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AGRICULTURAL BIOLOGICAL DIVERSITY

Soil biodiversity and sustainable agriculture: paper submitted by the Food and Agriculture Organization of the United Nations

Note by the Executive Secretary

1. The Executive Secretary is circulating herewith, for the information of participants in the seventh meeting of the Subsidiary Body on Scientific, Technical and Technological Advice (SBSTTA), a background paper prepared by FAO on soil biodiversity and sustainable agriculture. This information note supplements the progress report by the Executive Secretary on the implementation of the programme of work on agrobiodiversity, including the development of the international pollinators initiative (UNEP/CBD/SBSTTA/7/9). As noted in paragraph 21 of that progress report, syntheses of case-studies and analysis of lessons learned are under preparation for various dimension of agricultural biodiversity. As recommended by the liaison group on agricultural biodiversity, which met in January 2001, the present information note has been prepared by FAO to provide a synthesis of case-studies and lessons learned on the soil biodiversity.

2. The paper is being circulated in the form and language in which it was submitted to the Secretariat of the Convention on Biological Diversity.

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[*] UNEP/CBD/SBSTTA/7/1.

SOIL BIODIVERSITY AND SUSTAINABLE AGRICULTURE

Soil organisms contribute a wide range of essential services to the sustainable function of all ecosystems, by acting as the primary driving agents of nutrient cycling, regulating the dynamics of soil organic matter, soil carbon sequestration and greenhouse gas emission; modifying soil physical structure and water regimes, enhancing the amount and efficiency of nutrient acquisition by the vegetation. and enhancing plant health. These services are not only essential to the functioning of natural ecosystems but constitute an important resource for the sustainable management of agricultural systems.

I. INTRODUCTION

Soil Biodiversity and the Convention on Biological Diversity

1. Soil biodiversity has been identified as an area requiring particular attention under the programme of work on agricultural biodiversity of the Conference of the Parties (COP) to the Convention on Biological Diversity (CBD). This programme was initiated at COP-3 (decision III/11, Buenos Aires, 1996) to promote the positive and mitigating the negative impacts of agricultural activities on agricultural biological diversity; the conservation and sustainable use of genetic resources of actual or potential value for food and agriculture; and the fair and equitable sharing of benefits arising out of the use of genetic resources. The programme of work was subsequently developed, with the support of the Food and Agriculture Organisation of the United Nations (FAO), in collaboration with partners, and on the basis of advice and recommendations of the Subsidiary Body for Scientific, Technical and Technological Advice (SBSTTA) and was launched at COP-5 (decision V/5, Nairobi, 2000). It has four main objectives: assessment; management practices and policies; capacity building; and national plans and strategies and mainstreaming. FAO was invited to support development and implementation of the programme. Moreover, governments, funding agencies, the private sector and NGOs were invited to join efforts.

2. Parties recognised, *inter alia*, the need to improve understanding: of the multiple goods and services provided by the different levels and functions of agricultural biodiversity; of the relationship between diversity, resilience and production in agro-ecosystems; and of the impacts of traditional and newer practices and technologies on agricultural biodiversity and on the sustainability and productivity of agricultural systems. Special attention was paid to the role of soil and other below-ground biodiversity in supporting agricultural production systems, especially in nutrient cycling. It was agreed, under programme element 2.1, to carry out a series of case-studies, in a range of environments and production systems, and in each region. Recognising a critical gap in knowledge, Parties had previously been encouraged to conduct case studies on the issue of symbiotic soil micro-organisms in agriculture (Annex 3, COP decision III/11) and subsequently on soil biota in general (decision IV/6, Bratislava, 1998).

3. This paper has been prepared as a contribution to the item on agricultural biodiversity of the 7th meeting of SBSTTA to present work in progress and especially to highlight the important roles and functions of soil

biodiversity - a critical, yet much neglected component of biological diversity and agricultural ecosystems. It emphasises the importance and value of the sustainable management of soil biodiversity and illustrates a range of opportunities and ongoing work. It contributes simultaneously to the above CBD decisions on agricultural biodiversity and to FAOs mandate for improving agricultural (including forestry) production and food security, particularly in regard to integrated land resources management. The material has been derived through networking with partners and resource persons, literature review and Internet search, and a global survey of soil biodiversity expertise and activities. In accordance with COP decisions III/11, IV/6 and V/5, more concrete case studies from countries are strongly encouraged to enable FAO to supplement this initial overview with a useful synthesis of relevant case studies and practical experiences. This would further assist SBSTTA in identifying and prioritising further work in this important area of below-ground biodiversity.

Soil Biodiversity - the Root of Sustainable Agriculture

4. Soil is a dynamic, living matrix that is an essential part of the terrestrial ecosystem. It is a critical resource not only to agricultural production and food security but also to the maintenance of most life processes.

5. Soils contain enormous numbers of diverse living organisms assembled in complex and varied communities. Soil biodiversity reflects the variability among living organisms in the soil – ranging from the myriad of invisible microbes, bacteria and fungi to the more familiar macro-fauna such as earthworms and termites. Plant roots can also be considered as soil organisms in view of their symbiotic relationships and interactions with other soil components. These diverse organisms interact with one another and with the various plants and animals in the ecosystem forming a complex web of biological activity. Environmental factors, such as temperature, moisture and acidity, as well as anthropogenic actions, in particular, agricultural and forestry management practices, affect to different extents soil biological communities and their functions.

6. Soil organisms are an integral part of agricultural and forestry ecosystems; and they play a critical role in maintaining soil health, ecosystem functions and production. Each organism has a specific role in the complex web of life in the soil:
   - The activities of certain organisms affect soil structure - especially the so-called “soil engineers” such as worms and termites - through mixing soil horizons and organic matter and increasing porosity. This directly determines vulnerability to soil erosion and availability of the soil profile to plants;
   - The functions of soil biota are central to decomposition processes and nutrient cycling. They therefore affect plant growth and productivity as well as the release of pollutants in the environment, for example the leaching of nitrates into water resources;
   - Certain soil organisms can be detrimental to plant growth, for example, the build up of nematodes under certain cropping practices. However, they can also protect crops from pest and disease outbreaks through biological control and reduced susceptibility;

- The activities of certain organisms determine the carbon cycle - the rates of carbon sequestration and gaseous emissions and soil organic matter transformation;
- Plant roots, through their interactions with other soil components and symbiotic relationships, especially Rhizobium bacteria and Mycorrhiza, play a key role in the uptake of nutrients and water, and contribute to the maintenance of soil porosity and organic matter content, through their growth and biomass;
- Soil organisms can also be used to reduce or eliminate environmental hazards resulting from accumulations of toxic chemicals or other hazardous wastes. This action is known as bioremediation.

7. The interacting functions of soil organisms and the effects of human activities in managing land for agriculture and forestry affect soil health and quality. Soil quality is the capacity of a specific kind of soil to function, within natural or managed ecosystems boundaries, to sustain plant and animal production, maintain or enhance water and air quality, and support human health and habitation. The concept of soil health includes the ecological attributes of the soil, which have implications beyond its quality or capacity to produce a particular crop. These attributes are chiefly those associated with the soil biota: its diversity, its food web structure, its activity and the range of functions it performs. Soil biodiversity *per se* may not be a soil property that is critical for the production of a given crop, but it is a property that may be vital for the continued capacity of the soil to support that crop.

8. The sustained use of the earth’s land and water resources - and thereby plant, animal and human health - is dependent upon maintaining the health of the living biota that provide critical processes and ecosystem services. However, current technologies and development support for increased agricultural production have largely ignored this vital management component. The improved management of soil biota could play a vital role in maintaining soil quality and health and in achieving the goals of agricultural production and food security and sustainable land use and land resources management.

Why should soil biodiversity be managed?

9. Given escalating population growth, land degradation and increasing demands for food, achieving sustainable agriculture and viable agricultural systems is critical to the issue of food security and poverty alleviation in most, if not all, developing countries. It is fundamental to the sustained productivity and viability of agricultural systems worldwide.

10. Sustainable agriculture (including forestry) involves the successful management of agricultural resources to satisfy human needs while maintaining or enhancing environmental quality and conserving natural resources for future generations. Improvement in agricultural sustainability requires, alongside effective water and crop management, the optimal use and management of soil fertility and soil physical properties. Both rely on soil biological processes and soil biodiversity. This calls for the widespread adoption of management practices that enhance soil biological activity and thereby build up long-term soil productivity and health.

11. It is well known that land management practices alter soil conditions and the soil community of micro-, meso- and macro-organisms. However, the relationship between specific practices and soil functions is less clear. In general, the structure of soil communities is largely determined by ecosystem characteristics and land use systems. For example, arid systems have few earthworms, but have termites, ants and other invertebrates that serve similar functions. On the other hand, the level of activity of different species depends on specific management practices as these affect the micro-environment conditions, including temperature, moisture, aeration, pH, pore size, and type of food sources.

