Principles, functioning and management of ecosystems cultivated under Direct seeding Mulch-based Cropping systems (DMC)

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This document is a translation of the first chapters of a practical handbook of direct seeding on permanent soil cover in Madagascar (also called DMC, for Direct Seeding Mulch-based Cropping systems), originally published in French in 2009. Although this handbook focuses on Madagascar, the principles and the processes described here have a much broader scope and can be used worldwide.

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FOREWORD

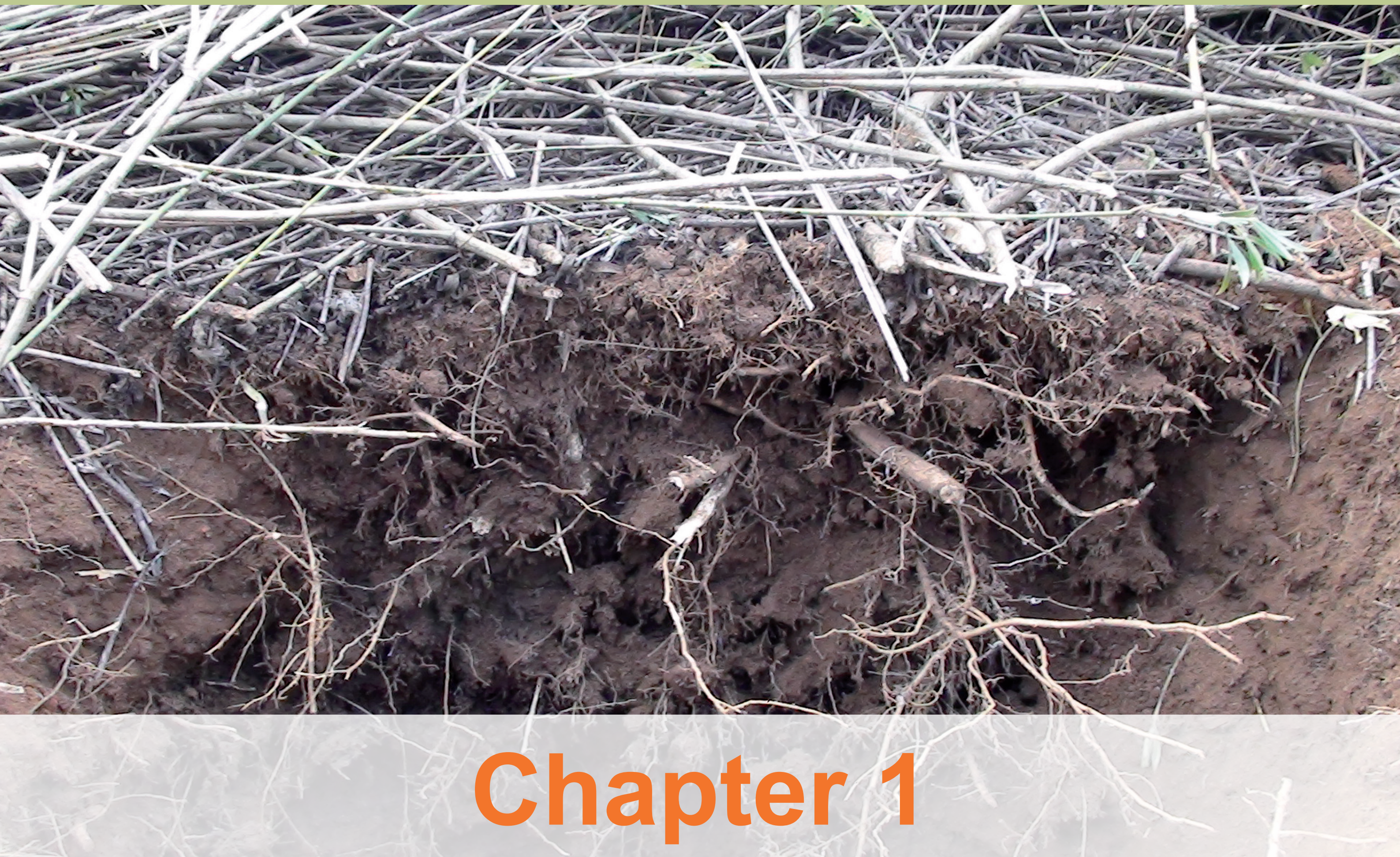
Conservation Agriculture (CA) relies on three main principles:
- Minimal soil disturbance;
- Permanent soil cover;
- Crop rotations.

Direct seeding Mulch-based Cropping systems (DMC) as developed by CIRAD and its partners are part of CA practices, trying to optimize their performances.

Based on the understanding of soil/plants/microorganisms interactions and the importance of the primary biomass production in the functioning of the soil system, DMC introduces multifunctional cover crops, growing intercropped or in sequence with the main commercial crop. The introduction of cover crops leads to better utilization of available natural resources, maximization of biomass production and higher organic restitutions to the soil system.

This document presents a conceptual model unravelling how soil, plants, micro and macro-organisms interact in a living soil, and how cropping systems can be managed to make them operate as best as possible with DMC.

Upland rice after stylosanthes



Chapter 1

Principles and functioning of ecosystems cultivated under Direct seeding Mulch-based Cropping systems (DMC)

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Cover crop : eleusine + crotalaria

1. Functioning of a natural forest ecosystem

In a natural ecosystem such as a forest, the soil is undisturbed and is permanently protected by a very diversified plant cover. This creates favourable conditions (humidity, aeration, temperature, nutrient substratum, etc.) for a strong biological activity.

Very diverse plants and organisms interacting in the soil assure a high biomass production and fulfil various ecosystem functions such as:

* production of organic matter by photosynthesis using water and carbon dioxide;
* soil protection and runoff reduction by permanent plant cover;
* recycling of nutrients and water by deep roots; atmospheric nitrogen fixation by bacteria associated with plants (in root nodules of leguminous plants, or in the rhizosphere);
* mineralization and solubilization of nutrients by living organisms, assuring a regular supply to plants;
* soil enrichment in stable organic matter and carbon sequestration;
* soil aeration by strong root systems;
* soil temperature regulation; and
* all the processes of soil genesis with:

- alteration of parent rock into clay (faster or slower depending on climate and rock type) by strong root systems and their root exudates, fungi, microorganisms of the soil, etc.

- progressive break down of large size plant debris (making them accessible to microflora) with the intervention of a great trophic diversity: large collembola, diptera, macro arthropoda, enchitrea, small collembola, oribatids, etc.

- bacterial humification. The rapidity and the final products of this humification vary according to vegetation type, climate and microflora;

- bioturbation by the soil fauna (indispensable function of pedogenesis, mixing mineral and organic material, allowing the formation of the clay-humic complex and soil aggregation processes): earthworms, ants, termites, coleopteran larva, etc.

- aggregation and stabilization of soil aggregates by the fauna (bioturbation, microflora activation), fungi (by mycelium/hyphae), bacteria colonies, root exudates, polysaccharides, etc.

These various functions carried out by plants and soil living organisms ensure an active pedogenesis and maintain a regularly renewed soil. The high turn-over of organic matter and nutrients, along with the absence of losses by leaching, makes it possible to sustain, in a long-lasting way, a high production, even on soils with a reduced fertility. This biomass production permits the maintenance of pedogenesis. The ecosystem is stable and resilient.

The living soil

Macrofauna and microorganisms play a major role in the life of the soil. They are essential to its formation: parent rock alteration, decomposition of organic matter, mineralization process and humus formation, bioturbation, etc.

They also play a key role in the formation and stability of soil aggregates and, hence, in soil structure. Microflora (bacteria, mycorrhizae, trichoderma, etc.) is also fundamental for plants food supply:

* mineralization of organic matter;
* fixation of atmospheric nitrogen;
* solubilization of mineral elements by oxidation or chelation, making them available to plants;
* extraction of soil nutrients not readily available (by modification of pH and redox potential, and increase of interception surface by mycorrhizae, etc.).

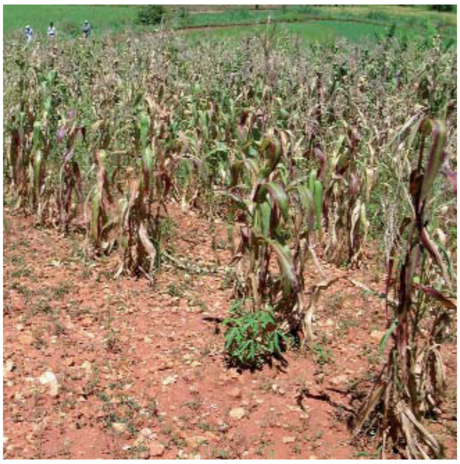
They are so important for the plants that they stimulate them by their root exudates, “releasing” by rhizodeposition 20 to 50% of the carbon caught by photosynthesis.

Some plants deficient in phosphorus, for example, may, via their secretions, favour in a preferential way the development of bacteria able to extract fixed phosphorus from the soil and make it soluble.

Functioning of a natural forest ecosystem

2. Functioning principles of cultivated ecosystems

2.1. Principles of conventional agriculture



Erosion and phosphorus deficiency in maize, in a conventional system

Conventional agriculture is based on soil tilling and use of chemicals. The soil becomes a mere physical support for plants and a nutrients reservoir. The response to the diverse agricultural constraints is mainly an adaptation of operational sequences which aim to assure different fundamental agricultural roles:

- restructuring the soil by mechanical tilling;
- controlling weeds by tilling and herbicides;
- supplying nutrients to plants with chemical and/or organic fertilizers;
- irrigating, when possible;
- controlling bioaggressors with pesticides.

Plant breeding and selection give focus on maximizing input efficiency and adapting plants to poor environmental conditions (disease resistance, etc.).

2.2. Principles of traditional slash-and-burn systems

Traditional agricultural systems based on slash-and-burn methods operate on alternating between the forest ecosystem and conventional systems with soil tilling (but with minimum inputs). The general degradation of ecosystems (decreasing biological activity, soil compaction, increasing weed pressure, etc.) is extremely rapid during cultivation periods. This is partly compensated by regeneration during long fallow periods.

2.3. Principles of Direct seeding Mulch-based Cropping systems (DMC)

<u>*Main principles of DMC systems*</u>

The management principles of DMC ecosystems are to mimic a natural forest ecosystem, in particular its litter, by:

Three fundamental principles

1. To minimize soil and litter disturbance (no soil tillage).
2. To maintain permanent cover of the soil.
3. To produce and return high biomass to the soil by associations/successions of a diversity of multifunctional plants.

* **Minimization of soil and litter disturbance.** The soil and litter must be disturbed as little as possible. Therefore, they are not tilled through plant cover ensuring minimal soil and litter disturbance (3-10% depending on the mastery and nature of the tools used). Seeding is either manual, via seed holes, or by machine, in rows. Low soil disturbance, favourable to the development of increased biological activity, slows down mineralization and helps maintaining the plant cover.

* **Permanent and total soil cover.** The soil is permanently protected under thick plant cover. This plant cover can be :

- dead: crop residues, weeds and/or cover plants are totally controlled prior to main crop seeding, or
- alive: a perennial plant cover is simply controlled during the time of cultivation and allowed to grow after the crop harvest.

This plant cover permanently protects the soil against erosion, maintains favourable conditions for the development of an intensive biological activity and contributes to weed control.

* **High biomass production and restitution to soil.** This biomass is renewed annually by various multifunctional plants (crops and cover plants) **intercropped and/or in succession,** which permits soil cover maintenance despite mineralization. These plants carry out various ecosystem functions.

However, DMC ecosystems are intensified compared to a natural ecosystem, in order to allow production of crop and/or fodder which are exported (this implies a return of inputs in order to restore nutrients taken by the system).

These three principles lead to the development of three "pillars":

The three "pillars" of DMC systems

* Permanent plant cover. The thick litter, as established by these three fundamental principles of DMC, is supplied by high biomass production and not disturbed by soil tillage. It protects the soil and modifies the dynamics of organic matter, water and nutrients;

* A diversity of plants performing multiple functions. Plants either intercropped or cropped in succession in the DMC systems, according to the third principle. Plant diversity particularly assures the production of aerial biomass (litter supply) as well as root biomass (exploration of a large volume of soil, production of subterranean biomass, soil restructuration, nutrient mobilization and recycling, etc.);

* High biological soil activity (fauna and microflora), made possible by the first two "pillars". This supplies the soil with organic matter and promotes the development of organisms in:

- restructuring and aerating the soil by strong root systems;
- maintaining humidity (low runoff, high water infiltration and storage, limited evaporation) and buffering temperatures by the plant cover;
- providing an energy substratum: fresh organic matter (decomposing litter and roots after plant death), as well as exudates released by young roots (sugars, hormones, enzymes, etc.).

In return, this high biological activity contributes to improving and stabilizing the soil structure (structuring and stabilizing soil aggregates by macrofauna, soil fungi, colonies of bacteria, etc.).

Biological activity is essential in soil genesis and plays a fundamental role in the nutrient cycle at litter level (organic matter cycle: mineralization, humification and carbon sequestration, accumulation of organic nitrogen; solubilization of nutrients by oxidation or chelation) as well as the level of the absorbent complex (nature of bases and retention). It reinforces the second "pillar" (multifunctional plants), that supplies the first pillar (the litter).

These three "pillars" (plant cover/litter + multifunctional plants/roots + associated biological activity) mutually

The plant cover / litter

Soil plant cover is fundamental for the proper functioning of DMC system.

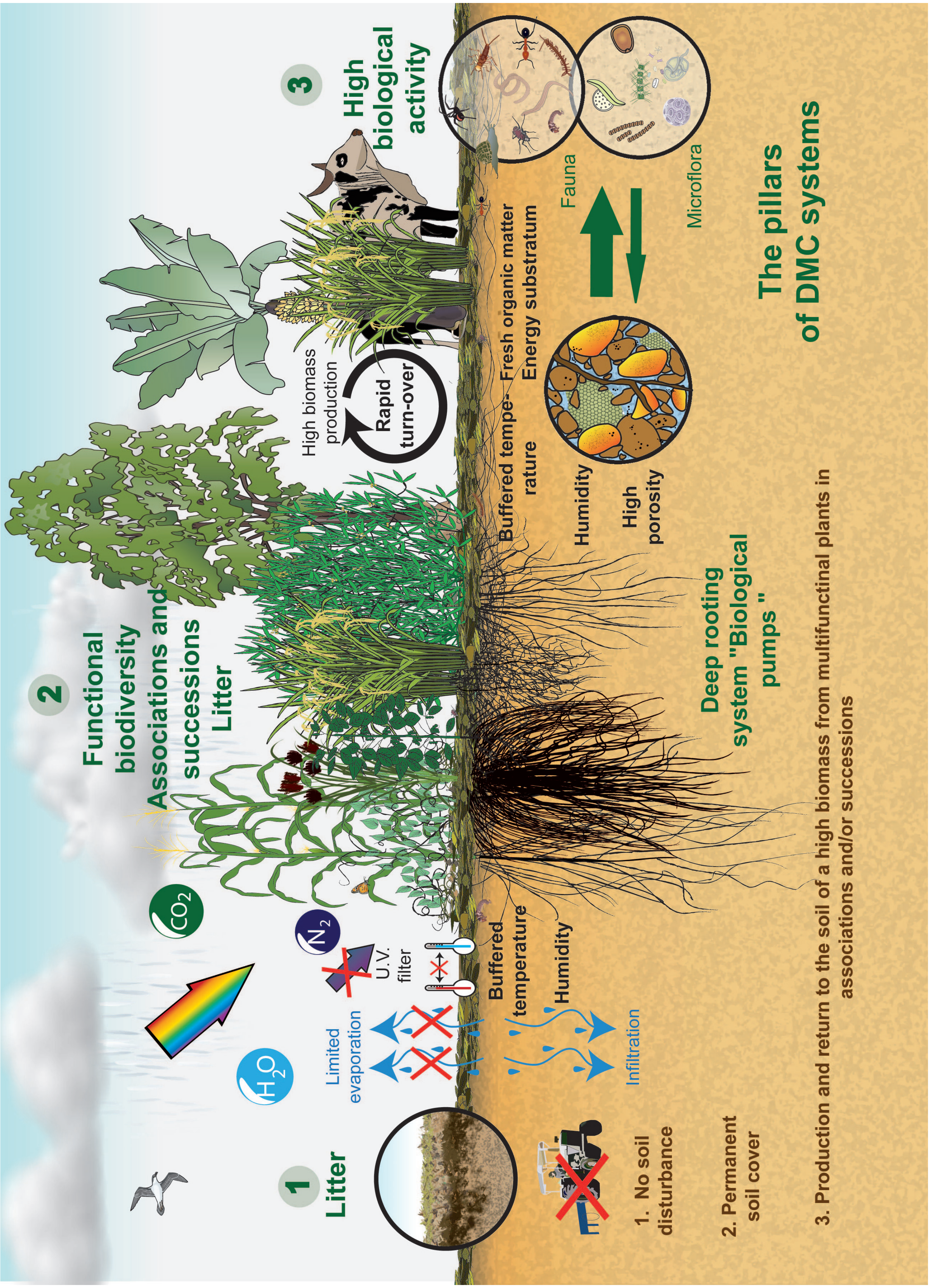
It needs to be maintained as completely and continuously as possible.
It is composed of crop residues and dry matter, often predominant in quantity and biodiversity, from plants associated with the main crop or carried out in annual succession.
In exceptional climatic conditions it can be difficult to maintain the plant cover because it can severely limit plant growth.
Conversely, the plant cover can be extremely thick because sometimes they are composed by biomass residues from several successive years, according to quality and quantity of biomass, and climatic conditions. This is the case in the Malagasy highlands where scraps of corn stalks, grown two or even three years earlier, can be found.
This regular supply and permanent maintenance of a plant cover without soil disturbance makes DMC systems different from most of the techniques sometimes brought together under the term «conservation agriculture», including SCT (Simplified Cultivation Techniques).

