribute may then be described by:

$$dQa = \frac{qa - qstd}{qstd} \qquad (3)$$

where q_a=attribute 'a', q_{std}=attribute in reference standard. dQa may be positive, negative or zero. A positive dQa indicates aggraded attribute; a negative value, degraded; and zero, a sustained condition.

In the following section we present information that relates the total amount of organic matter with soil quality.

Total Soil Organic Matter

In agro-ecosystems, the amount of soil organic matter is an important indicator of soil quality (Hajek et al., 1990). Soil organic matter has been studied in the Canadian Prairies over time (Biederbeck et al, 1984; Freyman et al. 1984), space (Gregorich and Anderson, 1985: Pennok and de Jong, 1987) and composition (Schnitzer, 1991).

A decline of SOM with respect to a standard reference involves a decrease in soil quality. Losses of SOM remove plant nutrients, deteriorates soil structure and decreases the water holding capacity of soils. Increasing the levels of SOM in soils of Saskatchewan and Alberta improves soil quality by increasing the amounts of mineralizable nitrogen and crop production (Campbell et al.,1990). These findings, however, do not hold true in all soil systems. Soils with similar or higher SOM levels may mineralize substantially less nitrogen (Table 1). The biochemical rates of element mineralizaiton are related not only to the amount of SOM but also to other intrinsic soil properties such as clay minerals and pH. Andept soils have a high SOM content but

low N mineralization rates due to stabilization of organic matter as organo-allophane complexes and low N recycling from dead microbial biomass (Monreal and McGill, 1990).

Abiotic factors such as precipitation and temperature also affect soil quality. Waterlogging of soils for extended periods, i.e. Gleysols or meadow complexes, result in SOM accretion but low rates of N mineralization, potential emmissions of CH_4, N_2O and actual low crop productivity (Ayres et al., 1985). From an environmental and crop production standpoint, the accretion of SOM in wet soils would not increase soil quality.

In general, the amount of total soil organic matter alone may not always reflect the general state of soil quality. Other attributes like nutrient mineralization rates may be used with total organic matter to better asses soil quality. Campbell et al., (1991) suggested that the product of the potentially mineralizable N by its rate of mineralization may be used as an index of soil quality.

Chemical Composition of Soil Organic Matter

Some alterations of the chemical composition of soil organic matter may increase soil quality by improving intrinsic soil attributes (Dormaar, 1983; Arshad et al., 1990). Organic matter represents a continumm of partially decayed (non-humus); fully decomposed and resynthesized plant and animal residues (humus). Chemical characterization of SOM indicate that humic substances consist of aromatic rings which are joined by long-chain alkyl structures to form a flexible network (Schulten et al., 1991). It has been assumed that soil microbes decompose the aliphatic chains in preference to the aromatic moiety. The aromatic unalterd portion becomes part of the recalcitrant organic matter (Campbell et al., 1967; Anderson, 1979; McGill et al., 1981). Hence, chemical stabilization would protect SOM from microbial attack and biochemical losses.

The role played by the chemically recalcitrant organic matter in soil properties has not been elucidated. From a nutrient cycling view-point, lesser amounts of stable SOM may result in greater availability of carbon, energy and nutrients for soil organisms and thus improved plant nutrient availability. In a study conducted in Alberta, zero-tillage improved soil quality by increasing the amounts of organic-C and N with respect to a soil under conventional tillage. The improvement in soil quality was also reflected in the chemical nature of SOM. The aggraded soil under no-till showed greater relative proportions of aliphatic-C and a reduction of aromaticity (Arshad et al., 1990). The shift in the relative amounts of these two functional groups was considered by the authors as an improvement of soil quality.

Does a reduction in aromaticity, however, result in better soil quality? Recent studies conducted by the present authors suggest differently. Soil organic matter in adjacent cultivated and uncultivated Gleysols of Ontario was characterized by solid state ^{13}C-NMR and pyrolysis field ionization mass spectrometry (Py-FIMS). The cultivated soil has been continuously cropped to corn (CC) for the last 25 years and cultivated between 80-100y according to historic settlement records. The adjacent undisturbed soil was under a mixed hardwood forest. The quantitative ^{13}C NMR procedure is described by Monreal et al., (1992).