12. Management strategies, including tillage, crop rotations and use of plant residues and manure, change soil habitats and the food web and alter soil quality, or the capacity of the soil to perform its functions. For example, soil compaction, poor vegetation cover and/or lack of plant litter covering the soil surface tend to reduce the number of soil arthropods. Farming practices that minimise soil disturbance (ploughing) and return plant residues to the soil, such as no-tillage farming and crop rotation, allow to slowly rebuild and restore soil organic matter. Reducing tillage tends to also result in increased growth of fungi, including mycorrhizal fungi

13. The goal of efficient agriculture is to develop agro-ecosystems with minimal dependence on agrochemical and energy inputs, in which ecological interactions and synergy among biological components provide the mechanisms for the systems to sponsor their own soil fertility and crop production functions. The mix of soil organisms in the soil also partially determines soil resilience, the desirable ability of a given soil to recover its functions after a disturbance such as fire, compaction and tillage.

14. There is a recognised need to bring together experience and ideas on the management of agricultural biodiversity in agricultural ecosystems, and, through international and national biodiversity strategies and action plans and harmonised policies, to bring about a transformation of unsustainable agricultural practices to sustainable practices and systems. Nonetheless, the fundamental role of soil biodiversity in maintaining sustainable and efficient agricultural systems is still largely neglected in this process and in the majority of related agricultural and environmental initiatives.

II. THE CHALLENGE OF MANAGING SOIL BIOTA

Soil biodiversity management and farmer practices

15. Farming communities are concerned with land management issues such as water availability to plants, access to sources of fuel and fodder, control of soil erosion and land degradation, especially avoiding soil nutrient depletion and pollution of air, soil and water resources. At the global scale, the aggregated effects of these issues are embedded in the concerns of the international conventions on desertification, climate change and biodiversity.

16. Nonetheless, farmers are essentially driven not by environmental concerns, but by economics, by issues of costs and returns and efficiency in terms of labour and energy and use of external inputs. A central paradigm for the farmer for the maintenance and management of soil fertility, without

undue reliance on costly and often risky external inputs, is to utilise his or her management practices to influence soil biological populations and processes in such a way as to improve and sustain land productivity. The means to create a more favourable environment within the soil and soil biological community for crop production involves site-specific decisions concerning crop selection and rotations, tillage, fertiliser and planting practices, crop residues and livestock grazing. These and many other factors influence ecological interactions and ecosystem function.

17. Soil biota can increase or reduce agricultural productivity depending on its composition and the effects of its different activities. *Vice versa*, farming practices modify soil life including the total number of organisms, the diversity of species and the activity of the individual organisms and the aggregate functions of soil biota. These changes can be beneficial or detrimental to the soil biota and its functions and its regenerative capacity.

18. Through a review of literature and ongoing work, much has been reported on the loss of managed soil biodiversity and its functions in different agricultural systems under controlled-research conditions. This work has been largely driven by pure research and commercial or private sector interests rather than by poorer, smallholder farmers’ needs and by national goals. There has been relatively limited practical work on how farmers’ manage their resources to sustain and enhance their value and, in particular, to develop farming practices and systems that optimise the beneficial activities of this managed soil biota.

19. Over the last few years, the concepts of Integrated Plant Nutrient Management (IPNM) and Integrated Soil Management (ISM) have been gaining acceptance, moving away from a more sectoral and inputs-driven approach. IPNM advocates the careful management of nutrient stocks and flows in a way that leads to profitable and sustained production. ISM emphasises the management of nutrient flows, but also highlights other important aspects of the soil complex, such as maintaining organic matter content, soil structure, moisture and biodiversity.

20. Capturing the benefits of soil biological activity for sustainable and productive agriculture requires a better understanding of the linkages among soil life and ecosystem function and the impacts of human interventions. The complex interaction among soil, plant and animal life, environmental factors and human actions must be effectively managed as an integrated system. Greater attention to the management of soil biological resources - a hitherto neglected area in mainstream agriculture - will require a collaborative effort among scientists and farmers’ and across ecological zones and countries building on successful experiences.

21. The inter-regional Tropical soil biology and fertility programme (TSBF), is a research programme that addresses such issues. It focuses on the management of the biological and organic resources of soil, including understanding of the interactions between the soil biological system and inorganic fertilisers and other industrial inputs. It has played a pioneer role in networking with a wide range of partners, including the African Network for Soil Biology and Fertility (AfNet), South Asian Regional Network (SARNet), and various regional and global alliances, as well as the establishment of a Soil Biodiversity Network, the result of a workshop in 1995, in Hyderabad, India. The TSBF process has led to a Soil Biology Initiative among members in some 10 African countries to improve soil

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biological management practices and raise productivity in African farming systems, particularly of smallholders. Moreover, a 5-year, multi-country project "Conservation and sustainable management of below-ground biodiversity", has, during 2001, been accepted for funding by the Global Environment Facility (GEF).

The benefits from better management of soil biota

22. As noted above, soil organisms contribute a wide range of essential services to the sustainable functioning of all ecosystems. They act as the primary driving agents of nutrient cycling, regulating the dynamics of soil organic matter, soil carbon sequestration and greenhouse gas emissions; modifying soil physical structure and water regimes, enhancing the amount and efficiency of nutrient acquisition by the vegetation and enhancing plant health. These services are not only essential to the functioning of natural ecosystems but constitute an important resource for sustainable agricultural systems.

23. Direct and indirect benefits of improving soil biological management in agricultural systems include economic, environmental and food security benefits:

- *Economic benefits*: Soil biological management reduces input costs by enhancing resource use efficiency (especially decomposition and nutrient cycling, nitrogen fixation and water storage and movement). Less fertiliser may be needed if nutrient cycling becomes more efficient and less fertiliser is leached from the rooting zone. Fewer pesticides are needed where a diverse set of pest-control organisms is active. As soil structure improves, the availability of water and nutrients to plants also improves. It is estimated that the value of "ecosystem services" (e.g. organic waste disposal, soil formation, bioremediation, N_2 fixation and biocontrol) provided each year by soil biota in agricultural systems worldwide may exceed US$ 1,542 billion.[1]

- *Environmental protection:* Soil organisms filter and detoxify chemicals and absorb the excess nutrients that would otherwise become pollutants when they reach groundwater or surface water. The conservation and management of soil biota help to prevent pollution and land degradation, especially through minimising the use of agro-chemicals and maintaining/enhancing soil structure and cation exchange capacity (CEC). Excessive reduction in soil biodiversity, especially the loss of keystone species or species with unique functions, for example, as a result of excess chemicals, compaction or disturbance, may have catastrophic ecological effects leading to loss of agricultural productive capacity.

- *Food security:* Soil biological management can improve crop yield and quality, especially through controlling pests and diseases and enhancing plant growth. Below-ground biodiversity determines resource use efficiency, as well as the sustainability and resilience of low-input agro-ecological systems, which ensure the food security of much of the world’s population, especially the poor. In addition, some soil organisms are consumed as an important source of protein by different cultures and others are used for medicinal purposes. At least 32 Amerindian groups in the Amazon basin use terrestrial invertebrates as

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[1] Pimentel, D. et. al., 1997. BioScience, 47(11), 747-757.

food, and especially, as sources of animal protein - a strategy that takes advantage of the abundance of these highly renewable elements of the rainforest ecosystem.[2]

24. The improved management of soil biota and its diversity contributes both to the needs of farmers', especially in maintaining productivity and increasing returns from labour and other inputs, and to national interests through maintaining a healthy and well functioning ecosystem in terms of water quality (hydrological cycle) and preventing soil erosion and land degradation (nutrient and carbon cycles). There is a need to improve recognition of these multiple benefits and to promote actions that maintain/enhance soil biodiversity and its vital and valuable functions.

Understanding and assessment of soil biota

25. As mentioned in paragraph 2 above, Parties to the CBD were encouraged to conduct case studies on soil biota in agriculture (COP decisions III/11 and IV/6), including:

- *the measurement and monitoring of the worldwide loss of (symbiotic) soil (micro-)organisms;*
- *the identification and promotion of the transfer of technologies for the detection of (symbiotic) soil (micro-)organisms and their uses in plant nutrition;*
- *the estimation of potential and actual economic gains associated with reduced use of nitrogen and phosphorus chemical fertilisation of crops with the enhanced use and conservation of (symbiotic) soil (micro-) organisms; the identification and promotion of best practices for more sustainable agriculture and of conservation measures to conserve (symbiotic) soil (micro-) organisms or to promote their reestablishment.*

26. Under COP decision IV/6, Parties requested various organisations, particularly FAO, to, *inter alia,* provide inputs on methodologies for assessments of agricultural biodiversity and tools for identification and monitoring (including criteria and indicators; rapid assessment techniques; underlying causes behind the loss of biological diversity; and incentives to overcome constraints and enhance the conservation and sustainable use of agricultural biodiversity and the fair and equitable sharing of benefits). Assessment activities to be undertaken by Parties, with the support of bilateral and international agencies, as agreed under Programme Element 1 of the Programme of Work (decision V/5), also specified promoting assessments: of different components of agro-biodiversity that provide ecological services, for instance nutrient cycling; of knowledge, innovations and practices of farmers and indigenous and local communities in sustaining agro-biodiversity and ecosystem services for, and in support of, food production and food security; and of interactions between agricultural practices and the conservation and sustainable use of biodiversity.