A diversity of multifunctional plants

The associations and successions of crops play a key role in DMC functioning. The various plants used in the systems optimize the biomass production and carry out a number of ecosystem functions: soil structuring and protection, carbon sequestration, recycling and storage of nutrients, control of weeds and bioaggressors, etc.

They also promote the development of a high biological activity, contributing to the achievement of these functions. Systems are designed to better fulfil the prioritary functions in a given context, by choosing the plants that are most capable of removing the most limiting agronomic constraints.

The integration of strong and deep-rooted plants into the cropping systems allows, in particular, optimisation of the fundamental functions of soil restructuring and of recycling nutrients and water (role of "biological pumps").


1
Litter
1. No soil disturbance
2. Permanent soil cover
3. Production and return to the soil of a high biomass from multifunctional plants in associations and/or successions
Limited evaporation
Infiltration
U.V. filter
Buffered temperature
Humidity
2
Functional biodiversity
Associations and successions
Litter
Deep rooting system "Biological pumps "
Buffered tempe- rature
Humidity
High porosity
High biomass production
Rapid turn-over
Fresh organic matter
Energy substratum
3
High biological activity
Fauna
Microflora
The pillars of DMC systems

reinforce each other. They allow DMCs, by their nature and their quantity constantly renewed (functional biodiversity), to carry out multiple and complementary functions. These functions are common to all DMCs but they vary in intensity, according to the systems and the conditions under which they were achieved (quality and quantity of biomass produced and returned to the soil).

An intense biological activity

The intense biological activity created by a favourable environment and availability of abundant energy substratum (fresh organic matter and root exudates), permits some essential functions:

- stabilization of the soil structure;
- humification and mineralization;
- solubilization (by oxidation or chelation);
- reinforcement of plants natural defences

3. Functioning of cultivated ecosystems

3.1. Organic matter dynamics

Soil organic matter

In an ecosystem with high plant production, of diverse quality, the phytomass produced maintains the litter layer. The decomposition of this fresh organic matter by living organisms largely contributes to:
(i) plant nutrition (which assures a high biomass production) and,
(ii) carbon storage in the soil, in more or less stable forms, in relation to particle aggregation.

Four reservoirs of organic matter can be distinguished:

1. The "active" or "labile" reservoir, consisting of easily oxidizable organic compounds from plant debris (sugars, starches, simple and interstratified proteins and polysaccharides, hemicelluloses). It is mainly controlled by the supply of residues and by climate, and it is strongly affected by the soil management practices. In a tropical environment, this reservoir has two main functions: (i) assure plant nutrient supply and (ii) provide organic compounds responsible for soil aggregation and cation retention.

2. The "slowly oxidizable" reservoir, in relation to macro aggregates. This reservoir is influenced by soil management practices.

3. The "very slowly oxidizable" reservoir, in relation to the micro aggregates. This reservoir is poorly influenced by soil management practices.

4. The "passive" or "recalcitrant" reservoir, extremely stable form, in relation to carbon associated with the primary soil particles. This reservoir is controlled by the mineralogy of the clay fraction. It is influenced (at the plot scale) by soil management practices only when they engender a transport by erosion.

Importance of the organic matter

The organic matter in soil plays a fundamental role in:

- soil structure and stability (binding mineral particles in the clay-humus complex, contributing to aggregates, etc.);
- water retention and water availability for plants;
- nutrient storage and availability (significant contribution to the cation exchange capacity, mineralization products, etc.);
- soil pH regulation (buffer effect);
- stimulation of biological activity (energy substratum and supports);
- micro pollutants retention (improving their degradation), etc.

These different organic matter reservoirs undergo mineralization and humification, but in different ways, depending on the material and on the environmental conditions:

* Humification by heritage for the large molecules (polyphenols, lignin), poorly attacked by micro organisms;
* Humification by polycondensation of phenolic compounds, resulting directly from the decomposition of plant tissues;
* Humification by neosynthesis, by the soil microorganisms, using small molecules resulting from degradation of fresh organic material to form new and more resistant compounds: the polysaccharides (which play an important role in the aggregation).

As the litter is regularly fed with various qualities of organic matter, with a varied mineralization speed, mineralization is uninterrupted and continuously releases soluble nutrients that allow a regular supply to plants.

The products resulting from the humification of organic matter (humic acids, etc.) will be closely associated with polyvalent cations (Ca2 +, iron and aluminium hydroxides) with clays (resulting from the parent rock deterioration) in the clay-humus complex, thus supplying the passive reservoir of organic matter. This fraction, extremely stable and fine, (1000-year extended life) is progressively aggregated:

* into micro aggregates (< 250µm), with silts and fine particles of organic matter from plant, decomposition. These micro aggregates are coated with clays and strongly tied by plant roots, hyphae and fungal mycelium, and polysaccharides produced by microorganisms, and fungi stimulated by root exudates;
* into macro aggregates, aggregating micro aggregates, an intermediate fraction of the organic matter (50-200µm: leaf and root fragments), bacterial colonies and sand grains under the linking effect of hyphae/mycelium from soil fungi, polysaccharides and plant roots. Macro aggregates are less stable than micro aggregates and organic matter in these aggregates is less physically protected than in micro aggregates.

The soil fauna, particularly earthworms, play a fundamental role in these aggregation processes. They ensure the soil bioturbation and therefore bring into contact mineral (clays, silts, sands) and organic soil fractions. They contribute not only to the creation of aggregates (mixing mechanical action) but also to their stabilization (drought-humidity alternation, microorganisms' activation, etc.).

This process of aggregation (and therefore carbon sequestration) is continuous and its rate is directly proportional to the quantity and quality of organic matter (roots, stems, leaves, straws) returned to the soil system. The dynamics of organic matter is therefore fundamentally different between tilled agriculture and well-managed DMC systems.

Speed of residues decomposition

Mineralization speed strongly depends on the quality of the fresh organic matter. Residues rich in sugars, starches and simple proteins (and to a lesser degree in interstratified proteins and saccharides) with a low C/N ratio, decompose themselves far more rapidly than those rich in hemicellulose and cellulose, with a higher C/N ratio. The biggest molecules, such as fat substances and waxes, and especially polyphenols and lignin, with their aromatic nucleus, decompose far more slowly.
Mineralization speed also depends on the microflora activity and therefore on the environment conditions (aeration, humidity, temperature), the type of soil and the "attack" surfaces (fragment size).

Mineralization is relatively slow during dry periods and/or in cold environments (as in temperate climates). On the other hand, mineralization is particularly rapid in a tropical environment, humid and warm all year.
Tillage (and STCs) accelerates the mineralization process by fragmenting residues and destructuring macro aggregates. This exposes the organic matter that was protected inside, by creating (temporarily) a brutal oxygen supply and enabling a rise in soil temperature. The mineralization speed is only limited by humidity and/or temperature (in a temperate environment).

Dynamics of the organic matter in conventional systems with tilled soil

Conventional systems are characterized by:

* soil tillage, which leads to an irregular mineralization with peaks of extremely rapid mineralization;
* a rather weak biomass production (production of a small number of species, over a limited period; irregular and unbalanced plant supply, etc.);
* residues of a single kind, with relatively low C/N, which decompose rapidly and consequently produce little humus;
* organic matter poorly protected, due to the weak aggregation;
* erosion frequently strong, generated by soil destructuring practices and high runoff, that carry away from the plots even the most stable fractions of the organic matter.

Consequently, crop residues, even if fully maintained on the plot, are generally not sufficient to maintain the soil carbon stock. This is particularly true in a tropical environment where mineralization is extremely rapid. Moreover, in conventional systems, this biomass is often exported or burnt, which makes carbon returns to the soil extremely low. They are not enough to supply the various organic matter reservoirs (including the fauna and microflora active reservoir). This results in a discontinuity in the transformation process of the active compartment, with a reduction in the C flow to the stable reservoir of organic matter in the soil.

Dynamics of organic matter in an ecosystem cultivated under DMC system

Contrary to conventional systems, DMC systems are characterized by:

* the production and regular restitution of a high quantity of biomass, of varying quality, supplying the several organic matter reservoirs in the soil and maintaining a continuous carbon flow from the active reservoir to the stable reservoir;
* a slow and regular mineralization due to the absence of litter disturbance (no mechanical fragmentation of residues, protection of the various layers of successive inputs with varied decomposition speed and little exposure to microbial processes, no brutal oxygen flow, buffered temperature);
* a continuous aggregation that leads to protection of organic matter within the aggregates: clay-humus complex formation, protection of the carbon stable fraction (<53μm) strongly linked in the micro aggregates (<250μm), protection of the micro aggregates in the macro aggregates, etc.

Rice + oat on a thick cover after maize + cowpea

The high biomass production and the intense biological activity allow a dynamic functioning of organic matter in relation to the aggregation process. The fresh matter (temporary reservoir) goes through the mineralization process (supplying the plants which will supply the litter) and humification (supply of the transitional and the stable reservoirs of organic matter). These organic matter reservoirs are more or less protected within the aggregates, according to their size.

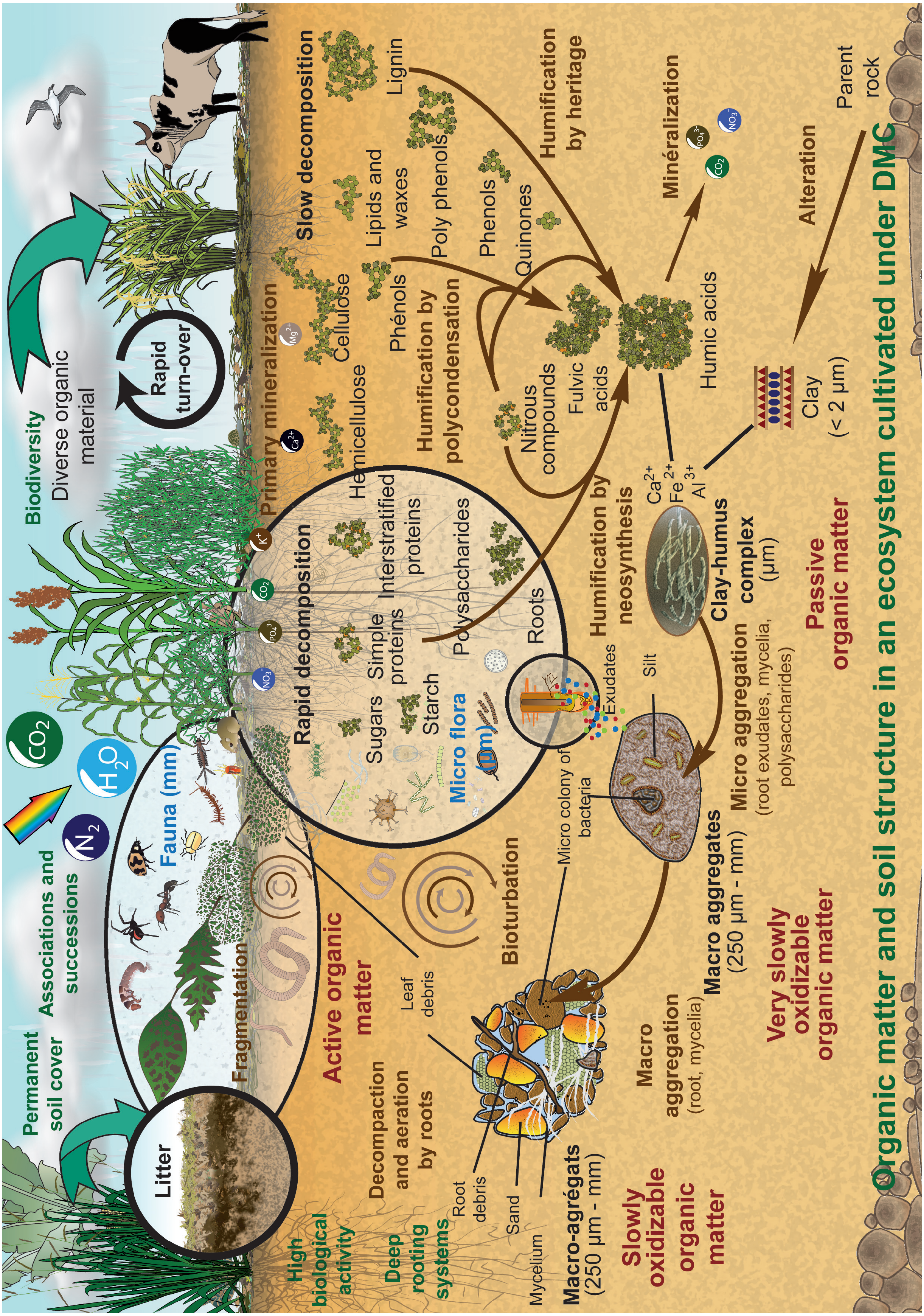
These processes (primarily, the high biomass production) lead to soil carbon sequestration and provide a fundamental ecosystem service at a planetary scale.

Thus, DMC systems work like a natural ecosystem and rely on a high and fast turn-over of the organic matter and on efficient aggregation processes. The main difference between well managed DMC systems and a natural forest ecosystem lies in the organic matter quantity and quality. In DMC, despite the diversity of cultivated plants, the woody part is not as abundant as in the forest and the residues produced have a higher amount of cellulose and less lignin. The decomposition rate is higher and the humification rate is lower. The carbon flow is faster than under natural vegetation with diverse species and a larger number of organic compounds composed of waxes, fat substances, lignin and polyphenols. To be efficient, DMC systems must insure, through plant intercropping/succession, a high production of material rich in cellulose, in order to maintain a carbon flow that allows the redistribution of organic compounds, at various humification stages, in the various compartments of the soil organic matter. Such systems have a very high organic matter turn-over and a particularly important organic matter active reservoir (20 to 25% in a tropical environment). In temperate environments, the flows of production and mineralization are less rapid than in tropical environments, and the active reservoir is proportionally smaller.

Biological activity and speed of mineralization

In conventional systems, the low level of fresh organic material inputs and the exposure of this organic matter with low C/N ratio, explain that despite a fast mineralization in the soil, the biological activity is globally weak. This biological activity is concentrated around relatively few organic matter fragments that are poorly protected or not protected at all.