Cultivation reduced organic-C in the 0-5 cm of soil by 65% and in the whole solum by 39% (Table 2). This information together with field observations of poor soil structure (Gregorich, 1992, unpublished information) indicate that the soil under CC is degraded. Characterization of organic-C by solid quantitative ^{13}C-NMR showed all functional groups of SOM were present in the 0-5 cm of the forest soil. Aromatic-C was 4.1 and 1.0 t ha^{-1} and it represented 12 and 9% of the total observed carbon in the forest and corn soils, respectively. In comparisson, aliphatic-C represented 47% of the soil organic carbon in both the forest and corn soils. Loss of SOM in the corn soil was followed by net degradation of C from each one of the chemical functional groups. Interestingly, cultivation induced higher proportional C losses from aromatics than from aliphatic compounds (Table 2). Losses of C from other functional groups varied between 59 and 77% of the total organic carbon. Differential C losses among the chemical functional groups suggest that chemical composition of SOM regulate rates of biochemical decomposition and the type of carbon lost from soils.

The previous NMR results were confirmed by Py-FIMS analysis conducted on separate soil samples but taken from the same field. Although Py-FIMS is considered a semi-quantitative technique, it shows significant amounts of fragments consisting of mono- and di-lignin aromatic compounds in the forest sample and very few of these fragments in the corn soil samples (Figure 2A,B).

Although the exact reasons for these results are unknown, biontic metabolism may be responsible for the depletion of aromatic compounds. Selective aromatic-C removal by erosion is not a factor since aromatic-C was observed by solid ^{13}C-NMR in different particle size fractions (Monreal, 1992, unpublished data). It is hypothesized that crop fertilization with 130 kg ha^{-1}y^{-1} of urea-N stimulated microbial activity. Aromatic compounds were then used as carbon and energy sources. It is further hypothesized that a significant proportion of the active soil microorganisms in the corn field consist of Pseudomonas.These organisms can grow on phenols and are not restricted to aliphatic amides (Dawes and Large, 1973). Further research into the

mechanisms decomposing soil aromatic-C in these Gleysols is warranted.

These results suggest the following:

- Under field conditions, aromatic compounds can be utilized by soil organisms as sources of carbon and energy at rates slightly higher than aliphatic compounds.

- In the cultivated Gleysol, organic-C is not stabilized as aromatic compounds. Therefore, any process of chemical stabilization must be related to the interaction of other functional groups of organic matter with clay colloids.

- Reduction of aromaticity did not increase the quality of the cultivated Gleysol as it did in the no-till system of Alberta (Arshad, et al., 1990). Conversely, loss in lignin type of compounds paralled losses of SOM and deterioration of soil properties. Further studies are needed to define the role excerted by aromatic compounds on soil physical properties like aggregation and soil structure.

In summary, deterioration of a Gleysol under CC was followed by losses of C from the soil organic pool and from each one of the chemical functional groups. Proportional losses of aromatic-C were 9% higher than from aliphatic compounds. These results suggest that chemical characterization of SOM by non-destructive and non-intrusive methods can provide reliable information on soil quality.

Accretion or depletion of total SOM and their chemical constituents is detectable after several years (i.e. >10 y) of cultivation. Controlling soil degrading processes, however, requires a fast response allowing a rapid change in land use and/or crop management srategy. Hence, soil attributes capable of showing changes over shorter periods (<5 yrs) are most useful in detecting the state of soil quality. Within this context, the total soil microbial biomass and the biochemical structure of active microorganisms may be more effective indexes than inert organic matter attributes.

Microbial Biomass

The soil microbial biomass includes live and dead bacteria, fungi, actinomycetes, algae, protozoa and microfauna (Jenkinson and Ladd, 1981) and can be measured by the chloroform-fumigation or the chloroform-extraction method (Joergensen and Brooks, 1990). The microbial biomass is the most dynamic fraction of soil organic matter as it comprises between 1 to 3% of the soil organic-C.

Observable changes in amounts of microbial biomass-C are detected earlier than for organic-C (Carter, 1986). Because microbial-C changes faster than soil-C, the ratio microbial-C/soil-C may reflect the equilibrium and rate of total SOM change in agro-ecosystems (Sparling, 1991). This dynamic fraction varies over short periods in response to environmental factors and over longer periods due to the effects of crop rotations and soil management (McGill et al., 1986; Campbell et al., 1990). Environmental stress caused by the additions of sewage sludge containing toxic metals also affects the microbial biomass (Brook and McGrath, 1984).

Specific microbial respiration (qCO_2) is defined as the amount of CO_2-C evolved per unit soil biomass-C. This specific soil respiration may be another useful attribute to be used as quantitative index of soil quality. This parameter was used to asses the impact of various crop rotations on organic-C (Anderson and Domsch, 1990).