27. Soils generally support one of the most extensive networks of living organisms on earth, but because of the interactions between physical, chemical and biological properties of soil, their investigation is complex, and understanding of the individuals, soil communities and their interactions is limited and fragmentary. This situation reflects the

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[2] Paoletti, M G. et. al., 2000. Proc. R. Soc. Lond. B. 267, 2247-2252.

general lack of information on microbial genetic diversity in agriculture, though the lack of knowledge is particularly acute for soil biota, maybe in view of their complexity and the difficulty of observation, being underground as well as largely invisible.

28. Soil micro-organism taxonomy and ecology is a vast area of study for which comprehensive data and information is limited. Existing data and information on species characteristics and taxonomic data is largely derived from collections. Large collection of fungi and plant bacteria are held by CABI and by UNESCO’s global network of Microbial Resources Centres (MIRCENS), that are hosted by various academic and/or research institutes and supported by UNEP, FAO, UNIDO and bilateral donors. International cooperation in the management of this global resource ensures an effective triangle of research, education and development. Efforts on taxonomy research linked to better understanding of soil biota functions are also being conducted by DIVERSITAS, which is coordinating information, and identifying priorities, on how soil and sediment species composition and community structure (species distribution and their interactions) influence ecosystem functioning.

29. There tends to be more widespread knowledge about detrimental soil organisms and their effects on plant growth in different farming systems, than their effects on soil processes and their interactions with other soil organisms and activities. Likewise more is known about the effects of certain beneficial organisms, than the management practices required to maintain, or enhance, populations and the activities of such organisms. The role of different soil populations is often not well understood, even though their overall importance is generally accepted. Rapid and accurate field methods to identify single, or even groups of, organisms according to function in the soil are also lacking and need more attention.

30. To improve agro-ecosystem management, a greater appreciation is needed of the effects of this living component of the soil on soil physical, chemical and biological properties and processes and on the air and water resources with which the soil interacts. Likewise, regarding the effects of agricultural practices on soil biota and their functions. Recognition is also needed of the effect of those interactions on soil degradation, food production and mitigation of environmental problems, including the greenhouse gas effect and water pollution. Improved understanding of the organisms and related processes and of effects of farm practices, can benefit agricultural systems through increasing crop productivity and quality, reducing impacts of pathogens and input costs and reducing negative environmental impacts.

The Ecological Principles behind Soil Biological Management

31. As noted above, soil biota may be beneficial, neutral or detrimental to plant growth. Thus soil biota and their ecological interactions must be effectively managed for maximum productivity. Land managers need unbiased information that will enable them to develop biologically-based management strategies to control or manipulate soil stabilisation, nutrient cycling, crop diseases, pest infestations and detoxification of natural and manmade contaminants. These strategies will require improved understanding of the effects on soil biota of habitats, food sources, host interactions, and the soil physical and chemical environment. Understanding the ecology regulating both beneficial and detrimental organisms is essential to

harnessing and controlling their activity in agro-ecosystems with a view to promoting viable, productive and sustainable systems.

32. Soil biota eat, grow and reproduce within the soil environment. They need food, a conducive soil habitat and, in the cases of symbionts, a host organism, to survive. The ecological principles behind soil biological management, that need to be understood and respected, include:

- <u>The supply of organic matter for food</u>: Each type of soil organism occupies a different niche in the web of life and favours a different substrate and nutrient source. Thus a rich supply and varied source of organic matter will generally support a wider variety of organisms. Organic matter may come from crop residues at the soil surface, root and cover crops, animal manure, green manure, compost and other sources.
- <u>Increased plant diversity</u>: Crops should be mixed and their spatial-temporal distribution varied to create a greater diversity of niches and resources that stimulate soil biodiversity. Each crop contributes a unique root structure and type of residue to the soil. A diversity of soil organism can help control pest populations, and a diversity of cultural practices can reduce weed and disease pressures. Several strategies could indirectly or directly contribute to creating different habitats to support complex mixes of soil organisms, for example: i) landscape diversity, over space and time, can be increased by using buffer strips, small fields, contour strip cropping, crop rotation, and by varying tillage practices; ii) a changing vegetation cover and sequence increases plant diversity and the types of insects, micro-organisms and wildlife that live on the farm; and iii) crop rotations encourage the presence of a wider variety of organisms, improves nutrient cycling and natural processes of pest and disease control.
- <u>Protecting the habitat of soil organisms</u>: Soil biodiversity can be stimulated by improving soil living conditions such as aeration, temperature, moisture and nutrient quantity and quality, for example through: reducing tillage and maximising soil cover, minimising compaction, minimising the use of pesticides, herbicides and fertilisers and improving drainage.

33. If farmers understand the effects of their different management practices on key categories of soil biota and their functions, and if they know how to observe and assess what is happening in the soil, then they can more successfully develop and adopt beneficial practices. However, it is not only the biophysical factors that affect farmer’s decisions but also socio-economic considerations. Common constraints to the use of different soil biological management practices include the labour and time costs, monetary cost, availability of inputs (for example, planting material, inoculants and capacities) as well as social acceptability.

International Expertise in Soil Biodiversity: Findings of a Global Survey

34. An informal global survey of soil biodiversity expertise[3] with special relevance to agro-ecosystems was conducted by FAO, in mid 2001, to ascertain expertise in respect to soil fertility and sustainable agriculture and to identify how soil biology experts might assist in

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[3] Conducted in September 2000 by FAO-consultants and soil biodiversity researchers Dan E. Bennack (University of Xalapa, Mexico) and George G. Brown (now with EMBRAPA Brazil)

delineating complex issues related to the biological management of soil fertility and contributing to the identification of better farming practices and agricultural systems. The resulting survey and database is expected to assist State Members of FAO and the CBD, and various partners, in catalysing work of experts on priority issues, extending expertise into non-traditional areas, and facilitating new modes of action to effectively conserve and manage soil biological diversity.

35. Some 123 of the 600 invited investigators, project members, extension professionals and post-graduate students from around the world responded to the survey. Four main themes were addressed: the professional backgrounds that characterise soil biodiversity experts; the location and conditions of field investigations that are being conducted; the soil organisms and soil properties and processes under investigation; and the agricultural management practices and their effects that are under study. Information was also gathered to ascertain the state of knowledge of the relationships between soil biodiversity, plant diversity and agricultural productivity and to identify case studies, projects, literature and contact points.

36. Awareness of the work programme on agricultural biodiversity adopted by the Conference of the Parties to the CBD, and of FAOs support to assist countries to implement this programme, was relatively low. However, the vast majority of soil biodiversity experts expressed their interest to assist in initiatives in the area of soil biodiversity and sustainable agriculture. The main findings emanating from the preliminary survey, based on responses, are presented below:

- Soil biodiversity experts often have multidisciplinary expertise however there was notable lack of sol biota specialists with expertise in natural resource management, rural/community development and plant pathology. A broad ecological approach is reflected by intersecting expertise in ecology, soil science and zoology, compared to the often narrower scope of microbiology, entomology, agronomy and botany specialists. Ecologists tended to have either a bias towards a systems-science approach or a population-community approach.
- Soil biodiversity experts are working in a variety of field sites, in both agricultural lands and natural undisturbed areas, and under a range of climatic and land use conditions. However, subtropical climate zones and arid regions are strongly under-represented. Forests (other than rainforests) and grasslands were the most common native vegetation types reported among field sites, followed by rainforest and savannah sites.
- Experts are studying a wide variety of soil organisms and soil processes, though specialists on earthworms, soil and litter arthropods, roots, nematodes and mycorrhizal fungi are more common. Many experts are working mainly in the area of organic matter inputs including decomposition rates, enhanced bio-availability, nutrient pools and transformations, soil physical properties. However, relatively less work was reported on soil and litter fungi, rhizobial bacteria (i.e. nitrogen-fixers) and fungal root pathogens. Work on soil processes such as nitrogen fixation, biogenic structures, soil physical processes and bio-accumulation/degradation was rarely reported.