Conversely, in soils under DMC, the high inputs of fresh organic matter (from aerial parts and roots) provide an abundant substratum to the soil macrofauna and microorganisms. Biological activity (which is not limited to organic matter mineralization) is better distributed and in general much more intense, although the organic matter mineralization processes (with high C/N and protected within the aggregates and/or within the litter) are slower.



Organic matter and soil structure in an ecosystem cultivated under DMC
Permanent soil cover
Associations and successions
N_2
H_2O
CO_2
Biodiversity
Diverse organic material
Rapid turn-over
Litter
Fauna (mm)
Fragmentation
Active organic matter
Leaf debris
Bioturbation
High biological activity
Deep rooting systems
Decompaction and aeration by roots
Root debris
Sand
Mycelium
Macro-agrégats (250 µm - mm)
Macro aggregation (root, mycelia)
Micro colony of bacteria
Macro aggregates (250 µm - mm)
Silt
Exudates
Micro aggregation (root exudates, mycelia, polysaccharides)
Slowly oxidizable organic matter
Very slowly oxidizable organic matter
Passive organic matter
NO_3^-
PO_4^{3-}
CO_2
K^+
Ca^{2+}
Mg^{2+}
Primary mineralization
Rapid decomposition
Sugars
Starch
Simple proteins
Interstratified proteins
Polysaccharides
Roots
Micro flora (µm)
Hemicellulose
Cellulose
Slow decomposition
Lipids and waxes
Lignin
Phénols
Poly phenols
Phenols
Quinones
Humification by polycondensation
Humification by heritage
Nitrous compounds
Fulvic acids
Humic acids
Humification by neosynthesis
Ca^{2+}
Fe^{2+}
Al^{3+}
Clay-humus complex (µm)
Clay (< 2 µm)
Minéralization
CO_2
PO_4^{3-}
NO_3^-
Alteration
Parent rock

Organic matter turn-over

In conventional systems, the limited biomass production and weak restitution to the soil of biomass with a low C/N ratio, associated with an irregular mineralization, with very high peaks (after tillage), means that organic matter is poorly renewed, and losses are high (and increased by erosion). In such conditions it is very difficult to maintain a soil organic matter content at a level favourable for agricultural production.

Conversely, in DMC systems, the high biomass production and restitution and the creation of conditions leading to a slow and regular mineralization, allow a rapid and important organic matter turn-over, and consequently improves or at least maintains the soil's organic status.

This does not mean that DMC systems mineralize less organic matter than conventional systems: the amount of mineralized matter largely depends on the soil organic matter rate, which is higher under DMC than in a conventional system!

In summary, the conventional systems rapidly mineralize small quantities of biomass and produce little humus, whereas DMC systems slowly mineralize large quantities of biomass and produce far more humus.

3.2. Soil structure

Soil structure in conventional systems

Conventional systems seek to ensure a good soil structure, by tillage, before planting crops. Even if this practice is relatively simple to implement (although sometimes very labour-intensive) it has many medium-term disadvantages:

* the improvement in the structure is limited to the tilled horizons, and remains, therefore, superficial. The creation of a tillage pan, frequent with these practices, avoids water and root infiltration in depth;
* the extremely negative impact of tillage on biological activity and organic matter means that the stability of the soil structure cannot be assured. The aggregation processes cannot operate and soil structure rapidly deteriorates. Soil structure improvement by tillage is only temporary;
* The bare soil is exposed to erosion (by the wind, by tillage or by runoff) and can harden the soil surface (particularly after a heavy rain, on a soil intensively tilled, where aggregates have been broken by intense tillage) or form a sealing crust (on "sealed" soils).

Soil structure in ecosystems cultivated under DMC systems

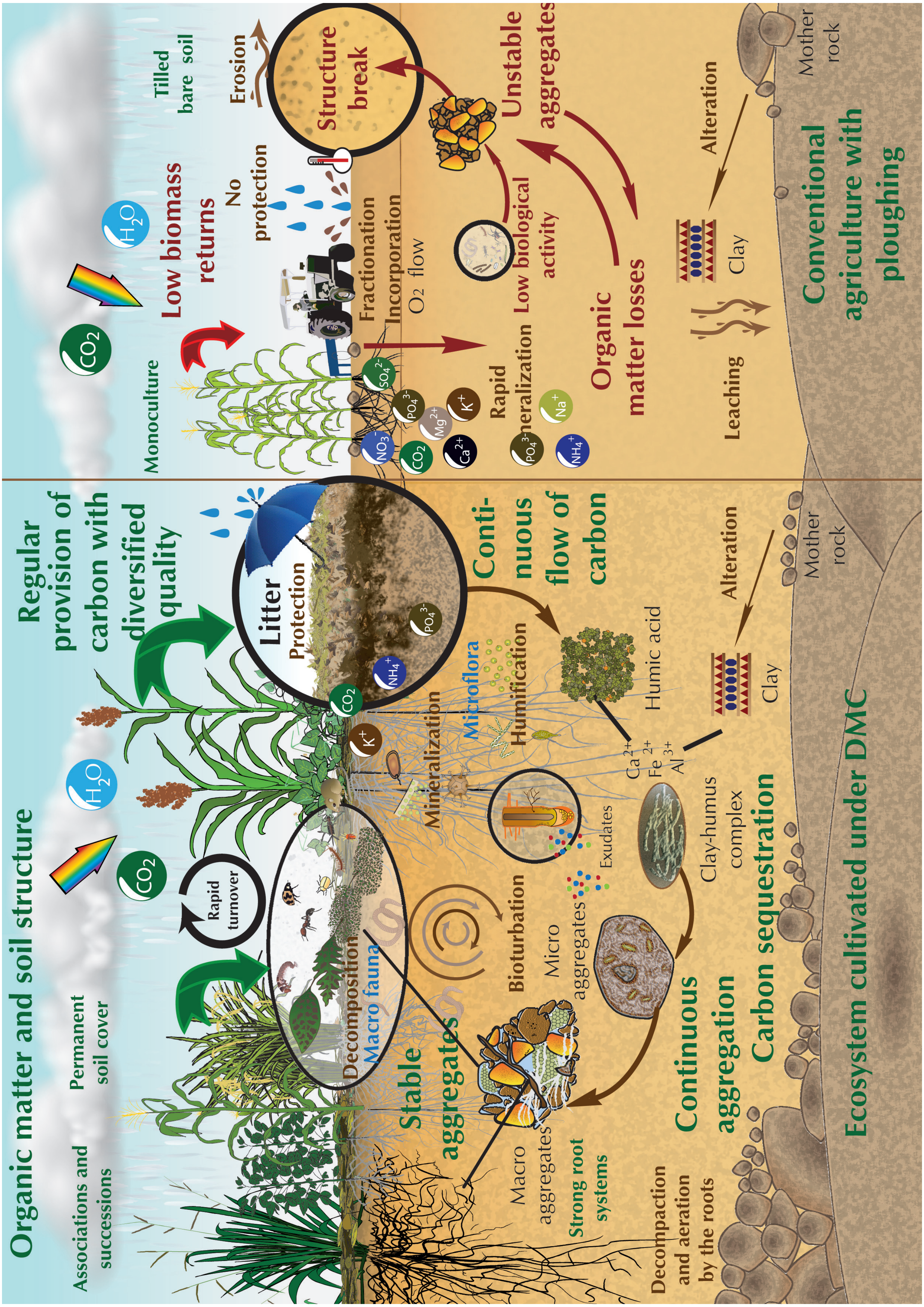
In direct seeding, just like in a natural ecosystem, the creation and the maintenance of a good soil structure are ensured by:

* the soil permanent plant cover that protects the soil against :
  - impacts of water drops (with a high kinetic energy);
  - wind and/or water erosion;
  - solar radiation (that dries the soil and generates a wide range of temperatures and UV rays which are harmful to biological organisms);
* soil aeration and its restructuring by the macro fauna (earthworms, termites, ants, springtails, macro arthropods, etc.) and by the activity of strong root systems of plants grown in intercropping and succession (particularly with the work of plants cultivated during the dry season). The root systems, extremely dense on the surface also play the role of a flexible and resilient armature, thus minimizing the compaction caused by the passage of heavy equipments used in mechanized agriculture;

Micro porosity and macro porosity

Soil macro porosity that allows good infiltration of water and rapid drainage, results mainly from the work of big roots and macro fauna activity.

Soil micro porosity that allows water storage is linked to soil aggregation processes and to small root activity.


Organic matter and soil structure
Associations and successions
Permanent soil cover
Rapid turnover
Regular provision of carbon with diversified quality
Litter
Protection
Decomposition
Macro fauna
Mineralization
Microflora
Humification
Continuous flow of carbon
Stable aggregates
Bioturbation
Micro aggregates
Exudates
Macro aggregates
Strong root systems
Decompaction and aeration by the roots
Continuous aggregation
Carbon sequestration
Clay-humus complex
Humic acid
Clay
Alteration
Mother rock
Ecosystem cultivated under DMC
Monoculture
Low biomass returns
No protection
Tilled bare soil
Erosion
Structure break
Unstable aggregates
Fractionation
Incorporation
O2 flow
Low biological activity
Rapid mineralization
Organic matter losses
Leaching
Clay
Alteration
Mother rock
Conventional agriculture with ploughing

* the incorporation of organic matter in the soil: in the surface at the litter level, and deeper for the roots. This organic matter of varying quality (from sugars and simple proteins, easily decomposable, to large molecules of lignin slowly decomposed, with a dominance of cellulose in direct seeding) will supply the various soil organic matter reservoirs, which are more or less stable;

* the formation and stabilization of aggregates thanks to an intense biological activity (binding role of the microflora and bioturbation by the macrofauna), a dense root system and regular biomass inputs constituting both an energy substratum for these organisms and the raw material for humification.

Soil tillage in conventional systems (with its negative effects) is therefore replaced by biological work in a living soil that allows storage and protection of the soil organic matter within stable aggregates.

3.3. Fertility of cultivated ecosystems

Fertility of conventional systems

In conventional systems the progressive loss of capacity to store nutrients in the soil (in particular due to the losses in organic matter rate, which strongly affects the cation exchange capacity of the soil) means that a significant amount of nutrients must be provided to crops, sometimes without even passing through the soil, as in the case of foliar fertilizers.

Losses by superficial runoff and leaching are high due to the high solubility of some fertilizers, rapid mineralization of organic matter and shallow plant rooting, as well as losses related to erosion (facilitated by soil tillage) and those by volatilization on a bare soil exposed to high temperatures. The fertility of these systems is unstable and its performances largely rely on external inputs (when they are accessible to farmers).

These performances rapidly decline after fertilizer inputs stop, especially when all the other fertility components of "soil" system often fail particularly due to the low biological activity, the low organic matter rate and the instability of the soil structure and when system losses are high.

Fertility of ecosystems cultivated under DMC

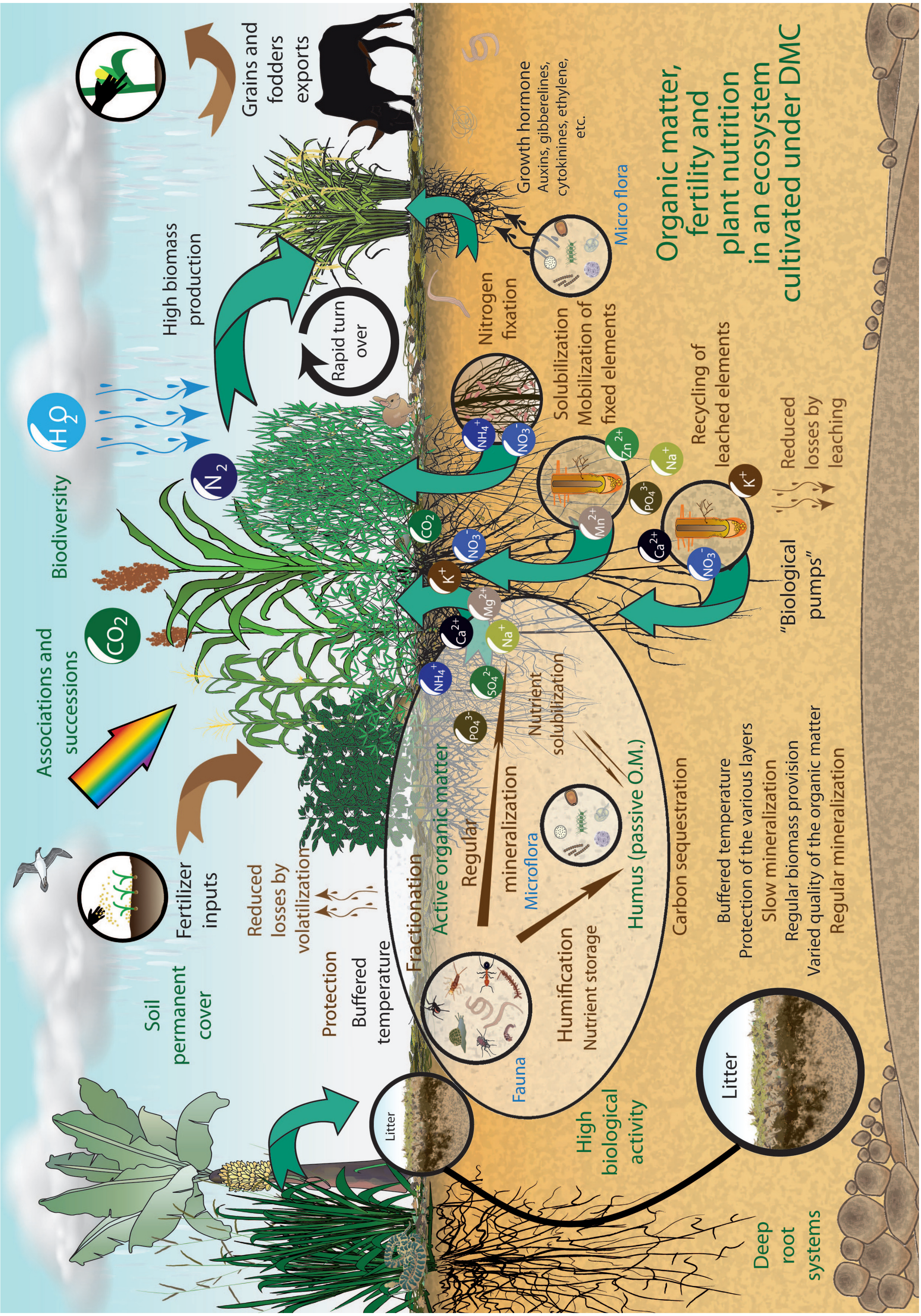
In ecosystems cultivated under DMC, the nutrients are, as in a forest ecosystem, mainly concentrated within the biomass (phytomass, litter and soil microflora), that supplies the soil superficial horizons. Cultivated plants extract most of their necessary nutrients from the litter and from the first centimetres of the soil. Fertility is global to the soil/plant system and is not limited to the soil. Thanks to reserves (within the phytomass and the soil organic matter) and to the low losses, the fertility of DMC systems is stable. The maintenance of this fertility is ensured by:

* a rapid turn-over of organic matter assured by a high phytomass production and an intense biological activity that allows the optimization of humification and mineralization processes. Thanks to a rapid turn-over, the annual biomass production can be significant, even in poor environments;