In the Canadian Prairies, measurement of biomass-C and specific respiration has helped to asses the affect of tillage, precipitation, temperature and crop rotations on the status of SOM (McGill et al., 1986; Biederbeck et al. 1984 and Campbell et al., 1991). The information of Table 3 also suggests that individual biological and biochemical attributes used in isolation may not always show the effect of crop rotations on soil quality. For example, microbial biomass size and specific respiration rates in both Chernozems did not reflect differences in organic-C between FW and CW rotations. The rate of CO_2 respiration reflected these differences, however, the interpretation of CO_2 respiration must be done with caution. Increasing CO_2 evolution from both Chernozems under CW with respect to the FW baseline may indicate increased metabolic activity, substrate availability or a stress reaction, but not necessarily the degree of soil quality.

Noteworthy, the set of biotic parameters in Table 3 were determined during incubation studies of freshly collected soil samples or samples stored for many months. This form of soil sample handling may tend to mask the true rate of processes under field conditions. Therefore, it may be necessary to quantify "in situ" the CO_2 respiration rates before making definite assesments on soil quality.

Monitoring quantitative changes of chemical, physical and biological soil attributes together may help to identify a biontic soil property capable of reflecting the state of soil quality. For this purpose, we assesed the state of soil quality by using equations 2 and 3 and identifying standard references. The chosen standards were the Brown Chernozem cultivated in 1967; an undisturbed grassed site within the thin Black Chernozemic plots; and a Gray Luvisol

cultivated in 1930 (Table 3). Based on the latter, the Brown Chernozem under CW is considered an aggraded system because it increased the quality of the organic-N attribute by 12.5%. In comparison, the thin Black Chernozem under CW is degraded because it reduced the thickness of the A horizon and the quality of the SOM attribute by 44% and relative to its standard reference (Table 4).

The information presented in Tables 3 and 4 show that specific respiration was the only biontic attribute capable of describing the state of soil quality in different crop rotation systems relative to their standard references. The application of the specific respiration concept as an index for soil quality requires further testing under a variety of field conditions. Spatial variabiltiy may then be assessed. Overall, these results suggest that measurements of microbial biomass over a growing season and of soil microbial respiration over a few days are an effective alternative and complement long-term (>5y) monitoring programs.

Biochemical Structure of Active Cells

In modern times, man uses many diagnostic tools in preventive and curative medicine. Enzyme assays, blood chemical tests and state of the art equipment like CAT-scan, X-ray and imaging solid NMR are only some of the tools used to determine the state of human health. Is it possible to apply similar diagnostic principles and equipment to heterogeneous agro-ecosystems to determine the health of our soil resource? In an earlier section we showed how solid ^{13}C-NMR and Py-FIMS are valuable techniques in soil quality diagnostic assesments.

In the next two sections we explore ways of using soil metabolic processes as diagnostic tools to reflect changes in land use and soil quality.

Metabolic Charges of Active Microbial Cells

The biochemical transformation of SOM is dependent on the available free energy of active soil microorganisms. This free energy controls the reaction rate of microbial transformations and possibly gas emmissions to the atmosphere. The concepts of cell free energy and metabolic reduction charges may be useful in the diagnosis of soil quality. The fast turnover of the energy nucleotide pools may reflect changes in land use over short periods. A diagnostic technique based on principles of microbial energy would provide information on soil quality in a few hours instead of weeks, months or years. The subsequent section discusses briefly the metabolic components that regulate available energy in live soil organisms.

The biochemical controls of biontic processes take place on different levels and time scales: molecular (gene, nano-second to millenia), interactions between communities; interactions between biotic and abiotic components (organic molecules with clay, or climatic influences, decades or centuries); substrate (quantity and quality); metabolic (intracellular allocation of C and N, growth and energy availability; seconds to hours). We examine further the last type of control.

Soil microbes use three basic strategies for growth:

1. Production of C skeletons
2. Production of energy (ATP)
3. Production of reducing power (NAD, NADP)

1. Microbial cells need to produce small molecules (intermediates of metabolism) to build macromolecules such as DNA, RNA, proteins and lipids. These C skeletons are essential to the cell's function and physical structure. The intracellular allocation of C is done through amphibolic pathways of metabolism (catabolism and anabolism) and is regulated by ATP and end products of metabolism. Catabolic reactions breakdown substrates into smaller molecules. Anabolism uses small C molecules and available energy to build macromolecules. At any given time both types of C flows may take place to replenish what the cell needs (Atkinson, 1969; Anderson and Wood, 1969).