37. From the findings there is a clear need to identify and facilitate the transfer of such research and its application in the agricultural development context. In addition the following suggestions are made:

- The notable lack of soil biodiversity specialists with expertise in natural resource management, rural/community development and plant pathology suggests a need for soil biodiversity experts to receive some formal training in these areas and social sciences in general. This would facilitate their interactions with farmer groups managing local land, water and biological resources.
- South-south co-operation and work could be encouraged in subtropical climates and arid regions, including desert and steppes, in order to strengthen the knowledge base and facilitate delivery of soil biodiversity expertise to these important, but often marginalised, agricultural production zones. This could for example address agricultural practices related to open range and pastoral systems in regions less suitable for cropping, as well as for dryland and irrigated cropping occur along major watercourses, deltas and floodplains in these regions.
- There may be some bias in the survey that led to relatively little work reported on rhizobial bacteria and fungi, including fungal root pathogens, and on soil processes such as nitrogen fixation, soil physical processes and bio-accumulation/degradation as well as soil biota interactions in regard to inoculants, tillage, inorganic fertilisers, pesticides and pH adjustments. However, these perceived gaps do raise important concerns that deserve follow-up. Firstly, it concerns the crucial and unique symbiotic relationships (plant-soil organisms) that either facilitate nutrient uptake (mycorrhizal fungi) or convert atmospheric nitrogen to readily utilisable forms - a vital area for agricultural productivity. Secondly, it may reflect a real gap in understanding of effects of certain agricultural practices, especially the use of certain agrochemical and biological inputs, on soil biological functioning and health.

III BUILDING ON TODAY’S SOIL BIODIVERSITY KNOWLEDGE FOR A SUSTAINABLE FUTURE

Ongoing Work and Case Studies for the Development and Transfer of Know-how and Promotion of Best Practices:

38. The survey commissioned by FAO also inventoried projects and initiatives concerning soil biodiversity, its assessment, identification, as well as its status and role in agricultural and other ecosystems (managed and natural). Over 100 projects were reported worldwide, either ongoing or being developed by private and public agencies, universities, research organisations and consortia. These address various soil biodiversity themes, including: (i) the significance of ecosystem complexity in maintaining soil organism diversity, (ii) the effects of agricultural management on soil organisms, and (iii) the role of soil biodiversity and specific soil taxa on various ecosystem functions.

39. Out of 140 cited case studies and literature references, some 20 case studies were considered of particular interest for promotion through FAO and CBD processes. These equally reflect soil-dwelling invertebrates (such as earthworms, mites, spiders, and termites) and cases dealing with micro-organisms (including nematodes, bacteria, fungi, and especially rhizobial bacteria and mycorrhizal fungi). Few case studies and reports considered soil biodiversity from multi-taxa, multi-functional or multi-disciplinary perspectives. Moreover, the state of knowledge of the relationship between soil biodiversity, plant diversity, and agro-ecosystem productivity is not

clear from the review of case studies and citations, which are mostly narrow in scope and highly taxon-specific.

40. Surprisingly there is no unifying theme considering that soil “biodiversity” might affect agricultural productivity in ways that differ from the effects of individual species. Some studies, for example, refer to the effects of individual soil taxa on agricultural productivity, but do not consider the effects of overall taxonomic diversity (including inter-specific or higher level comparisons). Other studies refer to the effects of landscape or crop (patch) heterogeneity on the presence, abundance or biomass of soil organisms, yet these studies often fail to consider simple measures of organismal diversity (such as species and/or higher taxon richness, or other diversity measures based upon relative abundance, population size, biomass, recapture, etc.). Some investigations consider the influence of agricultural practices on certain types of soil organisms, yet ignore the impact of these practices on taxonomic and/or functional diversity *per se*.

41. The importance of soil biodiversity to plant diversity and agricultural productivity has been the subject of anecdotal and empirical investigation for some time[4], but only recently has research in this area really blossomed. Pioneering investigations have been established through detailed experimental designs[5] and some integrative research programs are ongoing. Given the complex nature of relationships between soil biodiversity, plant diversity and agricultural productivity, it is expected that the number of projects, results and publications will continue to grow. There may be a need to encourage strategic alliances among individual investigators and basic and applied research institutions. There is a clear need for FAO and partners in the food and agricultural sectors to pay special attention to research and development in the area of soil biological diversity. In this way, the theoretical advances as well as practical applications of basic research might be more effectively incorporated into field activities and programmes. Partnerships among academic and other institutions undertaking soil biodiversity research and development programmes would accelerate the transfer of newly developed soil biodiversity management technologies into the field at appropriate scales of implementation.

42. In furthering SBSTTA’s consideration of soil biodiversity under the programme of work on agricultural biodiversity, it is intended by FAO to assist, in collaboration with partners and upon the basis of submissions by countries, in the preparation of a further paper to present a review and synthesis of available case studies.

Reporting on Soil Biodiversity: National Reports on CBD Implementation

43. As mentioned in paragraphs 2 and 3 above, Parties to the CBD have agreed to the implementation of the programme of work on agricultural biodiversity, including, *inter alia,* specific attention to soil biodiversity, (decision V/5). National reports to the COP and reports by international agencies supporting the convention provide a means to assess progress made. In this regard, from an overview of national reports it is

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[4] Kevan, D.K. McE. 1985. Soil zoology, then and now – mostly then. *Quaest. Entomol*. **21**, 371.7-472.

[5] Naem, S., J.H. Lawton, L.J. Thompson, S.P. Lawler and R.M. Woodfin. 1995. Biotic diversity and ecosystem processes: Using the Ecotron to study a complex relationship. *Endeavour* **19**, 58-63.

observed that, in general, countries report more on natural ecosystems than on agricultural ecosystems. Moreover, within agricultural systems the emphasis is on plant and animal genetic resources and often little or no information is given on soil biological diversity. Some reports stress research and monitoring, while others place more emphasis on conservation actions, but the overriding message is that almost everywhere there are initiatives upon which to build.

44. Some countries are preparing specific reports on soil biological diversity, for example the CBD focal point in Uganda, provided an example of its draft report on the conservation and sustainable use of soil biodiversity. However, such cases are few and far between. It is important for countries to review and report on the state of knowledge regarding soil biodiversity and also to link this information with other components of a given agricultural system through an ecosystem approach (looking at the status and trends of the overall ecosystem, its components and interactions, and the actual/potential impacts of past and current management practices). Without such a country-wide analysis, it will not be possible to identify priority areas requiring attention.

Opportunities for Integrating Soil Biological Management into Farmers' Practices

45. At ground level, options whereby farmers can actually manage soil biodiversity to enhance crop production include indirect processes, such as composting or the control of pathogens, and direct interventions, such as microbial inoculation.

- Direct methods of intervening in the production system aim to alter the abundance or activity of specific groups of organisms through inoculation and/or direct manipulation of soil biota. Inoculation with soil beneficial organisms, such as nitrogen-fixing bacteria, Mycorrhiza and earthworms, have been shown to enhance plant nutrient uptake, increase heavy metal tolerance, improve soil structure and porosity and reduce pest damage.
- Indirect interventions are means of managing soil biotic processes by manipulating the factors that control biotic activity (habitat structure, microclimate, nutrients and energy resources) rather than the organisms themselves. Examples of indirect interventions include most agricultural practices such as the application of organic material to soil, tillage, irrigation, green manuring and liming, as well as cropping system design and management. These must not be conducted independently, but in a holistic fashion, because of the recurrent interactions between different management strategies, hierarchical levels of management and different soil organisms.[6]

46. A few key areas of attention and a number of opportunities that are available and being utilised for managing soil biota are outlined below.

a) Soil biota assessment and sustainable land management

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[6] Swift, MJ. 1999. Towards the second paradigm: Integrated biological management of soil. In: JO. Siqueira, FMS. Moreira, AS. Lopes, LRG. Guiherme, V. Faquin, AE. Furtani Neto and JG. Cavalho (eds.) Inter-relacao fertilidade, biologia do solo e nutricao de plantas. UFLA, Brasil. pp. 11.24.

47. **What is known.** Soil biota can have both positive and negative effects on agricultural production. Negative impacts often occur when soil management systems are not well balanced with their environment. For example, inherent soil processes such as mineralization can no longer supply adequate amounts of nutrients for crop production because of long-term (continuous) removal, leaching, erosion or volatilisation. Consequently, such biological processes have in many systems been supplemented by the use of commercially available inorganic nutrient sources. However with decreasing organic matter content, and associated properties such as water retention and cation exchange capacity (CEC), the capacity of the soil to retain and make available the nutrients, as and when required, is significantly reduced. Thus soil quality or soil health evaluations need to focus not only on chemical (fertility) considerations, but on the dynamic soil condition - a combination of physical, biological and chemical characteristics - which is directly affected by recent and current land use decisions and practices. Land managers can only balance potential positive and negative impacts of their decisions on soil biota through understanding the effects of individual components and their interactions within the agricultural system. This includes understanding the numerous and intricate interactions among climate, soil type, plant species and diversity, soil biological community and soil management practices.