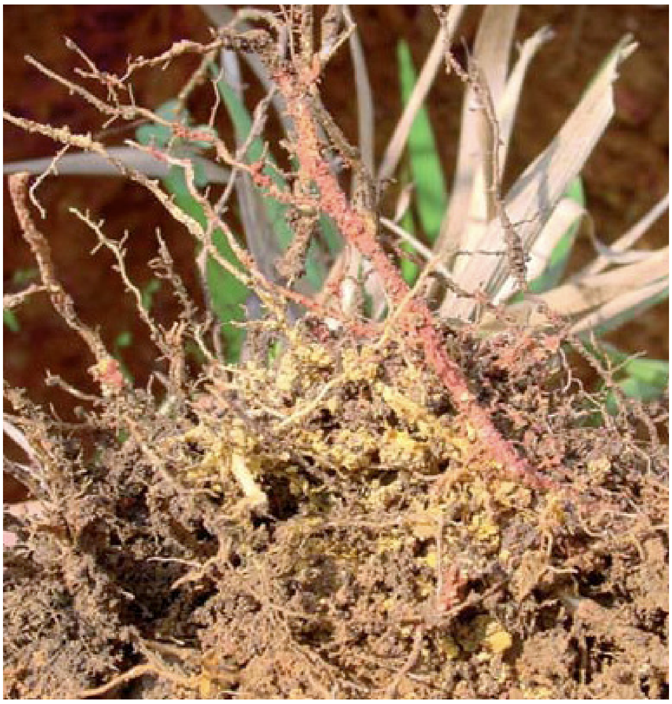
* a high organic matter rate (maintained by the high biomass production) and as a consequence, a high cation exchange capacity (CEC), a high capacity of buffering and high nutrient retention;

* the fixation of atmospheric nitrogen by leguminous plants and also by free bacteria (type *Azotobacter sp., Azospirulum sp., Arthrobacter sp.*,etc.) and/or *Tricho-*

Maize + Finger milet + Crotalaria
Photo: L. Séguy


Organic matter, fertility and plant nutrition in an ecosystem cultivated under DMC
Soil permanent cover
Fertilizer inputs
Associations and successions
Biodiversity
High biomass production
Grains and fodders exports
Protection
Buffered temperature
Reduced losses by volatilization
Rapid turn over
Nitrogen fixation
Growth hormone
Auxins, gibberelines, cytokinines, ethylene, etc.
Micro flora
Solubilization
Mobilization of fixed elements
Recycling of leached elements
Reduced losses by leaching
"Biological pumps"
Fractionation
Active organic matter
Regular mineralization
Nutrient solubilization
Microflora
Humus (passive O.M.)
Humification
Nutrient storage
Fauna
Carbon sequestration
Buffered temperature
Protection of the various layers
Slow mineralization
Regular biomass provision
Varied quality of the organic matter
Regular mineralization
Litter
Litter
High biological activity
Deep root systems

derma and *Actinomycetes* fungi, stimulated by plant root exudates (like *Eleusine coracana* or bracharias for *Azotobacter sp.*);



High biological activity around Brachiaria brizantha *roots*

* solubilization of nutrients by oxidation or chelation, due to activity of bacteria that develop in a favourable environment (porosity, aeration, humidity, energy substratum, etc.), and rich in organic matter;

* the extraction of fixed elements or in very low concentrations in the soil, by association of plants with mycorrhiza and/or by selective stimulation (by root exudates) of fungi population and/or soil-free bacteria capable of carrying out this function of nutrient mobilization (fungi of the genera *Trichoderma* and bacteria of the genera *Pseudomonas, Enterobacter, Bacillus, Agrobacterium, Rhizobium, Burkholderia*, etc. for phosphorus, *Bacillus* bacteria for potassium and manganese, *Thiobacillus* for copper, etc.). This function is specific of the "biological pumps", plants used as a cover having various abilities to influence the environment (redox potential, pH, etc.) and to stimulate the different microflora populations;

* the maintenance of a structure favourable for the deep rooting of plants, which allows exploration of a larger volume of soil;

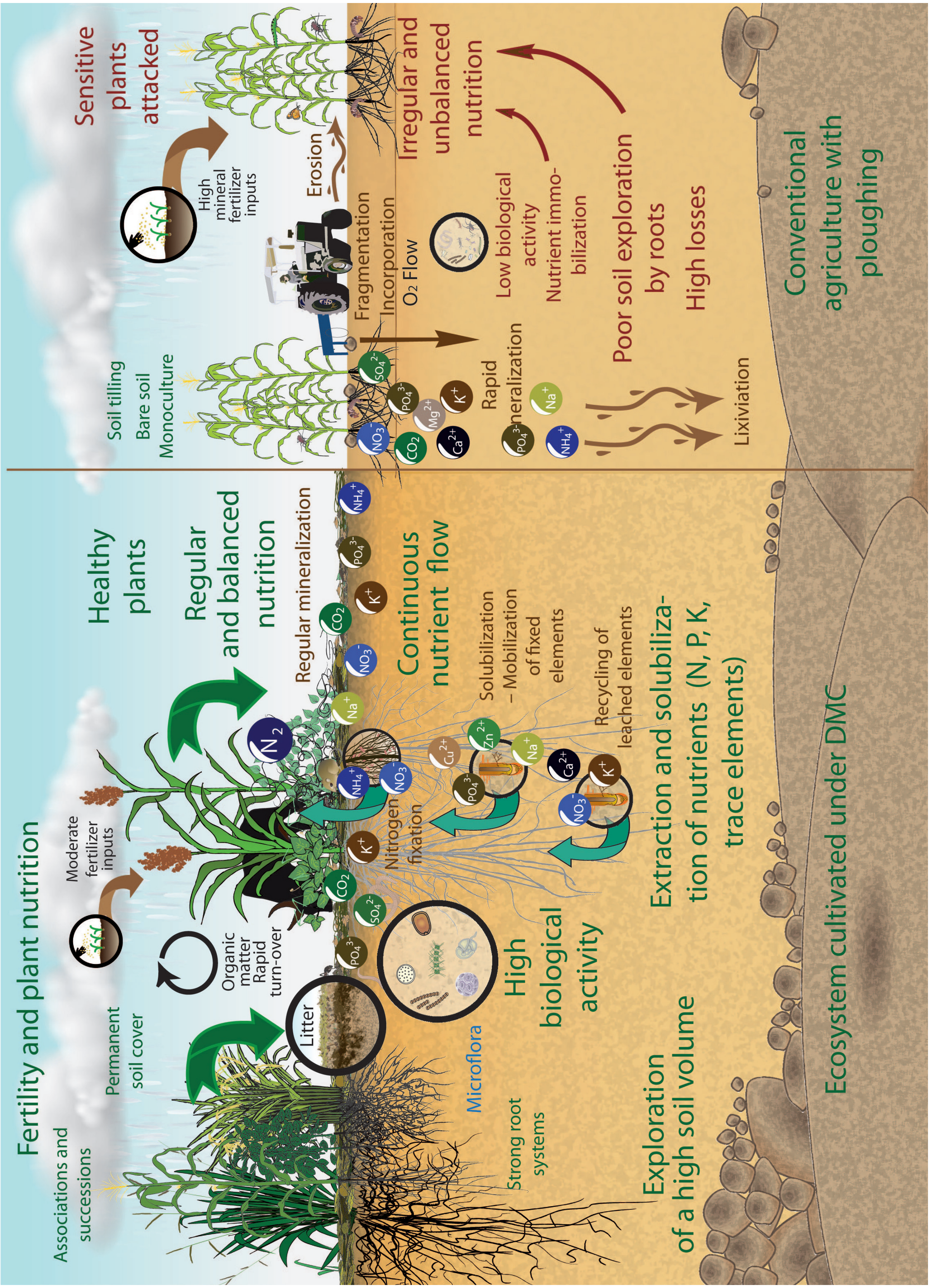
* Minimization of losses, whether by:
  - erosion, thanks to soil protection by permanent plant cover;
  - leaching, thanks to stabilization of clays within the clay-humus complex;
  - lixiviation of soluble salts, thanks to nutrient recycling by the "biological pumps", plants with root systems that develop in depth (particularly during the dry season to draw water);
  - volatilization (CH_4, N_2O, SO_2, etc.) thanks to the plant cover (buffered temperatures) and to aerobic functioning of the microflora in a well aerated environment, etc.

"Biological pumps"

"Biological pumps" are species incorporated into the systems that carry out (amongst others) fundamental functions mobilizing and recycling nutrients. With their powerful, deep rooted systems and their association with mycorrhiza and/or their stimulation of specific populations of bacteria, they are capable of recycling nutrients lixiviated deep in the soil, of extracting poorly available elements and to transform them into an important biomass that joins the soil litter and to supply cultivated plants. Millet for example is an excellent potash recycler, whereas stylosanthes is capable of recycling the bases (in particular calcium) and trace elements (B, Cu, Zn, Mn, etc.) and of mobilizing phosphorus.

The ability to limit these losses, however, depends on the DMC systems used. The best systems, that have low or almost non-existent losses, associate a high biomass production throughout the year (particularly during the mineralization peaks), use plants with very deep root systems (particularly in the dry season) and provide mineral fertilization of cover plants (with deep root systems) rather than to the crop. Beyond improving soil fertility, some plant covers (the genera Brachiaria grasses, and leguminous genera *Cassia* and *Stylosanthes* in particular) allow the neutralization of acidity (and thereby aluminium), via their high biomass production even in high acidity conditions (easily tolerated) and even on the most unsaturated ferralitic soils.

However, unlike a natural forest ecosystem, which does not have any nutrient output from the system when non-exploited, an ecosystem cultivated under DMC suffers nutrient losses by export of products. Therefore, fertility management goes through a return of exported elements to the system (soil + phytomass) under organic (manure, compost) or mineral (chemical fertilizers) form.


Fertility and plant nutrition
Associations and successions
Permanent soil cover
Litter
Organic matter Rapid turn-over
Moderate fertilizer inputs
Healthy plants
Regular and balanced nutrition
Regular mineralization
Continuous nutrient flow
N_2
Nitrogen fixation
Solubilization – Mobilization of fixed elements
Recycling of leached elements
Microflora
High biological activity
Strong root systems
Exploration of a high soil volume
Extraction and solubilization of nutrients (N, P, K, trace elements)
Ecosystem cultivated under DMC
Soil tilling
Bare soil
Monoculture
High mineral fertilizer inputs
Sensitive plants attacked
Erosion
Fragmentation
Incorporation
O_2 Flow
Rapid mineralization
Low biological activity
Nutrient immobilization
Irregular and unbalanced nutrition
Poor soil exploration by roots
High losses
Lixiviation
Conventional agriculture with ploughing

3.4. Plant nutrition (in nutrients)

Irregular and unbalanced nutrition in conventional systems

In conventional agriculture, plant nutrition is strongly dependent on external supplies of fertilizing elements. Organic inputs to the soil (manure, slurry, compost) limit losses of organic matter from the system and supply nutrients to plants on a relatively regular basis. However, they are often difficult to manage (availability, transport and spreading difficulties, etc.). In conventional agriculture, these supplies are mainly done through mineral fertilizers (more easily handled), the availability of nutrients for plants is very irregular. A peak is observed after each application (which leads to losses by lixiviation and runoff) and then to deficiencies. The balance of plant nutrition depends also on inputs and is difficult to achieve.

Regular and balanced nutrition in ecosystems cultivated under DMC

The management of DMC systems rapidly allow an increase in soil fertility, and in particular, the quantity of nutrients available for crops and generally an improved nutrient supply.

These systems allow particularly a regular and balanced nutrient supply to plants thanks to a progressive decomposition and mineralization of biomass, obtained by:

Plant nutrition

Carbon (42-50%), hydrogen (6%) and oxygen (42-44%), resulting from photosynthesis of carbon dioxide and water, account on average for 95% of plant dry matter.

Nitrogen accounts for 1 to 2% of that dry matter and comes, directly or indirectly, from the air, being biologically (bacteria) or chemically (nitrogenous fertilizers) fixed. Leaving aside a part of the sulphur (0.4% of plants), which comes also from the air (SO_2), all the mineral elements of plants come from the soil. With C, O, H, N and S, potassium (2-2.5%), calcium (1-1.5%), phosphorus (0.4%) and magnesium (0.4%), that is to say major macro elements, account for over 99% of the plants dry matter. The other macro elements (Cl, Na, Si) and the micro nutrients (B, Cu, Mn, Fe, Mo, Co, etc.) account for less than 1% of the total dry matter.

These mineral elements (cations or anions) are absorbed from the soil solution by plant roots. They are soluble, and therefore easily assimilated by plants, after oxido-reduction (case of N, P, S, Ca, Mg and Se) or chelation (for the others).

* a regularity of phytomass inputs;

* a diversity of input quality, using plants with differentiated mineralization speeds to constitute plant covers. A leguminous-based plant cover that rapidly mineralizes (in particular their leaves, very rich in nitrogen) and releases nutrients to the soil, which can be directly used by the following crop from the beginning of their cycle. Conversely, grasses with high C/N ratio and high lignin and polyphenols content, in particular those with thick stems (sorghum, maize, millet) slowly decompose and release nutrients later, supplying the following crops many months after their contribution to the litter;

* no soil disturbance, which protect the upper layers of the litter, while the layers in contact with the soil are mineralized.

Beyond its fundamental role in the organic matter mineralization processes, which allows regular plants nutrition, the microflora (and particularly bacteria, mycorrhiza and trichoderma) increases the quantity of nutrients accessible to plants (very high increase in the exchange surface as in symbiotic associations with mycorrhiza, solubilization by bacteria, etc.).

3.5.Water balance (and water supply to plants)

Low efficiency of water use in conventional systems

Conventional practices, with tillage and bare soil, generate high runoff, poor water infiltration (due to the rapid loss of the macro porosity reconstituted by tillage) and high evaporation (related to the high soil temperature on the surface).

The low micro porosity is not favourable for good water storage in the soil, which induces a low water reserve. Moreover, the frequent creation of a tillage pan under repeated soil tillage constitutes an obstacle to plants deep rooting. The volume of soil explored by the roots is low and consequently the useful water reserve is very low.

In such conditions, plants water supply strongly depends on the regularity of water inputs. In rainfed crops, without irrigation, plants growth is rapidly limited after a few days without rain, in particular during the very sensitive stages, such as flowering.

Optimization of water use by DMC systems

In DMC systems, the plant cover helps to reduce runoff and leaves more time for water infiltration. Moreover, water infiltration is rapid thanks to the good macro porosity created and maintained by DMC practices. This rapid infiltration avoids water logging during heavy rain falls (“flush” effect).

High production on sandy soil in a semiarid environment

The micro porosity, also created and maintained by DMC practices, generates a high water storage capacity of the soil (which limits leaching despite the high infiltration). A high infiltration and a high storage capacity lead to the formation of a high water reserve. This water reserve is easily accessible to plants that develop, in DMC systems, deep root systems in a well structured soil. The useful water reserve is consequently very high.