2. The production of microbial available energy is accomplished by synthesizing ATP (Adenosine 5'-triphosphate) from AMP (Adenosine 5'-monophosphate), ADP (Adenosine 5'-diphosphate) and inorganic-P. During heterotrophic metabolism most ATP is synthesized during electron disposal at the cell membrane. ATP is used in endergonic reactions (require free energy) of growth during the build up of macromolecules, i.e. Escherichia Coli needs 2.5 million ATP molecules sec^{-1} to support the energy needs during growth. The proportions of ATP to ADP and AMP define the adenylate energy charge (AEC) as follows:

$$AEC = \frac{(ATP + 0.5ADP)}{(ATP + ADP + AMP)} ,$$

where AEC is the molar ratio of the adenylates. AEC ranges between 0 and 1 (Atkinson, 1977).

Under favourable growing conditions, the AEC of active cells is high (0.9) and the rate of macromolecule synthesis through anabolic pathways increases. The latter promotes conditions of growth. Conversely, under adverse conditions of growth like low oxygen tension, substrate limitation or environmental stress, AEC is <0.65 and catabolic pathways

predominate. Under catabolism, the cell degrades its own macromolecules to maintain the cell's function and physical integrity. Continuous adverse conditions causes growth to cease and cells die (Atkinson, 1977).

3. Active cells need to balance their oxidation-reduction reactions to avoid internal disruption and death. Active organisms synthesize molecules like nicotinamide dinucleotide (NAD) and nicotinamide adenine dinucleotide phosphates (NADP) to dispose electrons during intracellular chemical reactions. NAD accepts electrons (NADH) and disposes them during catabolic reactions. NADP delivers the electrons (NADPH) necessary for the reduction of intermediates of metabolism during the synthesis of macromolecules. The catabolic reduction charge (CRC) and anabolic reduction charge (ARC) are defined as follows:

$$CRC = \frac{NADH}{NADH + NAD^{+}}, \qquad ARC = \frac{NADPH}{NADPH + NADP^{+}}$$

where both reduction charges represent the molar ratios of their respective components
(Andersen and Meyenburg, 1977).

These threee components, AEC, ARC and CRC, unify the concept of energy transfer within the cell. The turnover rates of the three nucleotide systems are very rapid: 1-10 sec^{-1} (Holmes, 1972). The internal concentrations of these different compounds are in the mM range, possibly saturating their respective enzyme systems (Cleland, 1967). An absolute change in the nucleotide concentration would have only a minor influence on the rate of enzyme reactions compared to a change in the charge of the compounds.

Metabolic Charges and Soil Quality

The energy of soil systems play a role in determining the status of soil quality (Anderson and Gregorich, 1984). One important form of soil energy is the adenylate energy charge of active soil organisms, however, the concepts of AEC, CRC and ARC have not been used to describe SOM dynamics. Adenylate energy charge is the only nucleotide pool quantified in soil systems. Incorporation of these basic concepts to SOM dynamic studies would improve the level of resolution at which we define the controls of biochemical transformations in natural ecosystems.

The AEC concept was applied to soils by Brookes et al., (1983). They found that AEC in fresh samples taken from a moist 300 y old grassland was high (0.85) and similar to values in actively growing microbial cells (Table 5). The AEC of soils is sensitive to environmental stress. Air drying decreases AEC but remoistening increases its value

(Brooke et al., 1983). Soil anaerobiosis of a grassland decreased AEC from 0.8 to 0.3 and soil re-oxygenation only partially recovered the AEC values (Table 5). No studies have been conducted to determine the catabolic and anabolic reduction charges in active soil organisms.

The above information showed the ability of AEC to respond to external and internal factors influencing the soil environment. This suggests that the biochemical structure of the soil microbial biomass may adapt differently to varying conditions of soil-crop management. In pure culture studies, the AEC and ARC of E. Coli rapidly respond to conditions of substrate starvation. The CRC shows to be less sensitive to stress (Fig 2). At the microsite of degraded soils, active microbial cells may deplete carbon below a growth limiting concentration faster than in microsites of aggraded soils (half saturation value for growth on glucose varies between 10 and 100 μg C ml^{-1}, Pirt, 1975). The rate of substrate desorption from degraded soil may limit the supply of carbonaceous substrates to active soil organisms. This is consistent with results obtained through kinetic modelling techniques used in earlier studies. The rate of desorption in paired of cultivated and uncultivated soils was always lower in the cultivated phase or in a FW rotation (Monreal and McGill, 1989). Growth limiting conditions caused by low concentrations of N or P may render similar effects. Hence, differences in soil substrate availability may induce continuous long-term differences in the AEC, CRC and ARC of the active soil microbial biomass.