48. **The case of soil bioindicators:** The potential of using different components of soil biota and its activity as biological indicators has been cited by different authors. Such indicators include soil microbial biomass, soil enzyme activity, soil micro-fauna, including bacteria (eubacteria and archacbacteria), fungi, algae and plant root pathogens, soil micro-fauna (protozoa, nematodes), macro-fauna, total soil biodiversity, etc. Soil organisms have been shown to be potentially useful indicators of soil health because they respond to soil management in time scales (months/years) that are relevant to land management[7]. For example, changes in microbial biomass, or abundance of selected functional groups of micro-organisms (e.g. Mychorrizal fungi), may be detected well in advance of changes in soil organic matter content or other soil physical or chemical properties[8]. One of the major difficulties in the use of soil organisms *per se*, or of soil processes mediated by soil organisms, as indicators of soil health has been methodological - what to measure and how and when to measure it and how to interpret changes in term of soil function[8]. Despite those difficulties there have been major advances in our understanding of the soil biota and its functioning at the community level in recent years[9].

49. **Gaps and needs.** More process-level information is needed to understand the role of soil biota in critical soil processes such as nutrient cycling and nutrient movement throughout the soil profile and in the soil surrounding plant roots. For example, soil nutrient use efficiency can only be

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[7] Pankhurst, C.E., 1994. Biological indicators of soil health and sustainable productivity. In: Greenland, D.J. and Szabolcs, I. (eds.) Soil Resilience and Sustainable Land Use. CAB International, Wallingford, UK, pp. 331-351

[8] Sparling, G.P., 1997. Soil microbial biomass, activity and nutrient cycling as indicators of soil health. In: Pankhurst, C.E; Doube, B.M. & Gupta, V.V.S.R. (eds) Biological indicators of soil health. CAB International, Wallingford, UK, pp. 97-119.

[9] Synthesis from Pankhurst, C.E., Doube, B.M. and Gupta VVSR, 1997. Biological indicators of soil health, CAB International, Wallingford, UK, pp. 419-435.

maximised when the interaction of soil biota with environmental factors, including temperature, water content, and energy source is understood. There is currently a fundamental knowledge gap in the interpretation and linking of various proposed biological, chemical and physical indicators. Measurement protocols and indexing techniques are needed for easy identification of the soil properties, processes and the effects of human management practices over time. Soil quality assessment and interpretation tools must be sensitive and responsive to the various soil properties and processes that respond to changes in soil and crop management practices and land use decisions. They also need to account for differences in inherent soil conditions among various physiographic regions and their response, both positive and negative, to management practices. They should help determine appropriate land uses and input needs and help land owners and operators to select or develop more environmentally-sound management practices, while providing the food, feed and fibre needed to satisfy increasing human needs.

50. **Opportunities/Areas for action.** The assessment of the health of soils, through the identification of key soil properties, which can serve as indicators of soil health, has become a major issue for land managers and the food and agricultural sector through the world. For example, FAO has recently been identified as the executing agency for conducting, in close cooperation with multiple partners, the GEF/UNEP Land Degradation Assessment in Drylands (LADA). Soil biota and its functions should be a key component of such assessments. In particular, there is a need to determine short- and long-term effects of agricultural management practices on soil biological community populations, biodiversity, functioning and resilience. Relating soil quality/ health to productivity, in terms of crop yield and profitability, and environmental effects from drainage, leaching, runoff and erosion is essential in order to evaluate the sustainability of various land management strategies.

51. There is recent progress in realising that soil health, by its broadest definition, is inseparable from issues of sustainability. The challenge ahead is to develop holistic approaches for assessing soil quality and health that are useful to producers, specialists and policy makers in identifying agricultural and land use management systems that are profitable and will sustain finite soil resources for future generations. Benefits of paying more attention to soil health and its assessment include its potential use in: the evaluation of land-use policy and of practices that degrade or improve the soil resource; and in the identification of critical landscapes or management systems and of gaps in our knowledge base and understanding of sustainable management.

b) Managing Interactions among Land Management, Soil Biodiversity and Agricultural Production

52. **What is known.** Land use and the type of farming system impacts upon soil life, while soil management controls and manipulates the organisms responsible for nutrient cycling, crop diseases and pest damage through its effects on soil physical and chemical conditions, biological habitat, food sources and plant-host interactions. Biotic processes impact on long-term productivity, soil fertility, soil aggregation, erosion and other indicators of soil quality. In turn, the soil biota and their interactions play a part in the success of any management decision. For example, intensive cultivation coupled with mono-cropping practices may

detrimentally affect the functioning of the soil biota leading to loss of plant nutrients and soil aggregate structure and resulting in soil degradation, environmental pollution and declining crop yields. On the other hand, minimum tillage practices and better crop cover, coupled with a more diverse cropping regime, may promote the more effective functioning of soil biota, resulting in improved soil structure and nutrient and water management and hence crop productivity.

53. **Case study of Biological nitrogen fixation:** The natural process of biological nitrogen fixation (BNF) constitutes an important source of nitrogen for crop growth and protein production in many soils and ecosystems. It therefore provides a major alternative to the use of commercial nitrogen fertiliser in agriculture. It has recently been estimated that global terrestrial BNF ranges between 100 and 290 million tons of nitrogen per year of which 40-48 million tons N per year is estimated to be biologically fixed in agricultural crops and fields[10]. In comparison, 83 million tons per year are currently fixed industrially for the production of fertiliser[11].

54. Biologically fixed N_2, either asymbiotic, associative or symbiotic, is considered a renewable resource, which should constitute an integral part of sustainable agro-ecosystems globally. The contribution of legume N fixation to the N-economy of any ecosystem is mediated by: the efficiency of the N_2 fixing system; the contribution of BNF to the soil N pool; and the total amount of N_2 fixed that actually is recycled by human practices and animal manure into the system. Several opportunities to enhance BNF inputs are available across different agro-ecosystems and socio-economic conditions, *inter alia*: through altering the number of effective symbiotic or associated organisms in the system (inoculation); screening and selection of the appropriate legume crop (selecting high BNF species well adapted to environmental conditions); and management practices that enhance N_2 fixation and recycling of net N_2 inputs into the cropping system (rotation, green manure application, no-tillage, strategic use of legumes, etc.)[12].

55. **Gaps and needs.** The complex relationships between soil biota, ecosystem functioning and land management practices must be well understood in order to develop guidelines for agriculture that will optimise resilience and sustainability of the ecosystem. A better understanding of the ecology of beneficial and harmful organisms is needed to utilise and control their expression in agricultural systems. An understanding of soil biota and their ecology must be developed, so that the ecological and biological effects of resident soil populations can be used to reduce inputs of non-renewable resources while still increasing productivity needed to meet food, feed and fibre demand.

56. **Opportunities/Areas for action.** There is a need to enhance scientific and farm knowledge of soil biota-manipulation and ecosystem interactions to

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[10] Cleveland, C.C.; Towsend, A.R; Schimel, D.S.; Fisher, H.; Howarth, R.W.; Hedein, L.O.; Perakis, S.S.; Latty, E.F.; Von Fischer, J.C.; Elseroad, A. and Watson, M.F.; 1999. Global patterns of terrestrial biological nitrogen fixation in natural ecosystems. Global Biogeochem. Cycles 13, 623-645

[11] Jenkinson, D.A., 2001. The impact of humans on the nitrogen cycle, with focus on temperate arable agriculture. Plant and Soil 228, 3-15

[12] FAO/AGLL Soil Biodiversity Portal (http://www.fao.org/ag/AGL/agll/soilbiod/default.htm). Montanez, 2000. **()** Overview and case studies on BNF: perspectives and limitations.

obtain better understanding of the processes they control and, thereby, to influence plant growth, soil biotic functions and soil productivity. This includes:

- development of fundamental understanding of the ecological characteristics and processes of the soil and root biology to predict accurately root, seed, soil and soil biota interactions;
- identification of fertility, cultural, spatial and temporal factors affecting these interactions;
- development of effective strategies to manage soil biota as an integrated aspect of soil and land resources management;
- development of improved methods to identify and characterise soil biota populations and their activities for farmer level in order to help in the interpretation of interactions between farmers' practices, soil function and agricultural production.

c) Soil biodiversity and biological management of pests

57. **What is known:** The rate and extent of build-up or maintenance of indigenous or introduced pathogens or pests depend on many environmental and cultural factors, including residues, organic matter and cover crop issues, plant stress, soil tillage, poor irrigation management and fertilisation practices and crop genetics. Intensive cropping, monocropping and the over-use of agro-chemicals often increases the build up of soil-borne pathogens (disease-carrying organisms), pests and weeds. This is also reflected following conversion to reduced or no-tillage practices, when carefully controlled herbicide use and prudent pest management practices may be required in the initial years until an ecological balance is restored and the natural biocontrol mechanisms become reestablished. Under no-tillage it has been reported that pathogens, pests and weeds are not necessarily greater but may differ from those prevalent under tilled systems; with appropriate management under no-tillage the equilibrium tends to favour beneficial organisms.