In addition to reducing losses by runoff, direct seeding reduces water losses by:

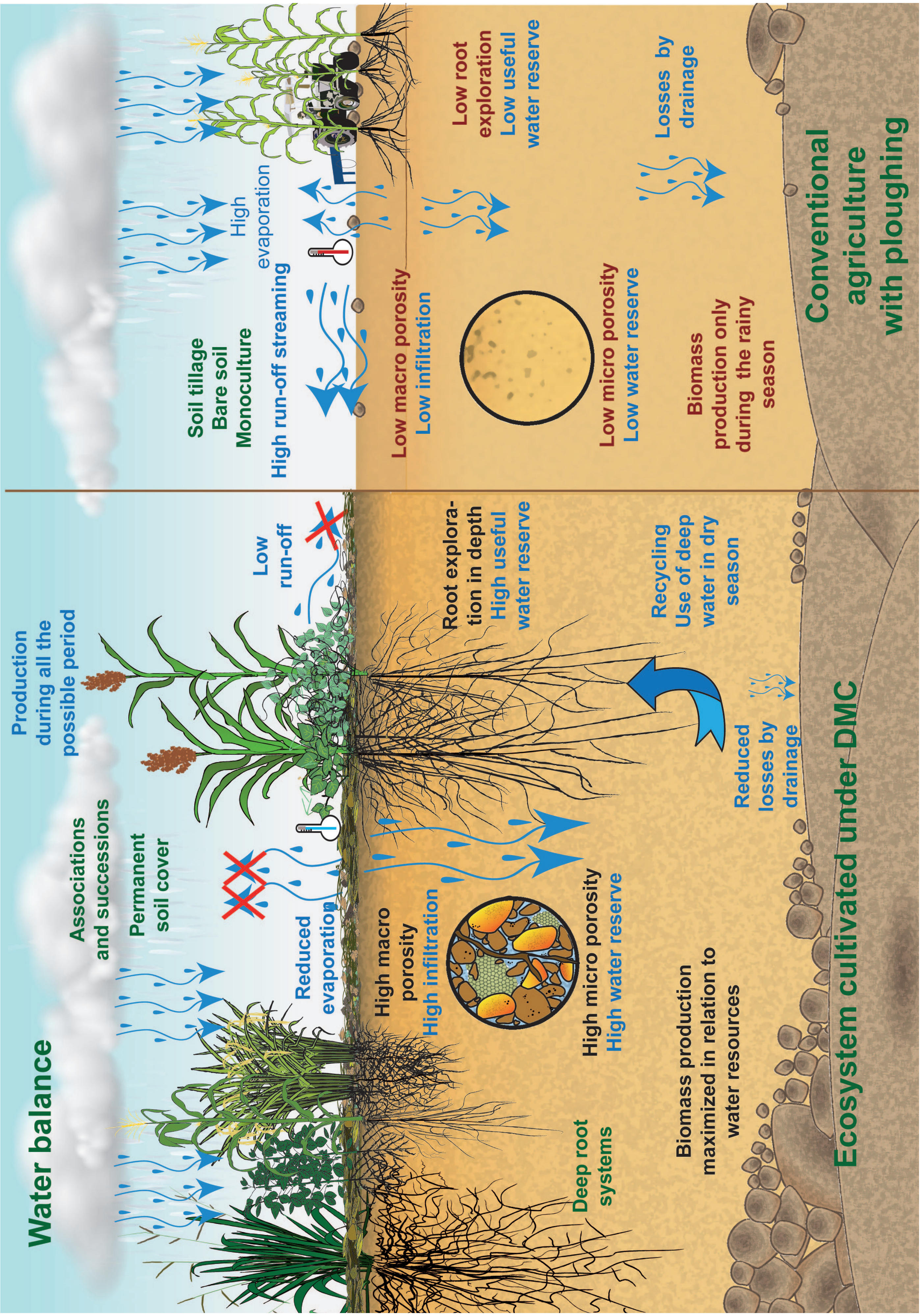
* reducing evaporation, thanks to the plant cover;

* reducing losses by leaching, thanks to the use of deep water by deep root systems, especially during dry periods (capillarity);

Climate hazards are thus buffered: reduced losses, significant water reserves used in case of drought and rapid infiltration during periods of high rainfall. Furthermore, direct seeding permits the sowing of crops from the first useful rains, and thus installing the crop cycle on the most favourable climatic period (which is particularly interesting in long dry season climates). Finally, condensation of dew is much higher on plant cover (interception surface is higher) than on bare soil. These “hidden rainfalls” can contribute to plant water supply in environments with a low rainfall but with high humidity in the air (for example by the seaside).

Consequently, plants have a more regular water supply, without water excess or prolonged dryness, and the period for a good water supply for plants is extended. Some crops can be cultivated with direct seeding in agro-ecological zones where they could not grow with conventional techniques.

Following a better water supply to crops, a good management of DMC systems must allow the optimization of biomass production (essential for the proper functioning of DMC systems) relative to the quantity of available water at plot level (whether from rainfall or irrigation). The water stored in a well-structured soil is therefore used as much as possible by plants to produce during “marginal” periods (uncertain rainfall, hardly usable by crops) as well as during dry seasons (thanks to their deep root system and to the use of capillarity) a high biomass that supplies the litter and improves the functioning of soil and of DMC systems. This biomass production during the dry season allows a significant increase in total production and is particularly interesting because it is produced at a period of low mineralization, with a positive differential “production – losses”, and it provides a very good soil cover for the next crop, even though it is done after a long dry season.


Water balance
Associations and successions
Permanent soil cover
Production during all the possible period
Reduced evaporation
Low run-off
High macro porosity
High infiltration
High micro porosity
High water reserve
Root exploration in depth
High useful water reserve
Deep root systems
Biomass production maximized in relation to water resources
Recycling
Use of deep water in dry season
Reduced losses by drainage
Ecosystem cultivated under DMC
Soil tillage
Bare soil
Monoculture
High run-off streaming
High evaporation
Low macro porosity
Low infiltration
Low root exploration
Low useful water reserve
Low micro porosity
Low water reserve
Losses by drainage
Biomass production only during the rainy season
Conventional agriculture with ploughing

3.6. Plant health

Plant health in conventional agriculture

Almost all conventional agricultural practices, with a short-term vision, rapidly lead to plants weakening and an increase in their sensitivity to insect attacks and diseases.

The low biological activity, particularly related to soil disturbance, to the decline of the organic matter rate and to the use of pesticides, and the low restitution of organic matter to the soil, leads to:

* an irregular and unbalanced plant nutrition (particularly with deficiencies in trace elements);
* diminished natural defences (without production of natural antibiotics and elicitors by the microflora).

These nutritional imbalances (aggravated by mineral fertilizers inputs, particularly nitrogen), but also the use of herbicides to control weeds (necessary when cultures grow slowly), lead to a physiological malfunction of plants. Protein formation processes are particularly disturbed, which leads to an accumulation of free amino acids, reducing sugars and mineral nitrogen, in the tissues. These elements are the favourite substratum for various bioaggressors that find, in these already weakened plants, very favourable conditions for their development. The plant nutritional imbalance consequently favours insect proliferation and epidemics. Under these conditions of severe attacks to plants, the use of pesticides to try to reduce the number of attackers is the simplest technical "response" in conventional agriculture.

These chemical "solutions" have a certain chemical short-term effectiveness (which allows them to grow rapidly despite significant cost), but have a large number of disadvantages in the medium term, including:

* risk of pollution;
* breakdown of ecological balances within the system, by destruction of predators of harmful insects;
* destruction of soil life, leading to a lower nutrient availability and, consequently, leading to nutritional imbalances and depriving the plants of the microflora protection (trichoderma, etc.);
* plant proteosynthesis disturbance by pesticides.

The trophobiosis theory

In his theory of the throphobiosis, Chaboussou (1985) explained that plant susceptibility to insects and diseases (fungi, bacteria and virus) is primarily a result of nutritional imbalance. A malfunction of protein synthesis leads to the accumulation in plant tissues, of free amino acids (especially asparagine), of reducing sugars and mineral nitrogen These soluble elements are the basic nutrients of insects, fungi, bacteria and virus that, when they have access to them, develop better and faster. At a high concentration, these soluble elements make plants susceptible to attacks, while bioaggressors have a low development on plants that have low quantities of these fundamental nutritive elements.
Such a physiological imbalance, with proteolysis dominant over proteosynthesis, determines the physiological state of the plant and it is especially related to:

* plant damage due to pesticides: insecticides, fungicides and especially herbicides, which disturb plant proteosynthesis (their selectivity is never absolute);
* an unbalanced mineral fertilization, particularly during nitrogen inputs and in case of potash deficiency;
* trace elements deficiencies (Mn, Cl, B which are enzymes activators and Cu, Fe, Zn and Mo which are enzyme components);
* water stress (floods, droughts).

As a consequence, plant sensitivity is increased and the development of bioaggressors is promoted. In the mid-term, the chemical "solution" increases problems, which explains the difficulties associated with conventional agriculture to obtain healthy crops.

Plant health in DMC systems

The health of plants cultivated in DMC systems is ensured in an integrated way by:

* a balanced and regular water and nutrients supply. Plants can easily draw water and nutrients from the

soil, throughout their cycle, including micro-nutrients, which are easily available to plants, thanks to:
- a high useful water reserve;
- storage of nutrients in organic form;
- regular mineralization;
- mobilization and solubilization of nutritive elements fixed in the soil (by microorganisms action, and favourable pH and redox potential of the soil).

Well-nourished plants (regular and balanced supply, in sufficient quantities) function better physiologically, are very healthy and are less attacked by bioaggressors. Rice, for example, is remarkably healthy after stylosanthes and it is minimally affected by rice blast after an intercropping of finger millet and crotalaria;

* the production by microorganisms (bacteria and fungi of the soil) of a whole set of substances:
  - antibiotics (production of Pseudomonas sp .against Fusarium sp, root rot, etc.);
  - growth hormones, elicitors (that reinforce the natural immune system against Xanthomonas campestris, Pseudomonas syringae, Colletotrichum lindemuthianum, etc.).

The impact of fungal diseases like fusarium wilt (Fusarium sp.), roots rot (Rhizoctonia sp.) or damping off (Pythium sp.) is sharply reduced in soils with organic amendments in which a high microbe activity develops, such as in DMC;

* the colonization by microbes (bacteria and fungi) and nematodes which destroy pathogens' propagules (spores of Cochliobolus sp., for example);
* the creation of conditions unfavourable to the development of pathogenic bacteria (particularly a well aerated environment) and the suppression of the transmission of soil pathogenic bacteria to leaves by "splash" effect (drops of water hitting the soil and projecting contaminated soil fragments under the leaves);
* plant protection against phytoparasitic nematodes by mycorrhiza;
* the use of a mixture of species (intercropped)and/or varieties: resistant species/varieties are less affected and limit the transmission of diseases to less resistant varieties (but used for their high production potential);
* the rational use of herbicides (and as much as possible, the non-use of these products), in order to minimize the disturbance of plants physiology (application before crops, on a thick plant cover, in low doses, etc.).

Fungicidal treatments are reduced as much as possible because of their harmful effect on soil microflora (which, on the contrary, has a very positive effect on plant nutrition and health). They are limited to seed treatment (in particular for leguminous plants), when necessary. Treatment on plants in growth is carried out at low doses, only when absolutely necessary, which might be the case during the first years, before all benefit effects of DMC become visible.

Using biological products to reinforce plants natural defences (elicitors) is also possible.

In addition to the balanced nutrition of crops, which sharply reduces susceptibility of plants, the control of bioaggressors, in particularly crop insect pests, is carried out in accordance with the principles of integrated pest management by:

* the reconstitution of an ecological balance with the natural predators of insect pests;

Dragonfly eating a cercopidae

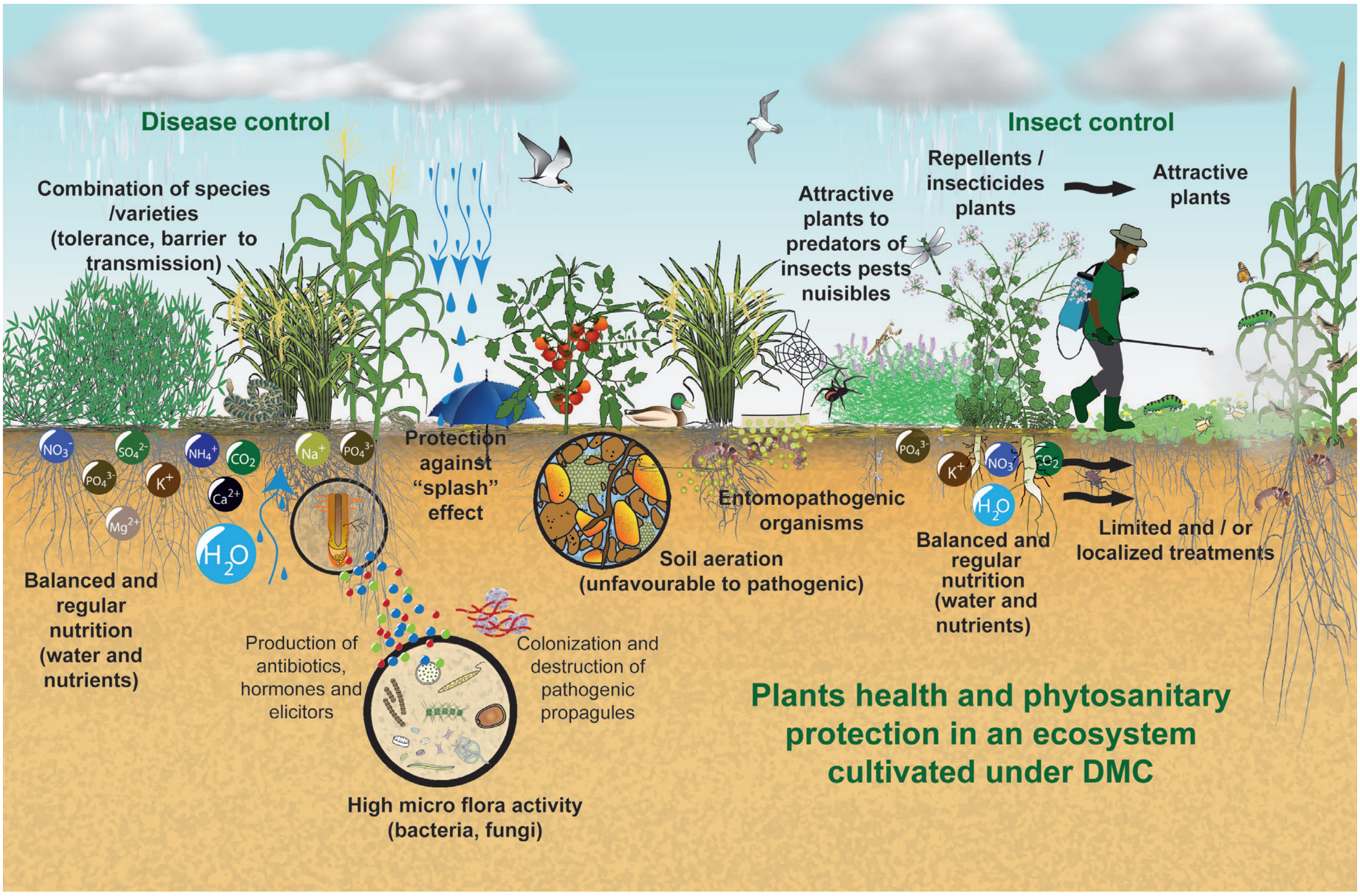
* the inoculation with entomopathogenic organisms (fungi like Metharizium spp.or Beauveria spp.; bacteria such as Bacillius thuringiensis; nematodes such as Steinematidae sp.), that are placed in extremely favourable conditions for their development; and/or

* the use of plants producing insecticide or repellent substances. The hairy vetch and the fodder radish, for example, are used in Madagascar to reduce the pressure of Heteronychus sp and the Desmodium genus is known for repulsing borers. Contrary to that, plants attractive to some insects (such as Arachis pintoï which attracts bugs, millet for locusts or the Pennisetum genus for borers) are used to “hijack” crop predators (“Push-Pull” approach). An insecticide is locally applied on attractive plants when there is a high presence of insects.

Caterpillar attacked by an entomopathogenic fungus

These principles of integrated pest control, which are not specific to DMC systems, are found by contrast in these systems conditions that facilitate their application (well-fed plants and therefore less sensitive, restoration of ecological balances favoured by low soil disturbance, biodiversity, etc.), or by increase of the beneficial effects (extremely favourable conditions for the development of inoculated organisms, etc.). Conversely, conventional systems complicate their implementation and limit their effectiveness.

If bioaggressors pressure is extremely high (in particular during the first years, before soil ecological balance is restored and soil improvement allows balanced plant nutrition), the use of pesticides may be necessary to manage certain crops. However, it is preferable during these first years to avoid growing crops particularly sensitive to local bioaggressors, which will limit pesticide use. This helps to promote a rapid return to an ecological balance and avoids the disturbance of proteosynthesis processes and the increase of plants’ sensitivity.



3.7. Weed control

Weed control in conventional agriculture

Weed control in conventional agriculture relies on tillage and on the use of selective herbicides (whenever they are accessible). This approach allows a good control of the major weeds as long as they do not develop resistance to the herbicides used. Conventional agriculture “adapts” itself to these resistances by the development, by the chemical industry, of active materials more and more efficient, but more expensive and often pollutant.

Without herbicides (often not available or too expensive for small-scale farmers in southern countries), the manual weeding of plots is often the only affordable practice. However, it consumes a considerable amount of work time. Weed control is difficult to achieve in time, which means that weed pressure is very often one of the first production limiting factors in these conditions.