Within this context, we hypothesize that the metabolic charge of active microbial cells in aggraded and degraded soils are different and their values approximate those of Table 6. Further, we hypothesize that AEC and ARC can be defined as dynamic functions of time and degree of soil deterioration by $AEC_t = AEC_{to} e^{-kt}$.

Higher levels of microbial available energy in aggraded soils may be followed by greater intracellular substrate-C allocation and lower fluxes of CO_2. Hence, an increase in the efficiency of substrate utilization would result in accretion of SOM in agro-ecosystems. These hypothesis can be tested in soil samples from long-term rotations where the degree of degradation has been quantified (Table 3).

In summary, we analysed the potential use of chemical, biological and biochemical soil properties as indexes of soil quality. Soil quality was defined quantitatively by determining the rate of change of physical and chemical soil attributes. Aggradation or degradation of individual soil attributes was quantified on the basis of a soil standard reference. The basic cell biochemical structure synthesizes

and transfers available energy through the adenylate energy charge (AEC); anabolic (ARC) and catabolic reduction (CRC) charges. These nucleotides turnover fast and respond rapidly to conditions of substrate limitation and environmental stress. It is hypothesized that AEC and ARC of soil microbial biomass may reflect degree of soil deterioration.

Conclusion

Analysis of information presented in this article permits the following conclusions:

The total SOM and its chemical composition may be used as indexes of soil quality. These indexes provide information on soil quality after years (>10y) of monitoring.

Under field conditions, active soil organisms depleted aromatic-C compounds from a cultivated Gleysol faster that C from aliphatic compounds.

The soil microbial specific respiration (qCO_2) was a biontic attribute that consistently reflected the degree of soil quality.

It is hypothesized that the latter biochemical indicator may provide information on soil quality during monitoring periods shorter than 5y. Further, the microbial adenylate energy charge and the anabolic reduction charges may provide information on soil quality during monitoring periods of days to months.

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Table 1. Total C and N mineralization rates in three different soils[1].

Soil attribute	Black Cher. Cultivated	Brown Cher. FW	Brown Cher. CW	Andept Cultivated
Total C (%)	6.6	1.94	2.15	7.3
Min-N ($ug\ g^{-1}d^{-1}$)	3.2	3.7	4.6	0.5
pH	6.2	6.7	6.7	5.9

1. Values readapted from Biederbeck et al., (1984) and Monreal and McGill, (1990).

Table 2. Soil organic matter composition in the 0-5 cm of two adjacent Gleysols as characterized by CP/MAS solid ^{13}C-NMR.

Type of carbon	C ($t\ ha^{-1}$) Forest	C ($t\ ha^{-1}$) Corn	Amount of C lost[1] ($t\ ha^{-1}\ y^{-1}$)	Amount of C lost[1] (% of original)
Organic	34.0	11.3	0.25	67
Aromatic	4.1	1.0	0.03	76
Aliphatic	15.9	5.3	0.12	67
Carboxylic	4.6	1.4	0.04	70
Acetal	1.7	0.7	0.01	59
Ketone	2.6	0.6	0.02	77
Solum C (0-50cm)	120.0	73.0		
$\%C_{observed}$ (0-5cm)	90.0	80.0		

1. Assumed 90 years of cultivation.

Table 3. The microbial biomass, rate of CO_2 evolution and specific respiration as biological and biochemical soil attributes.

Soil	Rotation	C (%)[4]	C (kg ha^{-1})		qCO_2
			CO2(d^{-1})	Biomass	(d^{-1})
Brown Chernozem[1]	FW	1.94a	7.7a	180a	0.043a
	CW	2.15a	11.5b	217a	0.053b
Thin Black Chernozem[2]	FW	1.99a	13.1a	417a	0.031a
	CW	2.40b	16.4b	442a	0.037a
Gray Luvisol[3]	FW	1.16	N.R	212a	N.R.
	HHWOB	1.75	N.R	466b	N.R.