58. Soil biota can influence the growth of some organisms including larger life forms such as certain insects, crop plants and weeds, both positively and negatively. In some cases, deterioration of soil productivity stems from changes in soil biotic communities, reducing their capacity to suppress root pathogens and pests by biological means. Pathogens and pests unchecked by ecological competition can achieve populations that are devastating to agriculture and pose serious threats to economic sustainability. The nature of the pest outbreak, whether bacterial, fungal, viral, nematode, insect or weed, indicates the kind of management strategies needed to restrict or eliminate its activities. The strategies available to farmers are cultural (cropping practice), chemical and biological; however, not all strategies are feasible for every cropping system. Ecologically-oriented pest management within a viable, integrated systems' approach is gaining popularity. Management of the edaphic (soil-based) phase of the life cycle needs to be explored to develop additional biological pest management options.

59. **Case study of alternatives to methyl bromide in managing pests:** Under the Montreal Protocol of 1991, methyl bromide was defined as a chemical that contributes to depletion of the Earth's ozone layer; and it was internationally agreed that consumption of this product will be frozen in developing countries in 2002. Farmers who are dependent on methyl bromide for suppressing soil-borne pests and diseases are having to shift towards

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more environmentally sustainable agricultural practices. Alternatives to the use of methyl bromide have been investigated and biofumigation is one such example, that uses the Brassica family (i.e. broccoli, cabbage, cauliflower and rape) for producing toxic compounds. Preliminary results have shown that biofumigation, also combined with solarization, could be a successful biological alternative for producing fumigant-like chemicals in the soil for suppressing soil-borne pests and diseases and helping promote soil health[13].

60. **Gaps and needs.** Use of soil biota in pest management could increase crop efficiency, decrease the need for tillage and decrease the use of synthetic chemical pesticides. Often individual pathogens have been studied in isolation, which limits knowledge of activities *in situ* with the whole biotic community. A greater awareness of the full range of the soil biota community and its impact on its own soil community dynamics, plant growth and chemical-plant interactions are critical. Integrative approaches have the potential to be used to manage the production system and natural soil organism-plant interactions for pest suppression, either from adding beneficial organisms that can suppress the pests or managing or increasing such organisms that are resident in the soil. Further study is required, so that the ecological and biological effects of the resident soil organism population on pest growth can be used effectively in pest management strategies. Moreover, the use of soil biotic dynamics and integrated approaches to managing soil-borne pathogens or pests may also require additional soil management practices.

61. **Opportunities/Areas for action.** Soil micro-fauna play an important role in suppression of plant pathogens and represent a significant biological control potential. There are opportunities to develop effective and economically feasible disease and pest control strategies that reduce pathogens and pests through the introduction of antagonists or by managing resident soil biota to increase their activity. Efforts to manipulate and exploit the friendly fauna populations for crop benefit must be compatible with microbial symbionts, and other plant-growth promoting rhizosphere organisms, and with fungi and bacteria that are being promoted for biological control of diseases. This is clearly an area with great opportunities for further research.

d) Bioremediation: The Use of Soil Biota in Environmentally-friendly Treatments for the Decontamination of Soils

62. **What is known.** The goal of bioremediation efforts is to reduce the potential toxicity of chemical contaminants in the field by using micro-organisms, plants and animals to transform, metabolise, remove or immobilise toxicants. There is already a significant knowledge-base about many pathways for organic degradation, and several important contaminant degradation mechanisms are under detailed investigation[15]. Different types of organisms can be bioremediation agents, for example, micro-organisms (primarily bacteria and fungi) are nature's original recyclers. Their capability to transform natural and synthetic chemicals into sources of energy and raw materials for their own growth highlights their value as cheaper and more environmentally-benign alternatives to chemical or physical remediation processes. Plant roots can also indirectly stimulate microbial degradation of contaminants in the rhizosphere. The intrinsic

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[13] http://www.fao.org/WAICENT/FAOINFO/AGRICULT/AGP/AGPP/IPM/Web_Brom/Default.htm

ability of certain plants for uptake, translocation, transformation and detoxification of contaminants also offers a newly recognised resource that can be exploited. Research continues to discover and verify the bioremediation potential and unique properties of many organisms.

63. **Case study of Bioremediation:** These techniques are used to remove environmental pollutants from sites where they have been released or more often to reduce their concentrations to levels considered acceptable to site owners and/or regulatory agencies. Many bioremediation techniques exist to treat *in situ* soil contaminants and a number of organisms have been involved, particularly bacteria – such as *Achromobacter, Acinetobacter, Alcaligenes, Bacillus, Nocardia, Pseudomonas* – and fungi such as *Trichoderma, Rhodotorula, Mirtirella, Aspergillus*[14]. The rate at which microbial communities adapt their metabolism to toxic compounds is crucial in bioremediation. A recent addition to the growing list of bacteria that can sequester or reduce metals is *Geobacter metallireducens*, which removes uranium, a radioactive waste, from drainage waters in mining operations and from contaminated groundwater[15]. The concept of phytoremediation - the use of plants for abatement and containment of pollution - is developing as an acceptable management technique. This concept is also being applied in other environments, such as riparian zones and filter strips.

64. **Gaps and needs.** A tiny fraction of the soil microbial diversity of the Earth has been identified, and an even smaller fraction has been examined for its biodegradation potential. Understanding of biochemical and transformations of contaminants in soil has advanced in recent years. However, knowledge of the specific pathways for degradation/ detoxification and of the role of specific organisms and communities is limited. Biological approaches on the molecular level can clarify the expression and regulation of xenobiotic (contaminant) degradation and help provide methods to develop plants and micro-organisms with enhanced detoxification ability. This knowledge is essential for understanding the ability of soil to maintain a biological buffering barrier for pollution and in the design of systems to decontaminate soil and water.

65. **Opportunities/Areas for action.** Despite the successful contributions of existing knowledge, the understanding of biotransformation and biodegradation pathways and mechanisms in the field is incomplete. Opportunities are wide for further research (for example of microbial physiology and ecology, enzymology, biochemistry and plant-micro-organism interactions) and technology applications. Opportunities exist for the development of knowledge and techniques that will minimise the impact of agrochemicals and other xenobiotics in the environment and of approaches to promote the degradation of xenobiotics in soils. Improved methods and decision-making tool are needed for soils that require remediation with a view to improving soil productivity, protecting human health and preventing environmental degradation.

e) The ecological impact of agricultural biotechnology.

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[14] Microbial transformation and degradation of toxic organic chemicals. 1995. Young LY, and Cerniglia CE eds., Wiley-Liss, New York.

[15] US-EC Task Force on Biotechnology Research. Biotechnology and Genetic Resources. Proceedings of a workshop; 1992 October 21-22; Airlie, Va. Available from the NSF Biological Sciences Directorate, Arlington, Va

66. **What is known:** Agricultural biotechnology, if appropriately integrated with other technologies, offers opportunities for developing more productive and sustainable systems, for example the development of plant varieties and animal races for overcoming specific constraints such as soil and climatic limitations and specific pests and diseases. Biotechnology includes a wide array of techniques and applications, from natural fermentation processes and cell culture to genetic engineering, protein engineering and DNA amplification. Transgenic materials provide greatly increased opportunities but also potentially significant risks of affecting soil biodiversity and the ecosystem at all levels, for example, through upsetting the delicately balanced and complex food web.

67. There is a need to assist national and local governments in the formulation and application of policies that ensure the proper ownership and receiving of benefits deriving from the use of soil biodiversity, in particular the technologies and products that derive from the manipulation and extraction of particular components of the soil biota (especially micro-organisms and their products). Taking into account issues of bioprospecting, traditional knowledge and farmers' rights, this raises the important consideration of finding ways in which soil biodiversity and associated knowledge systems, can be managed for the benefit of farmers and rural communities and to ensure that legal and international property rights regimes support this aim.

68. An example of the beneficial use of biotechnology in the management of soil biodiversity is in the development of improved microbial inoculants. Effective wild-type strains are isolated from the environment for use as microbial inoculants in agriculture and recombinant DNA technology (i.e. genetic engineering) may be used to further improve microbial strains. Microbial characteristics that are being targeted for improved inoculant performance include: the survival ability of the inoculated strain, as in the case of strains that are better adjusted to soil constraints such as salinity, acidity or aridity; competitive nodulation of legume roots, as in the case of symbiotic nitrogen-fixing Rhizobium bacteria); and interactions with beneficial micro-organisms, for example compatibility with mycorrhizal fungi, and interactions with detrimental micro-organisms, for example for the inhibition of plant pathogens in the rhizosphere.