Weed control in DMC systems

In DMC systems, weed control is mainly assured by the insertion of plants in the cropping systems (crops or cover plants) that are capable of dominating naturally most of the weeds, that produce high biomass (supplying in this way the cover crop) and that can be easily controlled. This domination is effected by weed competition for light (shadow effect), for nutrients and/or by allelopathic effects (production of substances that interfere with germination and/or growth of plants, acting as natural herbicides). These substances are released by the living plants (root exudates in particular) or when they decompose. Plants such as oats or buckwheat are particularly efficient in “cleaning” infested plots thanks to their strong allelopathic effects. Covers based on species of Sorghum genus are used to control plagues such as *Cyperus rotundus* (capable of developing through many mulch layers). A plant such as *Stylosanthes guianensis* perfectly controls striga thanks to its thick mulch and its effects on seeds germination (it initiates germination but is not parasitized by striga whose seedling dies rapidly in the absence of host). These plants which naturally control weeds allow to the progressive reduction of their seed stock in the soil and bring down pressure on subsequent crops.

These plants can be controlled mechanically (mowing, rolling, manual stripping) or chemically (with total or selective herbicides) depending on their characteristics. Annual plants (oats, vetch, velvet bean, etc.) are generally easy to control by simple mowing or rolling, or with herbicides at low doses. Perennial plants (*Brachiaria spp, Cynodon dactylon,* Kikuyu grass, etc.) require higher herbicide doses and are generally more difficult to control mechanically, except *Stylosanthes guianensis*, although perennial, can be easily controlled by simple mowing, at the ground level. Some plants can also be controlled by urea (the clover, for instance), by submersion (in rice fields) or naturally by frost (in temperate or altitude subtropical climate).

This control can be total in the case of dead covers, or temporary/localized in the living covers that are controlled only during the time of culture and/or on the crop rows, and that re-colonize the plot after harvest.

The types of plant to be included into the crop sequence/intercropping depends therefore on the weed flora, on the crops to implement (some plants can have allelopathic effects on others) and on the means available to control cover plants

Weeds control by the plant cover
Rice after stylosanthes

Herbicides in DMC

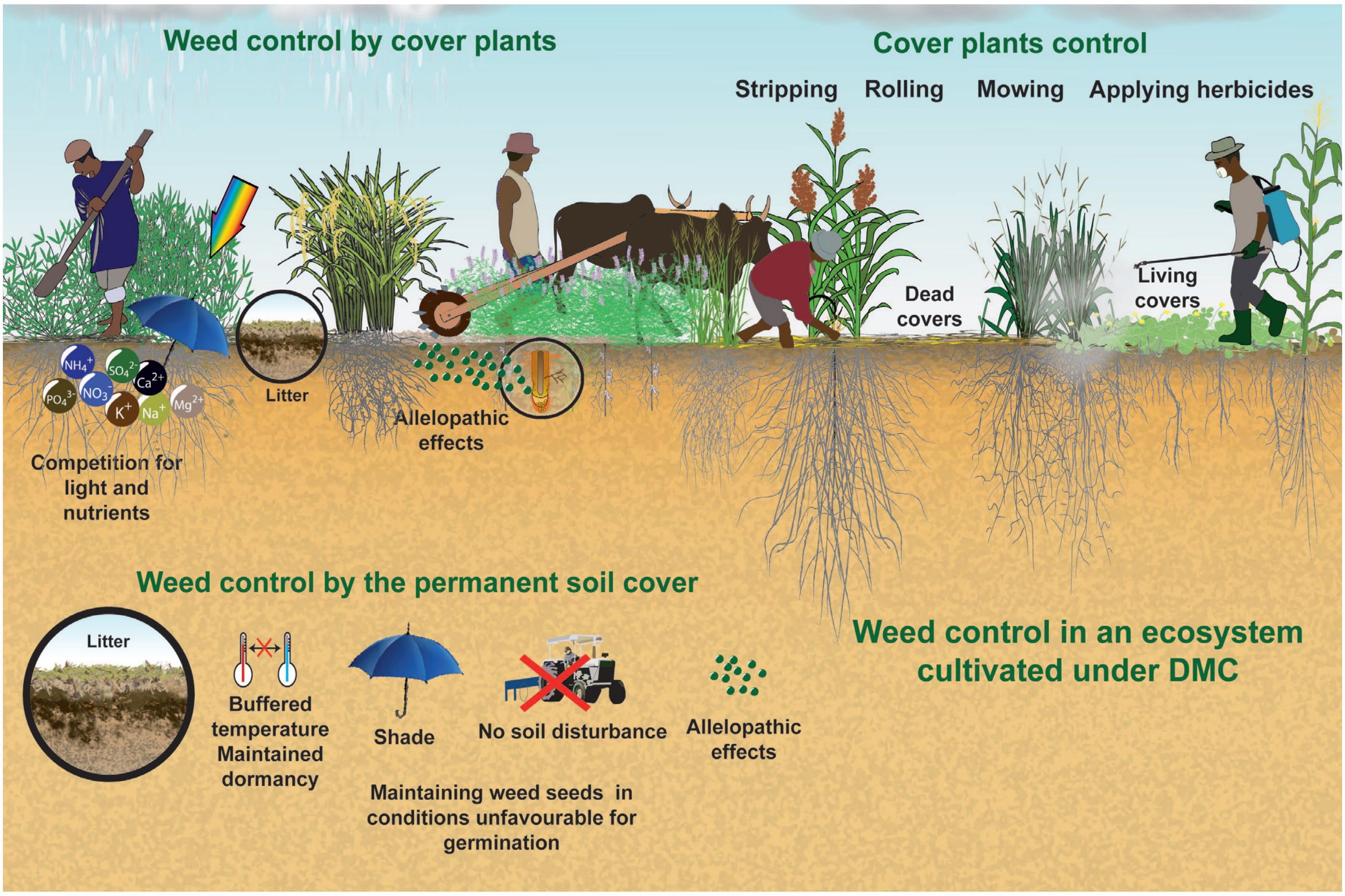
In established DMC systems, with high biomass production, the use of herbicides is limited to the cleaning of plots (if needed) before seeding and/or to control cover crops that cannot be controlled mechanically. In this case, control is done by the use of total herbicides, aplicated before cultivation, generally at low doses, on a soil covered by a high biomass, which reduces their impact on the crops and the pollution risks. The use of "selective" herbicides is limited as much as possible, especially as efficiency of pre-emergent herbicides is very low when applied to mulch, in a soil rich in organic matter. A post-emergence herbicide might be used (if it is available) in case of "accident", when insufficient cover, has poorly controlled weeds.

During the first years of DMC preparation, before a biomass sufficient to control weeds has developed, the use of herbicides is often necessary. As far as possible, the use of herbicides should be limited by growing first plants relatively easy to clean, like maize, associated with cover plants able to rapidly control weeds.

In the following crop, the soil cover crop (dead or alive, obtained from crop residues and/or cover plants) has a shading role and can have an allelopathic effect. If thick enough, this cover prevents emergence of most weeds.

Furthermore, the absence of soil disturbance avoids repositionning of weed seeds in conditions favouring their germination (hence the importance of mastering the seeding to avoid "pollution" of the plot by pulling up to the surface soil containing weed seeds). Under these conditions, only seeds coming from plants fruiting in the plot, which have not been controlled in time and those seeds transported by the wind and animals (the main sources of infestation in DMC) are even sprouting.

Weed control in DMC is mainly determined by the plant cover. The year "zero" of DMC preparation should allow total control of perennial weeds and provide a thick plant cover, which will insure the control of annual weeds thereafter. During this year of DMC preparation, weed control is assured in a "classical" way, through tillage and use of selective herbicides of crops, intercropped plants that will contribute to reduce weed pressure, and provide plant cover for the next season.



In the following years, weed control relies mainly on the quantity and the quality of the biomass produced and maintained in the soil, and the weed stock. Control of weeds that emerged through the insufficient cover requires either:

* selective herbicides (sometimes difficult to find, especially in systems intercropping several plants, with different characteristics), or;

* localized application of a total herbicide (with a herbicide broom or a sprayer with a plastic cover), or;

* manual weeding (takes time).

Hoeing, is not recommended, tillage, even superficial, changes the dynamics of organic matter, accelerates decomposition of the plant cover and stirs the weed seeds to a favourable position for germination.

Total controle of weeds by living plant cover
Maize on Arachis repens

3.8. Soil temperature

Soil temperature in conventional agriculture

In conventional agriculture, bare soils are exposed to radiation from the sun (UV is very harmful to microorganisms). This exposure allows a rapid warming of soils (of interesting in spring, in temperate environments), but it leads to high thermal amplitude and extreme temperatures (particularly in tropical environments), unfavourable to the development of living organisms.

Soil temperature in DMC systems

In DMC systems, plant cover acts like a thermal cover. It protects the soil from solar radiation and limits heat loss by radiation during the night. The soil temperature under a plant cover is therefore buffered and thermal amplitude is limited.
In a tropical environment, extreme temperatures are thus avoided, creating favourable conditions for the development of biological activity, concentrated in the top few centimetres of the soil. Inversely, in a temperate environment, this cover can slow down soil warming up in spring, and consequently delay seed emergence and lead to low biological activity. However, it is possible to “play” on the albedo of the cover. Contrary to a light cover, which reflects a major part of the radiation, a dark cover retains heat and speeds up soil warming. It is also possible to uncover only the seeding row (star-wheels on seed drills for direct seeding set on the front of opening discs) for the faster soil to warm up. Moreover, on waterlogged soils, DMC provides a better internal drainage, so that the amount of water to be warmed up is reduced, than in conventional practices. Soil warming requires less energy and it is done faster.

3.9.Transformation of xenobiotics

Pollution in conventional systems

In conventional systems the applied herbicides and pesticides (sometimes in large quantities) are applied onto a bare soil. They can be rapidly fixed by the soil colloids and/or carried away by runoff, lixiviation and/or erosion, polluting soils, the underground waters and/or nearby waterways.

Detoxification by DMC systems

Conversely, in DMC systems, herbicides and pesticides are intercepted by the plant cover, which also limits the transfer by runoff and lixiviation. The functioning of the litter and of the soil in DMC systems also allows the bioremediation of polluting xenobiotics, which are degraded as if in a bioreactor, under the effect of fungi (basidiomycetes, pleurotus, Aspergillus sp., etc.) and bacteria, or incorporated in organic compounds less toxic and poorly mobile. Covers with sorghum are extremely efficient in detoxifying, particularly with their high lignin content that provides a substrate for those fungi which decompose lignin. In addition, mycorrhiza plays an important role in the protection of plants against heavy metals.

3.10. Balance

Soil functioning in conventional agriculture

Conventional agriculture is based on soil tillage, aiming to prepare it for the establishment of crops (seedbed) and to control weed pressure. However, the introduction of tillage in an ecosystem deeply modifies the dynamic of organic matter, which is essential to the proper functioning of the “soil” ecosystem.

By accelerating mineralization soil tillage increases the need for biomass to maintain the level of organic matter in the soil, while in parallel, the production of plant biomass is limited by the lack of crop diversity and their low intensity (mono-cropping, few intercropping or crop sequence) .

As a consequence, tillage in conventional agriculture leads to a loss of organic matter in the soil especially as the bare soils are exposed to erosion. This loss in organic matter is accompanied by a drop in biological activity (by a decrease in organic substrate and soil disturbance), consequently leads to:

* leaching of clays, lixiviation of bases and nutrients, and a universal decline in fertility;
* destructing of soil which amplifies the decline in biological activity (losses of habitat) and leads to superficial rooting and misuse of water and nutrients by plants;
* degradation of plant health, due to:
    - poor nutrition, irregular and imbalanced;
    - the destruction of the microflora (bacteria, mycorrhiza, trichoderma, etc.), which no longer plays the role of “digestion” of nutrients and does not furnish anymore elicitors and antibiotics, produced naturally; and
    - ecological imbalances, allowing the proliferation of pests.

Negative impacts of conventional practices on biological activity

Conventional practices have various negative impacts on soil organisms:

* tillage destroys a part of macro fauna and creates unfavourable conditions for micro organisms: exposure to ultra violet radiation from the sun, high temperature on soil surface, poor soil aeration in depth, low humidity linked to poor soil porosity, etc.;

* the loss of organic matter related to tillage and to the removal of straw (common in conventional systems), leads to a decrease in nutrients available for micro organisms;

* some chemical fertilizers are harmful to microorganisms (chlorides, sulphates, etc.)

* herbicides and especially insecticides and fungicides, have negative impact on the soil living organisms.

To compensate for these new constraints enhanced by soil tillage, intensive conventional agriculture has turned to:

* soil tillage intensification to compensate (in short-term) for soil destructuration;
* a chemical approach to compensate for the decrease in the chemical fertility of the soil (input of nutrients in the form of fertilizers), to control weeds use of increasingly powerful herbicides) and to protect crops whose natural defences have been reduced by malnutrition and the low biological activity of the soil.

Such an approach developed in temperate climates and allowed to achieve interesting results in the short-term essentially due to the characteristics of these environments:

* slow mineralization leading to low losses in organic matter;
* initial high soil fertility, allowing relatively high biomass production;
* moderate intensity of rain and thus moderate erosion;
* good access to inputs, etc.

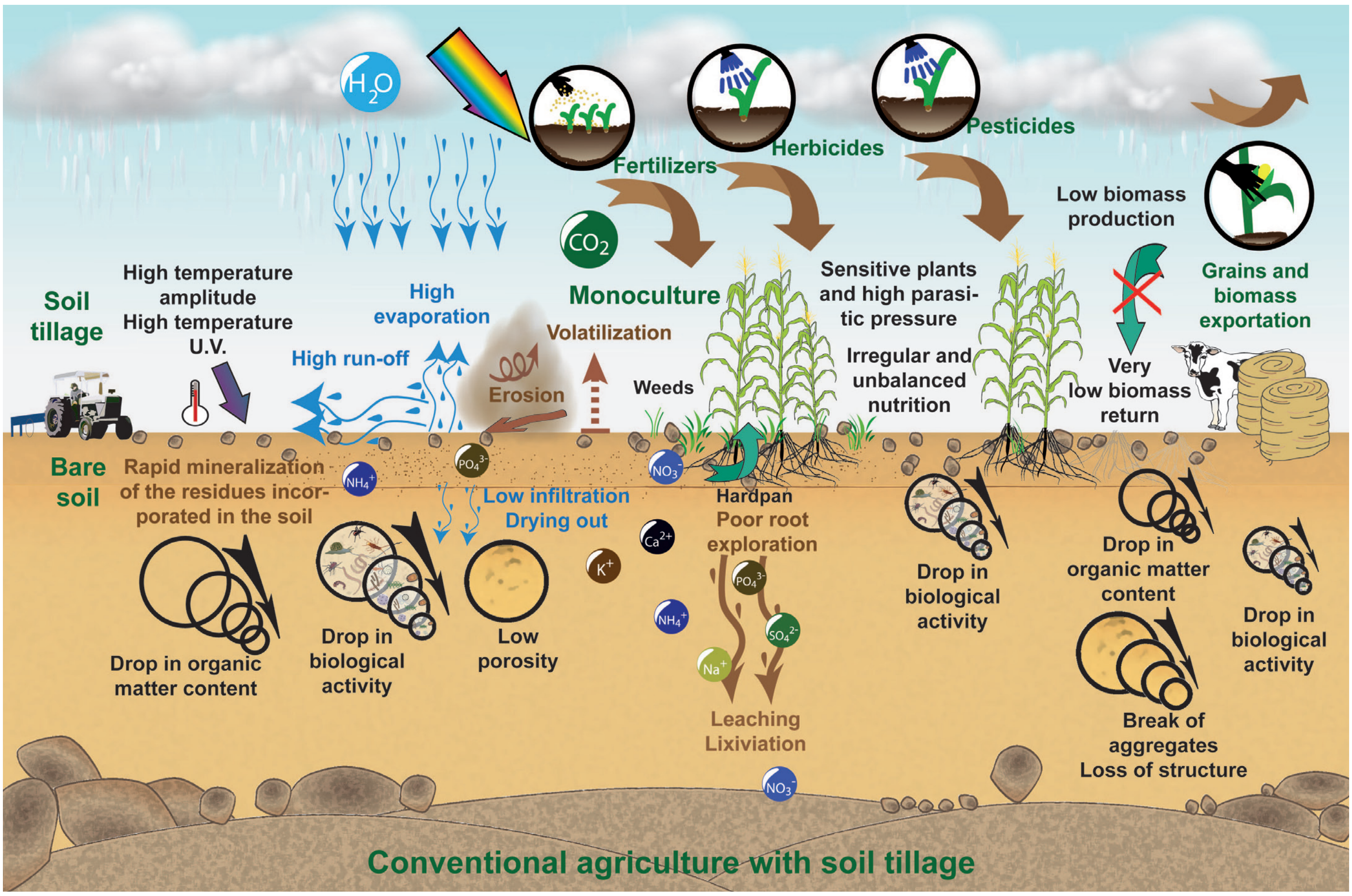
In the mid-term, the progressive degradation of soils, along with market evolution (decrease of selling prices, increase of input prices as needs increase), leads to: (I) difficult implementation of practices out of the “chemical” logic (integrated pest management, reasoned fertilization); (II) strong temptation to increase doses used; (III) intensive agriculture can only exist due to subsidies (set to disappear). Environmental problems gene-

Manual tillage (over 100 days/ha)
Malagasy Highlands

rated by the massive use of chemicals also put them in question (groundwater and river pollution, disturbance of fauna, residues in products, users' health, etc.).