Data readapted from:

1. Biederbeck et al., (1984);
2. Campbell et al., (1991) and Greer, (1989)
3. McGill et al., (1986); N.R.=not reported.
4. Statistical differences within columns correspond to those reported by each author.

Table 4. Physical, chemical and biochemical indexes of soil quality.

Soil	Rotation	Year	A horizon (cm)	Erosion ($t\ ha^{-1}y^{-1}$)	Org. N[2] ($t\ ha^{-1}$ 7.5cm)	qCO_2 (d^{-1})	Soil Quality $dq_{Norg.}$	Soil Quality $dQ_{Norg.}$	State
Brown	Reference	1967	17.0[1]		1.6				
	FW	1990	14.0	21.6	1.5	0.043	0.004	-0.063	Degraded
	CW	1990	17.0	2.4	1.8	0.053	0.009	0.125	Aggraded
Thin Black	Reference	1958	22.5		2.7				
	FW	1987	14.0	34.6	1.2	0.031	0.058	-0.556	Degraded
	CW	1987	16.0	23.9	1.5	0.037	0.046	-0.444	Degraded
					Total C ($t\ ha^{-1}$ 7.5cm)		$dq_{Corg.}$	$dQ_{Corg.}$	
Gray Luvisol	Reference	1936	25.0		15.3[3]				
	FW	1990	12.5	33.0	12.1	N.R.	0.123	-0.209	Degraded
	HHWOB	1990	20.0	7.2	24.9	N.R.	0.369	-0.627	Aggraded

1. A horizon thickness was estimated from ^{137}Cs measurements made by the present authors in 1990 (Monreal et al., 1992).
2. Initial organic-N for both Chernozems was estimated as described by Monreal et al., (1992).
3. For the Gray Luvisol, the initial organic carbon was estimated with %C=1.437 and a bulk density of 1.42 g cm^{-3} (Monreal, 1992, unpublished data).

Table 5. The response of adenylate energy charge (AEC), catabolic reduction charge (CRC) and anabolic reduction charge (ARC) to environmental stress in soils and growing E. Coli cells.

Soil	Type of environment	Total C (%)	Metabolic charges AEC	CRC	ARC
Grassland[1]	Aerobic	4.81	0.85	NA	NA
	air-dried		0.45	NA	NA
	remoistened		0.76	NA	NA
Grassland[2]	Anaerobic	4.06	0.3-0.5	NA	NA
	Reoxigenated	4.06	0.8	NA	NA
Escherichia coli[3]	Exponential growth		0.9	0.05	0.45
	C starvation		0.6	0.10	0.20
	C readdition		0.85	0.05	0.50

Data readapted from:

1. Brookes et al., (1983); 2. Inubushi et al., (1989) and 3. Andersen and Meyenburg (1977).

Table 6. Hypothetical values for AEC, CRC and ARC in aggraded and degraded soils.

State of soil quality	Metabolic charges AEC	CRC	ARC
Aggraded	> 0.6	< 0.05	> 0.5
Degraded	< 0.6	> 0.05	< 0.5