69. On the other hand, the area under transgenic crops is rapidly expanding and yet it is not well known what might be the long term effects on the ecosystem of potentially higher herbicide applications or the indirect effects of transgenic plant root exudates (secretions). The decomposition of modified genetic material from plant remains in the soil could seriously affect the balance of soil micro-organisms and be an ideal medium for horizontal gene transfer. Incorporation into plants of genes from *Bacillus thuringiensis* (Bt) toxins that code for the production of insecticidal toxins can be incorporated into the soil through leaf materials, when farmers incorporate crop residues after harvest. Toxins may persist for 2-3 months, resisting degradation by binding to clay and humic acid soil particles while maintaining toxin activity[16]. Such active Bt toxins that end up and accumulate in the soil and water from transgenic leaf litter may have negative impacts on soil and aquatic invertebrates and nutrient

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[16] Palm et al. 1996. Persistance in soil of transgenic plant produced *Bacillus thuringiensis var. Kurstaki* endotoxin. Canadian J. Microbiology

cycling processes[17]. Increased and frequent use of glyphosphate applications has produced changes in the microbial composition of soil in the field associated with "Roundup Ready" soybean production[18]. The use of glyphosphate-resistant soybean changes the dominance of fungi versus bacteria in the soil, altering nutrient cycling processes, nutrient retention ability and the ability of the soil to suppress disease. There has been little attention to monitor and improve understanding of the effects of transgenic crop plants, such as herbicide resistant soya beans or cereals, on soil biodiversity and their functions.

70. Perturbations have been recorded by several authors with the introduction in the soil of genetically modified micro-organisms (such as *Pseudomonas fluorescens*), including displacement of indigenous populations, suppression of fungal populations, reduced protozoa populations, altered soil enzymatic activity, and increased carbon turnover[19]. Circumstantial evidence that genetic exchanges between strains of Rhizobia occur in a field environment has been provided by population studies. However, information on the time scale and on the conditions in which these exchanges take place, is still missing. More research on the consequences of the release of novel organisms in the rhizosphere before they can be safely utilised is necessary.

71. **Opportunities/Areas for action:** Genetically modified organisms (GMOs) need to be adequately assessed for their environmental or human health effects before they are released into the environment. However, it is very difficult to predict how GMOs will behave once in the agricultural ecosystem. Today, results show that soil organisms are extremely sensitive to the use of engineered plants, and the effects are unpredictable. The impact of modern biotechnology on the environment and on human and animal health needs careful assessment on a case by case basis and through applying, in each situation, the precautionary approach, as adopted by the CBD. Attention is drawn to the need to consider how to implement the precautionary approach effectively and thereby address the concerns over risks and potential benefits of GMOs. International bodies such as FAO, UNEP, UNESCO and the CBD process, in particular the Biosafety Protocol, may provide guidance and assistance to countries on this matter. However, final decisions on the use of biotechnology remain a national responsibility.

72. This section has attempted to provide an overview of a range of opportunities that are available whereby farmers can actually manage soil biodiversity to enhance agricultural productivity. Nonetheless, as already noted, the adaptation and adoption of such technologies and sustainable systems requires an integrated natural resources management and agro-ecosystems approach in view of the complexity of soil biodiversity and the multiple biophysical–human interactions. In particular, it is important to stress that each opportunity has socio-economic as well as technical and environmental implications, and only those options that are economically viable and socially and culturally acceptable will be of interest to farming communities.

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[17] Donegan, KK et al. 1995. Changes in levels, species, and DNA fingerprints of soil microorganisms associated with cotton expressing the *Bacillus thuringiensis var. Kurstaki* endotoxin. Applied Soil Ecology 2, 111-124.

[18] Kremer RJ et al. Herbicide impact on Fusarium spp and soybean cyst nematodes in glyphosphate tolerant soybean. American Society of Agronomy.

[19] Naseby DC, Lynch JM (1998). Soil enzymes and microbial population structure to determine the impact of wild type and genetically modified *Pseudomonas fluorescens* in the rhizosphere of pea. *Mol. Ecol.*, *7*, 367–376.

IV THE INTERNATIONAL FRAMEWORK REGARDING SOIL BIODIVERSITY CONSERVATION AND MANAGEMENT

International conventions and initiatives

73. In the dialogue between research institutes, international organisations, private and public sectors and recipient governments with the aim of effectively integrating soil biological management into environmental and sustainable development policies and initiatives, a number of international agreements and conventions serve as important signposts. In addition to the Convention on Biological Diversity (CBD), whose consideration of soil biodiversity is presented in paragraphs 1 and 2 of this paper, the following agreements and processes are of relevance. These also highlight the importance of fostering participation and partnership with the broad range of stakeholders concerned as a means to address more effectively the problems encountered.

74. UNCED-Agenda 21: The current set of international environmental conventions have been developed on the basis of the global policy statement - Agenda 21 Plan of Action – that was adopted at the UN Conference on Environment and Development in Rio I992. This “Earth Summit” called for countries to incorporate environmental considerations into their development plans and build national strategies for sustainable development. At the United Nations General Assembly's special session in 1997 – “Rio plus five” - countries agreed to have such national strategies in place by 2002, which should be the product of extensive consultation with the stakeholders concerned. Countries are being assisted by donors to develop and implement these national strategies. A “Rio plus ten” summit will take place in Johannesburg in 2002 to assess progress achieved since 1992. The national strategies for sustainable development provide a useful framework for addressing issues of soil biodiversity management and conservation as part of an integrated approach.

75. The UN Convention to Combat Desertification (CCD) aims to address land degradation and drought in dryland areas, with the aim of improving living conditions. The text of this Convention binds signatory governments to promote long-term integrated strategies to improve the productivity of land, rehabilitate degraded areas, and conserve and manage land and water resources in a sustainable fashion, in particular at community level. National Action Programmes to address land degradation are being drawn up by a large number of countries through a consultative process, for which donor support is being sought. Soil biological management, including the conservation and sustainable use of soil biodiversity and its functions, should be an integral part of such plans.

76. The UN Framework Convention on Climate Change (FCCC) aims to achieve stabilisation of greenhouse gas concentrations in the atmosphere at a level that will prevent dangerous interference with the climate system. Such a level should be achieved within a time frame sufficient to allow ecosystems to adapt naturally to climate change, to ensure that food production is not threatened and to enable economic development to proceed in a sustainable manner. The Kyoto protocol, which aims at a reduction of carbon dioxide emissions, was drafted in 1997, and awaits ratification. There are various links between climate change and soil management especially in regard to carbon sequestration (the storage or fixation of Carbon in soil organic matter and in plant biomass) and greenhouse gas

emissions (GHG). The most important greenhouse gases are carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). Photosynthesis in plants leads to carbon fixation and CO_2. Decomposition and burning of biomass, however, releases CO_2 back to the atmosphere. Methane is produced in wetlands and rice fields, and by ruminant animals. Soils also emit N_2O as a result of microbial processes. At a global level, the mining, manufacture and transport of mineral fertilisers contribute to CO_2 and N_2O emissions". Thus, changes to soil fertility management by incorporating or enhancing biological management of soil fertility could have significant implications for climate change.

77. Agriculture provides a major share of national income and export earnings in many developing countries, while ensuring food security, income and employment to a large proportion of the population. Farmers, governments and scientists are increasingly aware that declining soil fertility is becoming a major concern worldwide with social, food security and environmental implications. As a result, controlling erosion and improving the management of soil fertility have become a major issue on the development policy agenda. In this regard, the Soil Fertility Initiative (SFI) for Sub-Saharan Africa was launched as part of the Rome Declaration on World Food Security in 1996, among key collaborating organisations, including the World Bank, FAO, ICRAF, IFDC, IFA, IFPRI and USAID. This interactive process aimed at increasing synergies and catalysing comprehensive strategies and actions at country level to enhance soil fertility restoration and management and prevent further nutrient mining. The focus was placed on practical solutions, including better use of organic and mineral fertilisers, integrated land husbandry approaches as well as overcoming institutional and policy constraints, such as land tenure and marketing. The development of Soil Management Action Plans has been promoted in over 20 countries through participatory review and prioritisation processes. In Burkina Faso and Ghana, for example, such plans have been developed and approved by the government. In other countries, certain priority actions are being addressed through investment and technical assistance programmes and with donor support.

78. A multitude of programmes in the agricultural and land sectors are supporting improved soil and land resources management and provide great scope for expanding attention to the conservation and sustainable use of soil biodiversity and the important functions of soil organisms. FAOs support to Member countries could be further mobilised to integrate soil biodiversity management through, *inter alia*: projects to improve capacities and tools and farmer-led learning approaches for soil productivity improvement and conservation agriculture, initiated through its Technical Cooperation Programme, the Special Program on Food Security and work on sustainable livelihoods; projects to mitigate land degradation and promote integrated watershed management and production systems; and, the CBD/FAO joint Programme of Work on Biodiversity for Food and Agriculture.