When transferred to a tropical environment under a very aggressive climate (very rapid mineralization and intense rainfall) these conventional practices are catastrophic (except in the specific case of rice fields). They cause intense erosion and rapid loss of soil organic matter (faster when crop residues are exported or burnt), leading to overall soil degradation. The following production loss means that the biomass returned to the soil is insufficient to sustain soil fertility. Thus, tilled ecosystems enter in a vicious circle of degradation, very difficult to escape from. The organic matter inputs into the soil (crop residues restitution and organic fertilizer inputs) can only slow down soil degradation engendered by tillage, especially when erosion is high. The "chemical" option to compensate "damage" is very expensive and difficult to access, even in intensive commercial agriculture. It does not allow for the maintenance of soil fertility, is extremely polluting and scarcely profitable in the medium term.

For the majority of small farmers in the tropics, this "chemical option" is not accessible (knowledge, availability and specially cost of inputs). Conventional practices with tillage lead thus, sooner or later according to conditions (climate, soil initial fertility, slope, use of fire, etc.), to a degradation of what is often their only capital: the soil. This soil degradation is accompanied by a downward trend in yields, to the inability of cultivating the most demanding crops (farmers must use less demanding crops, but less demanded, such as cassava), and may even lead to the need of abandoning the land. These practices with tillage only increase the precariousness of small farmers, already in a very difficult situation, in a globalized economy.



One of the major «errors» of conventional agriculture, which partly explains its «headlong rush» into chemical agriculture (very profitable to the agro-industry), is to have disregarded the importance of the biological activity of the soil in the function of a cultivated ecosystem. Soil was viewed only as a physical support for plants and a reservoir for nutrients. Thinking that maintaining good physical and chemical characteristics of the soil was sufficient to ensure crop production, conventional agriculture has deprived itself of multiple ecosystem functions and services provided by soil macrofauna and microflora, including those essential to the maintenance of these physical and chemical characteristics (humification, aggregation, bioturbation, etc.). A dead soil, without biological activity, can only deteriorate, physically and chemically. Plant nutrition, deprived of the «digestion» (nutrient solubilization) normally made by soil micro-organisms, can only be done in the form of «perfusion» by soluble mineral fertilizer inputs (for the elements that chemistry knows how to make soluble), punctual and very difficult to balance.

Ignorance about the importance of the biological activity of the soil is responsible for the technical «solutions» proposed by conventional agriculture, supposed to respond to the new constraints, only addressed the symptoms (poor plant nutrition, diseases and insects) without tackling the causes of the problems (biological degradation of the soil, ecological imbalance, etc.). Even worse, the «solutions» for the short-term «treatment» of these symptoms (diseases, deficiencies, etc.) often lead to the aggravation of causes by weakening the soil microflora (adverse effects of soil tillage, fertilizers, herbicides, insecticides and mainly fungicides), by disturbing plant function (nutrition, proteosynthesis, etc.) and by destroying the ecological balance (effects of insecticides and soil tillage).

Moreover, due to economic constraints (adaptation to markets), but mainly by the desire, consciously or not, to simplify the work of farmers, agricultural extension agents or agronomists, a fundamental component of cropping systems (crops nature and their order of successional cropping/intercropping) gradually lost its role in the agricultural management of plots and farms. The «solutions» proposed are often limited to operational sequence adaptations (varieties, pesticides, fertilizers, etc.) and neglect the possibilities of “driving” the ecosystems by intercropping and successional cropping, which strongly influence the organic matter and the biological activity of the soil.

Soil functioning in slash-and-burn systems

In traditional slash-and-burn systems, the fallow period, if it is long enough, can partially improve soil fertility (physical, chemical and especially biological) rapidly lost during the growing season with tillage (and burn), on high slopes. However, with a population density greater than 15 or 20 inhabitants/km², land pressure makes it difficult to have a fallow period long enough to properly regenerate the soil. Above 40 inhabitants / km², the land pressure is such that soil regeneration is very limited and can no longer compensate losses. Soils degrade, yields decline and slash-and-burn cycles accelerate, aggravating soil degradation and yield decline in a vicious cycle.

The functioning of an ecosystem cultivated under DMC : ecological intensification

Unlike conventional agriculture, responsible for the major disturbance of the ecosystem (soil tillage), direct seeding on mulch-based cropping systems is inspired by the functioning of a natural ecosystem, without disturbing it, but by intensifying it. Thus, the dynamics of organic matter in DMC is similar to that of a natural ecosystem and soil organisms play a fundamental role. Over all, the massive use of energy by industrial scale cultivation in conventional agriculture is replaced by an economical use of energy and the ecological use of biological cropping energy.

The management of these DMC systems is based on a model of integrated functioning of the cultivated ecosystem. It aims primarily, through a high production and biomass restitution, to increase the amount of soil organic matter (and then to maintain it at a satisfactory level), and to increase the biological activity (intensity and biodiversity), essential to their proper functioning.
The control of these systems is made through plants, by their ability to produce high biomass with varied quality and to stimulate selectively, the biological activity, performing various agronomical functions.
The «soil» ecosystem, shaped by cropping practices, is not restricted to a supporting role for plants and a

mineral reservoir. It plays a major role and has several additional functions:

* in the storage, mobilization and regulation of nutrient elements and water flow;

* buffering effect on climatic hazards;

* in the regulation of bioaggressors, etc.

Thus, the main agronomic functions are ensured primarily by functional biodiversity in the systems (which are lost in conventional systems). While ensuring crop production (responding to farmers' needs and to market requirements), these systems include plants selected to ensure essential ecosystem functions (soil de-compaction, recycling and mobilization of nutrients, weeds and insects control, etc.).

The operational sequences only contribute to make these systems efficient, by allowing them to realise their potential.

In addition, the operating mode of DMC systems minimizes the effects on environment of «management errors» (over-fertilization or pesticide application in large quantities) thanks to cover crops and biological activity, unlike conventional systems, where such excesses cause high pollution.

Three inseparable principles

The three fundamental principles of DMC (no soil disturbance, permanent cover and crop diversity) are inseparable and work in interaction, with many synergies. The system, as a whole, is superior to the sum of its components.

For example, the maintenance of a permanent cover is not possible if the soil is disturbed and if this coverage is not supplied by a substantial phytomass. In addition, the application of only one or two of these three principles cannot maintain, and even less, increase the organic matter stock of the soil.

The «isolated» application of these principles can have a marked effect only under certain conditions, very specific. In very dry environments, for example, the maintenance of crop residues, even in small amounts (1-2 t/ha), has a significant impact on water infiltration and improves production remarkably by removing the main constraint (plants water supply).

DMC cropping systems are designed and adapted to eliminate primarily the main agronomic constraints, identified and prioritized. They are actively addressed to the causes of the problems rather than to their symptoms, by protecting (prevention) and restoring (remediation) soils and ecological balances. They also provide some ecosystem services, with a very positive impact within the field of carbon sequestration and greenhouse gas reduction (whereas conventional systems «lose» carbon).

Through their own design, DMC systems must constantly evolve in order to adapt to the major changes in constraints (which are gradually removed). As for a natural ecosystem, this ability to evolve is one of the conditions of their sustainability. To re-introduce the required diversity for the proper functioning of agricultural soil, one has to manage plant populations that provide a variety of services, over time and space, in intercropping or sequential cropping (intra or inter-annual).

A fundamental consequence is that there is a wide variety of DMC systems. These systems are designed to give priority to ecosystem functions that allow the removal of the major constraints (compaction, fertility, weeds, bioaggressors, etc.) encountered in a given situation (in an agricultural unit, on an individual farm, or even as part of a terroir). For a given ecosystem function, the impact of DMC systems on production and on the environment is therefore, by nature, dependant on the chosen crop system (with its potential to render this type of service) and on the conditions of its realization (which allow, or not, the expression of this potential). The more robust DMC systems are those that are able to provide the expected ecosystem functions under a variety of conditions. It is important that these systems are as resilient as possible, i.e., able to return to normal development and function after suffering a significant disturbance. Finally, DMC systems in ope-

Functions as yet unknown

Each plant is able to perform various functions and to render various services to the ecosystem. The functions performed by a species are highly variable and are still poorly known. Plants, very often, act in interaction with the microflora selectively stimulated by root exudates. The understanding of these phenomena and the discovery of various plants capabilities to provide specific services is a fundamental area of research for the improvement of the performance of direct seeding mulch-based cropping systems.

ration must integrate as best as possible on farms, within the constraints and resources of the farmers, and meet their demands and needs, in a given socio-economic context (demand and market opportunities, risk limitation, etc.).

4. Operating conditions of DMC systems

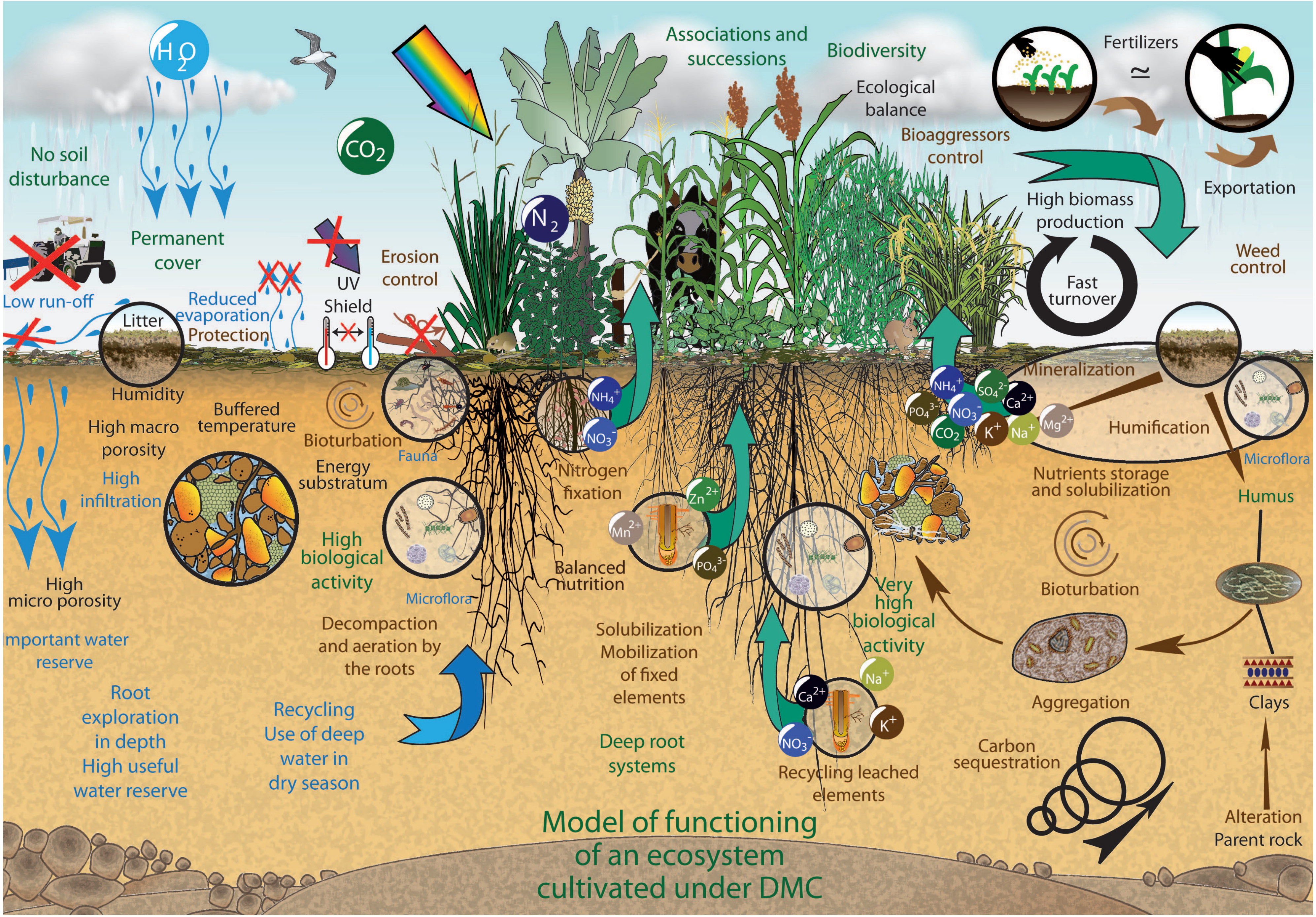
DMC systems are based fundamentally on the quality and quantity of biomass produced and returned to the litter and to the soil (aerial and root biomass). Biomass quality plays on the types of ecosystem functions performed, while the amount directly influences the intensity of these functions. There is a threshold of biomass contribution to the soil, above which systems operate properly in DMC, and below which they are malfunctioning. This threshold corresponds to the amount of mineralized organic matter. It varies depending mainly on climate, on biomass quality, on soil and its management (tillage or not). If supplies are above this threshold, the soil (and the crops) benefit even better and faster as the differential «biomass restitution - biomass lost by mineralization» is high.

Conversely, systems with organic matter restitution lower than losses (the case of systems with low biomass production and / or high exportation, for animal feed, in particular) cannot sustainably maintain the level of soil organic matter. They only slow down degradation and ensure a limited number of agronomic functions properly, which limits their performance and interest. Very often, these systems that are within the generic term of conservation agriculture, do not allow the maintenance of permanent cover. Thus, they do not correspond, strictly speaking, to the definition of direct seeding mulch-based cropping systems, which is a special type of conservation agriculture (which offers a wide variety of systems, based on a certain number of principles to be respected)

A large diversity of DMC systems

Each DMC system has a higher or lower potential to provide various ecosystem services. Moreover, the conditions for the execution of these systems, or not, allow them to express this potential.
Consequently, the ability to render a given ecosystem service is specific to each system, and to its execution conditions (effective production of biomass in particular).
The most efficient systems are those that perform many functions rapidly.
A system cannot perform all the functions with the same level of efficiency. By contrast, the wide variety of DMC systems allows the choice of the best adapted systems at a given time, to fulfil priority agronomic functions and to remove the major constraints in a given situation.
Gradually, as systems develop, they need to adapt in order to ensure the functions that become essential.

Permanent soil cover. High biomass production.