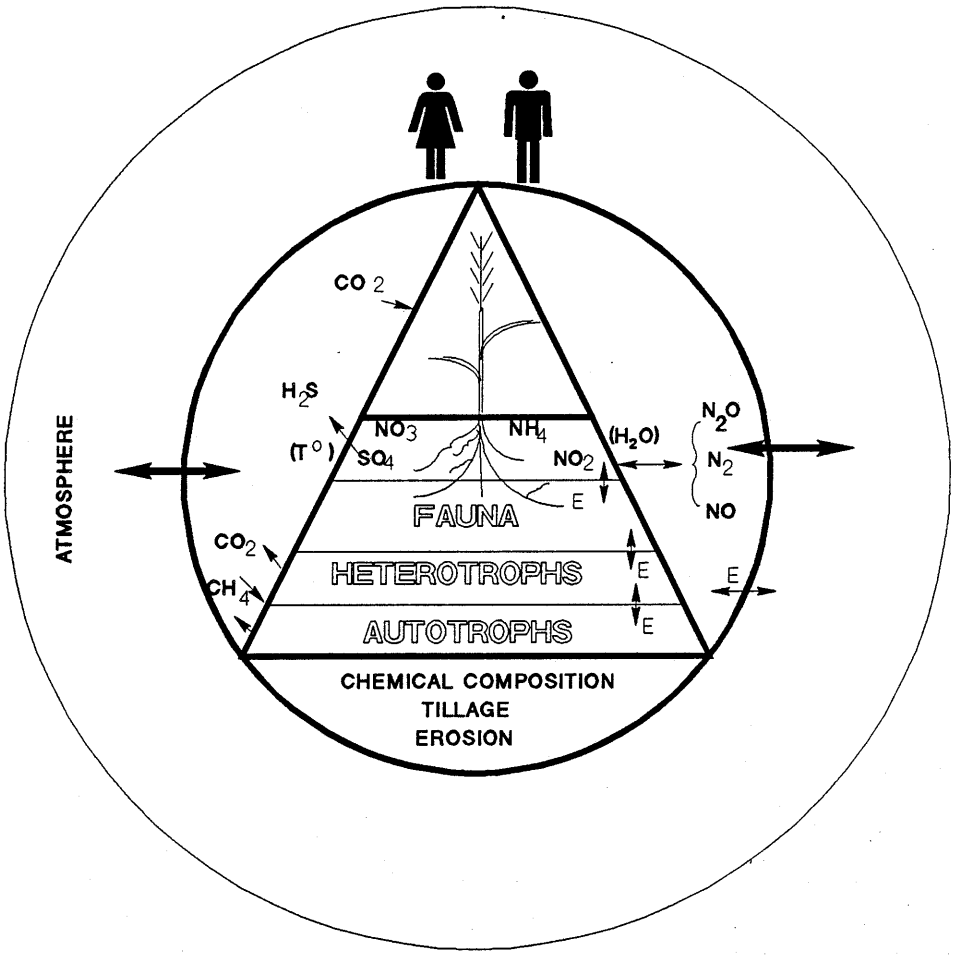

Figure 1. Soil as a hierarchical multilevel system

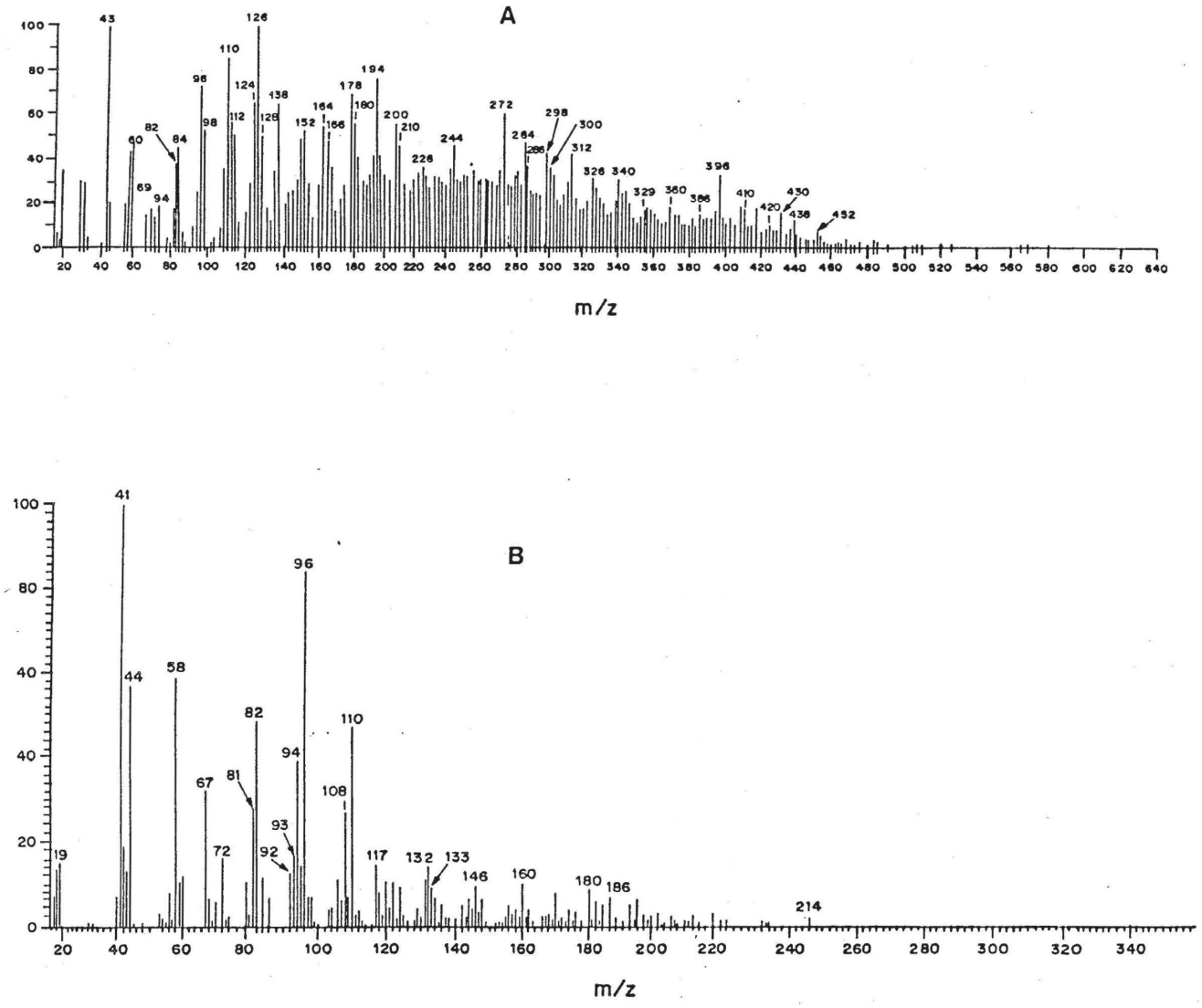

Figure 2. Pyrolysis-field ionization mass spectra of soil samples: (A) Ah under forest, (B)Ap in corn field. The mass signals relate approximately to poly-saccharides (m/z 