79. More specifically, the FAO-Netherlands Partnership Programme (FNPP) is a two-year programme that is supporting work by FAO towards the conservation and use of agricultural biodiversity within sustainable ecosystems and its contribution to global food security. One of the four main areas of attention is on improving understanding and implementation of the ecosystem approach, including adaptive management and best practices. In this regard, the sub-component on soil biodiversity aims to help catalyse more applied work in the agricultural and land sectors with the support of

scientific institutes that are currently focusing their research on certain categories and functions of soil biodiversity and on specific technologies. There are three main aims and axes of cooperation:

- Sharing of knowledge and information on the roles of diverse soil organisms in providing key goods and services and the impacts of existing and new agricultural technologies and management practices, with a view to developing guidance for agricultural and environmental-CBD fora;
- Collaboration among relevant programmes, networks and national and inter-national bodies to identify and promote improved soil biological management practices for different conditions and their integration into ongoing land management and soil productivity efforts; and,
- Establishing partnerships among farmers/land resource users and researchers/ development programmes to monitor and assess different practices and prepare case studies and to integrate soil biodiversity issues into documentation and training materials.

80. This FNPP soil biodiversity project is identifying and establishing linkages as appropriate with ongoing programmes and networks, for example:

- the GEF/UNEP project and network on the Conservation and Sustainable Management of Below-Ground Biodiversity hosted by the Tropical Soil Biodiversity and Fertility program (TSBF) of UNESCO-Diversitas: ;
- Networks including the CYTED Macro-fauna network, for which EMBRAPA-Brazil is planning to host a meeting in February 2002), and various mycorrhiza and rhizobia networks such as the “Asociación Latino Americana de Rhizobiología” (ALAR), the “Caribbean Mycorrhizal Network” (CARIVAM) in Latin America, as well as gender/indigenous knowledge networks, such as the FAO-LINKS gender, biodiversity and indigenous knowledge network and the soil and gender network of University of Berne;
- Research bodies such as Institut de Recherche et Developpement (IRD-UR), in France, on Biodiversity and Soil Functioning which is holding a macro-fauna meeting (Paris, December 2001); the NERC Soil biodiversity Program and CABI in UK; the CLUE project and the Wageningen simulation project on biodiversity, which is assessing the impact of soil biodiversity on ecosystem functioning, in Holland;
- Agro-biology/ecology bodies such as Centro de Pesquisa em Agrobiologia of EMBRAPA, Brazil and University of Padova Agroecology Laboratory;
- Soil biodiversity projects such as CYTED Project (Latin America) and SHIFT Project (GTZ-EMBRAPA), Manaus, Amazonas, Brazil; EU Soil biodiversity and ecosystem functioning program; and the UNU People Land Management and Environmental Change Project (PLEC), which is concerned with indigenous approaches to above-ground agrobiodiversity.

81. An international technical workshop on “Integrated Soil Biological Management and Sustainable Agriculture” is scheduled for mid 2002, with support of the FNPP programme, and in collaboration with technical partners, to further review the state of the art, with a focus on practical experiences, and to help identify priorities for action. Consultation has been initiated with Embrapa, Brazil, as a possible host institution. This review process should take into account the crucial role of soil biodiversity in agricultural production and in providing wider ecosystem services, and the need for appropriate management technologies, building on local knowledge systems and ensuring integrated approaches.

V. CONCLUSIONS AND AREAS FOR CONSIDERATION

Conclusions

82. Soil biologists and agriculturalists are challenged to address a major global concern: ***"How to provide greater food security for all nations on earth in a sustainable way?".*** In addressing soil biodiversity and relevant societal concerns it is necessary to take an ecosystem approach and a multi-disciplinary approach in order to better understand biophysical and human interactions and the complexity of the living systems. However, as noted by E.O Wilson and Wake[20], as underground biodiversity is incredibly complex, it may require to initially focus, for example to assess specific functions of soil biota in productive agro-ecosystems and impacts of specific farming systems, technologies and practices. Nonetheless, this should subsequently lead to the development of integrated soil biological management as a means to maintain renewable soil fertility and ecosystem services.

83. Soil biota provide key ecosystem services that are responsible for naturally renewable soil fertility, for mediating carbon sinks in the soil and many other functions. The conservation of healthy communities of soil biota and prudent use of specific soil organisms through biological soil management can be used to maintain and enhance soil fertility and ensure productive and sustainable agricultural systems[21]. Moreover, the consequences of neglecting or abusing soil life will weaken soil functions, and contribute to greater loss of fertile lands and an over-reliance on chemical means for maintaining agricultural production. This emphasises the need to enhance collaboration among soil biology specialists and agricultural practitioners, those concerned with land degradation and other stakeholders in promoting improved soil biological management.

84. In view of the complex nature and limited knowledge of soil biodiversity there is a need to identify and assess the feasibility of potential soil biodiversity activities and applications in order identify priorities and to evaluate costs and benefits to different user groups. In particular, in view of the following notable gaps in knowledge:
- Soil biota are highly diverse and numerically staggering, yet only major taxonomic and functional groups are well known;
- Critical ecosystem services provided by soil biota (e.g., organic matter decomposition, nutrient cycling and pest control) are still under intense investigation;
- Little is known of the colonisation-extinction dynamics of soil biota or how the additions and deletions of keystone taxa or functional groups will influence sustainable agricultural productivity;
- Not all strategic objectives and programmatic activities will benefit equally (i.e. immediate gains will be realised in some areas, mid- to long-term gains in others, and little or no benefits may be seen in other areas).

Areas for Consideration

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20 1 Wake, M.H. 2001. Integrative biology: its promise and its perils. In: Biological Science: Challenges for the 21st Century. G. Bernardi, J.C. Mounolou and T. Younés, eds. Biology International 41, 71-74.

[21] Matson, P.A., W.J. Parton, A.G. Power, and M.J. Swift. 1997. Agricultural intensification and ecosystem properties. *Science*, **277**, 504-509.

85. In accordance with the programme of work on agricultural biodiversity and taking into account the above findings, there is a need for promoting coordinated actions and concerted attention on soil biodiversity with a view to enhancing its contributions to agricultural productivity and sustainability and to combating land degradation, including, as appropriate, the biological restoration of soil fertility (i.e. in fragile areas such as dryland, coastal and mountain environments and following natural disasters such as droughts, floods or excessive rains). In this regard, an <u>International Soil Biodiversity Initiative</u> is proposed to encourage country Parties to the CBD and FAO Member Nations to make progress, especially in the areas of: Technical assessments; Adaptive management of soil biota; Capacity-building; and Mainstreaming of relevant soil biology issues into various institutions and processes.

86. The main objectives of such an initiative could, *inter alia:*

1). Promoting the assessment, sharing of knowledge, information and case studies and awareness raising (i.e. on the roles and importance of diverse soil organisms in providing key goods and services and on the positive and negative impacts of existing and new agricultural technologies and management practices), with a view to developing guidance for field workers/technicians and for national and international priority setting and policies.

2). Enhancing collaboration among relevant programmes, networks, research institutes and national and international bodies to, firstly, develop indicators and field methodologies for monitoring and assessing soil biodiversity and its functions and the effects of land use/management practices on soil quality and health, and thereby, to identify and promote improved soil biological management practices for different conditions and their integration into ongoing agriculture/land management efforts.

3). Strengthening capacities and partnerships among farmers/land resource users, researchers and development programmes: to monitor and assess different practices and prepare case studies; to integrate soil biodiversity issues into documentation, training materials and policies (guidelines, compendia of “best practices”, etc.); and to facilitate participatory research and technology transfer on soil biodiversity/biological management, with a view to promoting sustainable agriculture and improved land management.

87. The suggested approach should be a participatory and Integrated Soil Biological Management (ISBM) process that involves the range of stakeholders in a flexible and iterative process of creating, sharing, and improving experiences of integrated soil biological management. A focus is suggested on the following user groups: i) Resource-poor farmers, small-scale producers (men and women) and rural communities (especially those living on marginal and/or degraded lands as these are particularly amenable to soil biological management practices); and ii) Policy makers and promoters of sustainable agriculture in Low Income Food-Deficit Countries (LIFDCs), including research institutes, extension programmes, NGOs and international funding partners.

88. A focus should be placed on developing and refining existing opportunities (direct and indirect management interventions) for different biophysical and socio-economic conditions, and their integration with other management strategies (soil and water, crop and livestock, integrated pest

management, etc.) The challenge will be to identify and promote integrated systems that are economically viable, environmentally sustainable and appropriate both socially and culturally. This could be initiated through pilot-level demonstration projects, with subsequent scaling-up processes through global and regional programmes and in collaboration with partners (CGIAR, TSBF, NGOs and others). Case studies of intervention practices could be developed into training materials and management guidelines, and then applied research could be sponsored to generalise these guidelines into management practices relevant to particular agro-ecological zones and for farmers, extension agents and technicians at various levels and of various economic means (i.e. low and high-input farmers).

89. In accordance with the call for case studies under the CBD programme of work on agricultural biodiversity, contributions illustrating experiences in the conservation and sustainable use of soil biodiversity are solicited from all concerned actors in the agriculture and environment sectors, in order to facilitate the review and prioritisation process for further work.

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