72-132), lignin monomers and dimers (m/z136-340), n-fatty acids (m/z 340-452), wax esters (m/z592-732), (Schulten and Leinweber, 1991).

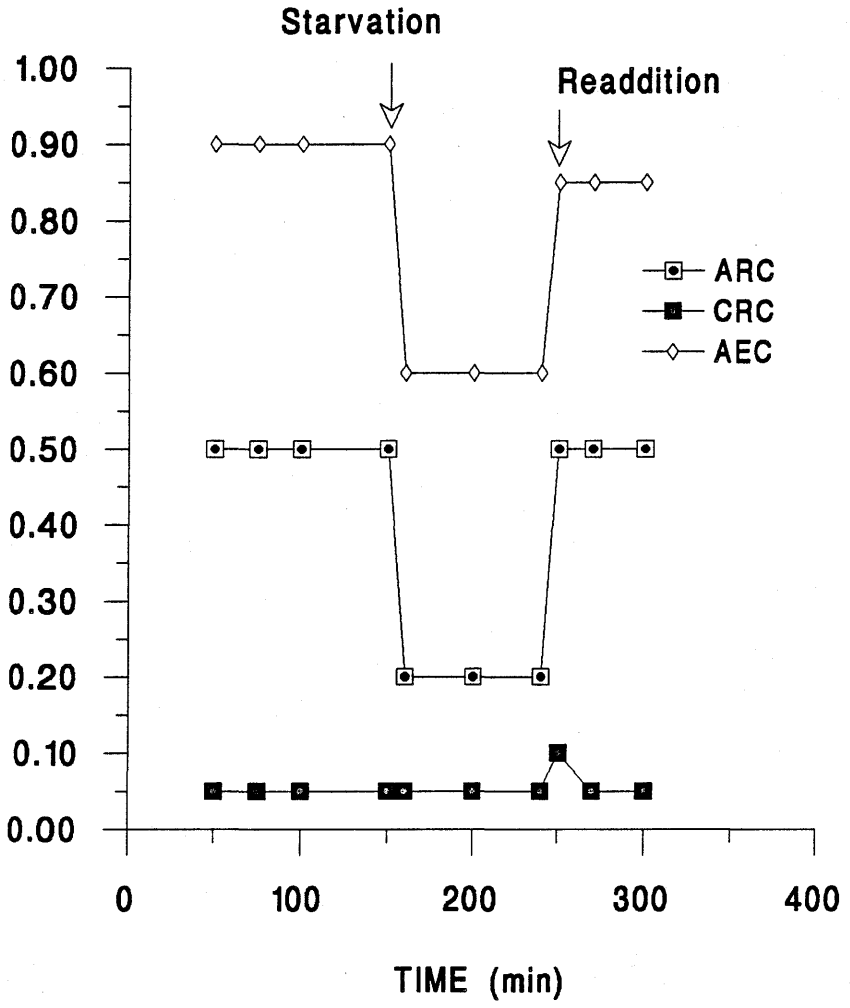

Figure 3. Metabolic charges in E. Coli during succinate starvation and readdition. Readapted from Andersen and Meyenburg (1977).