Model of functioning of an ecosystem cultivated under DMC
H_2O
No soil disturbance
Permanent cover
Low run-off
Litter
Reduced evaporation
Protection
UV Shield
Erosion control
CO_2
N_2
Associations and successions
Biodiversity
Ecological balance
Bioaggressors control
Fertilizers
≃
Exportation
High biomass production
Fast turnover
Weed control
Humidity
High macro porosity
Buffered temperature
High infiltration
High micro porosity
Important water reserve
Root exploration in depth
High useful water reserve
Bioturbation
Fauna
Energy substratum
High biological activity
Microflora
Decompaction and aeration by the roots
Recycling
Use of deep water in dry season
NH_4^+
NO_3^-
Nitrogen fixation
Zn^{2+}
Mn^{2+}
PO_4^{3-}
Balanced nutrition
Solubilization
Mobilization of fixed elements
Deep root systems
Very high biological activity
Na^+
Ca^{2+}
K^+
Recycling leached elements
SO_4^{2-}
CO_2
Mg^{2+}
Mineralization
Humification
Microflora
Humus
Nutrients storage and solubilization
Bioturbation
Aggregation
Clays
Carbon sequestration
Alteration
Parent rock

Maize + cowpea
High organic content in the surface horizon

To benefit quickly from the effects of DMC, it is necessary to obtain a high differential between «biomass restitution to the soil» and «lost biomass» in the early years of entry into DMC systems. This high differential allows these systems to perform their ecosystem functions, and lead quickly to soil improvement and to the re-establishment of ecological balance. These improvements, in a virtuous circle, facilitate the achievement of a high biomass production and allow the easy supply to the DMC «pump» in subsequent years. On degraded soils, obtaining a high biomass production in the early years, passes through the fertility restoration by fertilizers input (organic or mineral), controlled burning and / or use of cover crops able to produce a high quantity of biomass on low fertility soils. The more degraded the soils are, the more difficult, longer and / or more expensive is the "start up" of DMC systems. Below a certain level of degradation, it is not profitable during the early years and requires investment. However, in numerous agronomic situations, the great diversity of systems and of possible operational sequences in DMC allows to adapt practices to the great diversity of socio-economic situations. It allows the proposal of economically profitable systems, sustainable and motivating, compatible with the means and the risk levels acceptable by different types of farms. The variety of possible systems, as well as their interest, and the ease of implementation, depends however, largely on biophysical (climate, soil, etc.) and socio-economic conditions (farming systems, livestock production systems, market conditions, rules community, etc.). Some small restrictive environments (available space and means, low pressure on biomass, etc.) offer many opportunities for improvement, by easy-to-manage systems. In contrast, restrictive environments (high pressure on biomass, low production potential, limited means, etc.) require a delicate adaptation of DMC systems and their management.

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Beans after rice

Chapter 2

Management of ecosystems cultivated under Direct seeding Mulch-based Cropping systems (DMC)

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Oats in beans

The management of ecosystems cultivated under direct seeding mulch-based cropping systems (DMC) aims to enable them to reproduce the functioning of a natural forest ecosystem based on three «pillars» (see Chapter 1):

* permanent soil cover/litter (supplied by a high biomass production, not disturbed by tillage);

* high functional biodiversity: different species ensure a variety of fundamental ecosystem functions (soil structure, mobilization and/or recycling of nutrients, weed control, bioaggressor control, detoxification, etc). They also provide high biomass production (plenty of fresh organic matter, especially thanks to efficient use of water), that when returned to the soil feeds the litter and the soil carbon stock, by a significant and fast turnover of organic matter;

* high biological activity, favoured by the permanent soil cover and the high biomass production by a variety of plants. This intense biological activity contributes to the performance of various functions, and plays a key role in the cycle of organic matter, in soil structure and nutrition, and in plant health.

The management of DMC systems therefore corresponds to the management of plant populations (and indirectly of soil biota), in order to produce crops of interest in maximizing the total production of biomass ensuring various ecosystem functions. The choice of species (and varieties) is made on the basis of their ability to perform certain functions, in order to remove, as quickly as possible, the main agronomic constraints (compaction, fertility, bioaggressors, etc), in a given bio-physical (soil, climate, flora, weeds, bioaggressors, etc) and socio-economic (production, terroir, markets, etc) environment, while satisfying the production goals.

The basic principles to optimize biomass production

* Maximize production using all available spaces (intercropping in the cultivated plots and cover crops on wastelands), also for as long as possible (crop sequence, use of annual plants capable of growing in the dry and/or cold season, use of perennial plants, early seeding, systematic replacement of missing plants, etc).

* Rectify soil fertility as quickly as possible (organic or mineral fertilizers, controlled burning and/or vegetable "biological pumps") and optimize the use of nutrients (reducing losses, recycling, mobilizing less available elements, etc).

* Optimize the use of water, producing a maximum of biomass during the rainy season and using the water infiltrated deep in the soil during the dry season (recycling plants with a deep root system, capable of prolonging their growth very late into the dry season).

* Associate as many plants as possible with different characteristics (in order to optimize production under various climatic constraints) and with a high aerial and root biomass.

* Do not immobilize the land only for biomass production (except when the available space allows it easily). Profit, as much as possible, cover crops by associating them with another crop.

In practical terms, we can distinguish two main management methods of DMC systems:

* dead mulch systems, where crop residues and/or cover crops are completely dried by broad spectrum herbicides, mechanically controlled (angle roll, mowing, stripping) or die naturally (end of annual crops cycle, frost, etc).

* living mulch systems, where a perennial cover crop is simply controlled during the cropping period but not killed, so that it reinstates itself after the cropping period.

Soil under Stylosanthes guianensis cover

In all cases, the performance of these systems is primarily based on the biomass produced and returned to the plot, which allows the soil to regain and maintain the favourable physical, chemical and biological properties.

1. Production and management of biomass in DMC systems

The needs of the biomass to cover losses by mineralization and to ensure proper functioning of DMC systems depend largely on the weather (and on the type of residue). In a cultivated ecosystem, using only crop residues is generally insufficient to correctly supply the soil with fresh organic matter, especially in a tropical environment where mineralization is fast. Cultivated plants must be «strengthened» by plants that allow the complete use of resources and thus increase total biomass production. The transition from conventional (tillage) to DMC systems is made even more quickly and easily when selected systems produce a large biomass in the first year(s).

1.1. Biomass production (fresh organic matter)

Periods of possible production

The period of possible production is mainly determined by the weather and by the water regime of the plots, and also by the cultivated plants. To maximize biomass production, the basic principle is to occupy as much as possible the not used areas with crops, either in space (intercropping) or over time (crop sequence).

Many cover crops have been selected for their ability to grow efficiently in marginal conditions and thereby extending as far as possible the period of biomass production: (i) during the cold season in temperate climates, (ii) as far as possible during the dry season when it is pronounced, (iii) before or after the main crop when the rainy season is longer than the cycle of the crop (very quickly at the beginning or end of the rainy season) or, (iv) during a «small» rainy period in bimodal climates with two rainy seasons.

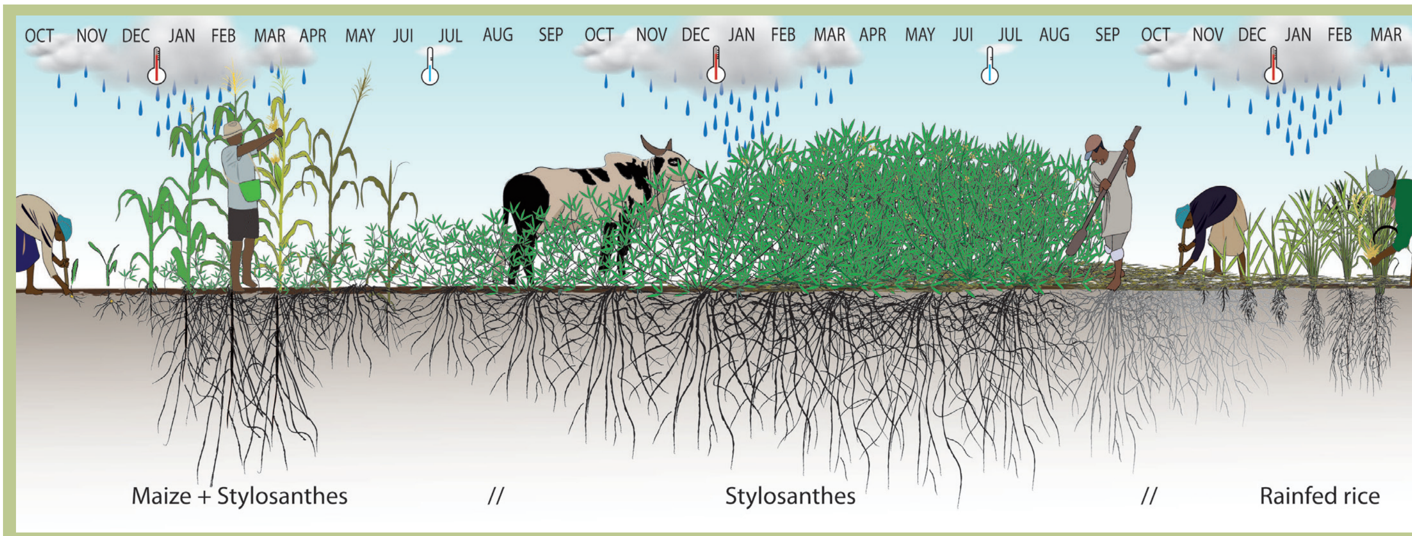
However, climatic conditions favourable to a high biomass production (heat, sunlight and rain) are also very favourable to the decomposition of organic matter and to mineralization. To ensure the proper functioning of DMC we must ensure a very high biomass production in these periods to compensate the rapid decomposition, and to produce as much as possible during marginal periods, which allows a significant increase of the total biomass production (and during which losses are slower).

Intercropping and crop sequence

Intercropping is used whenever possible since it helps to ensure a production of biomass generally larger and more stable. This is a basic principle in ecology: diversity gives more chances of having plants adapted to real production conditions (soil, climate hazards, etc), and plants complementarity allows a better use of resources. Species diversity can also provide functional biodiversity which ensures functions and various ecosystem services (carbon sequestration, nutrient recycling, weeds and bioaggressor control, etc).

When the available space is sufficient, the easiest solution to implement is to alternate crops and cover plants with very high biomass production. The best solution is to install in the crop one (or more) perennial cover plant (s) by shifting the seeding, and to allow it (them) to develop in the following year (improved fallow).

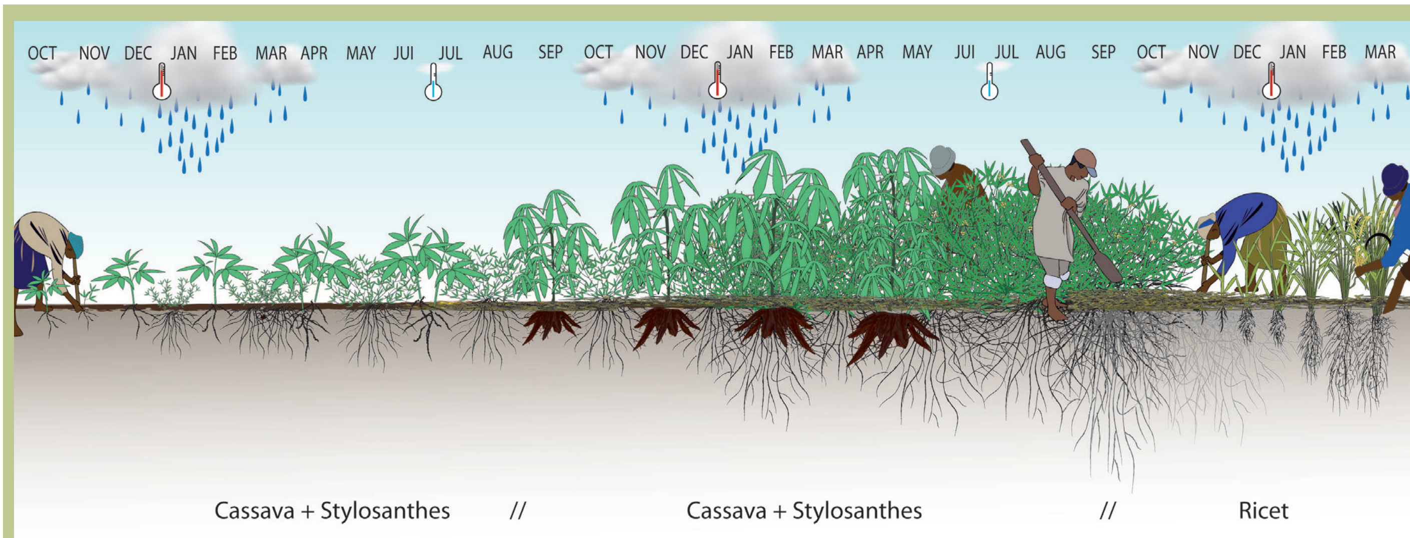
Maize + cowpea intercropping in Malagasy highlands



Example of DMC system when there is sufficient space to alternate crops and cover plants

The available space is however seldom sufficient to allow immobilizing soil without crop production for more than one year.

An intermediary practice, very interesting on poor soils, is to cultivate a long cycle crop such as cassava (12 to 24 months depending on the region) intercropped with a cover plant which thus has sufficient time to develop strongly, without immobilizing the soil.



Example of an intermediary system allowing high biomass production without immobilizing the soil

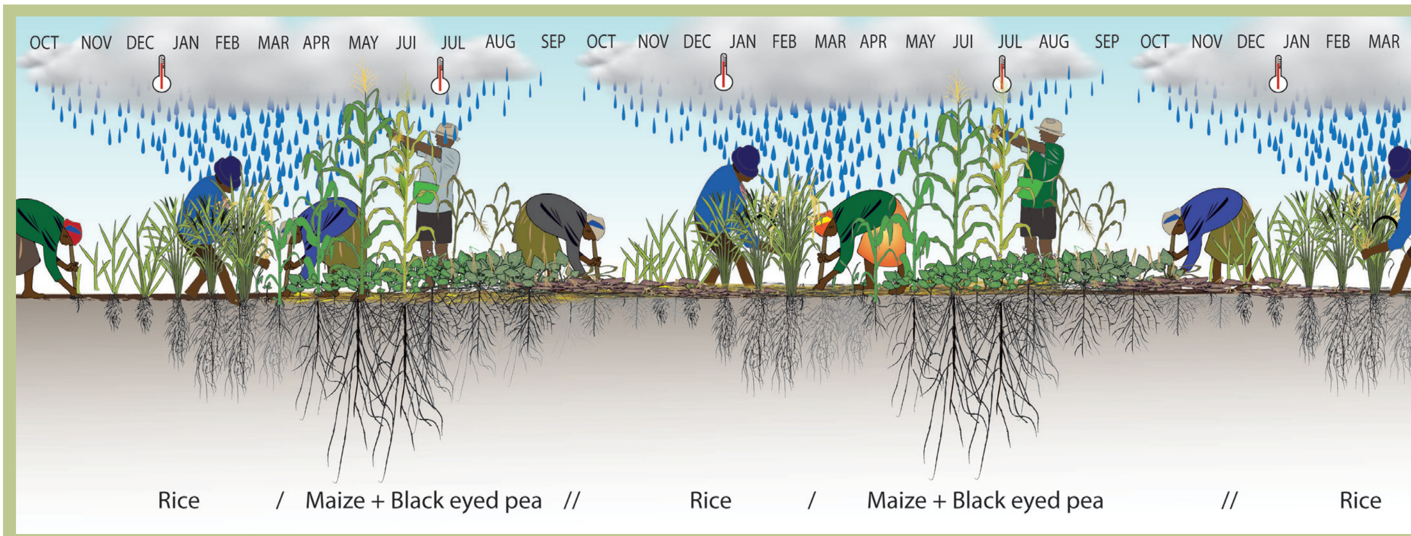
The production of a food and/or commercial crop each year is, however, very often necessary. The additional production of biomass must be done by intra-annual successions (if the weather permits) and/or intercropping.

Cassava + Stylosanthes
Lake Alaotra

The longer the hot and wet season and the higher the rainfall (or the better plants can be supplied with water by the soil during the dry season), the easier it is to manage crop sequence and/or intercropping and to produce a high biomass. However, in these cases it should produce a very high biomass over periods as continuous as possible (especially during the dry season with covers using the deep water) to compensate for the high degree of mineralization.

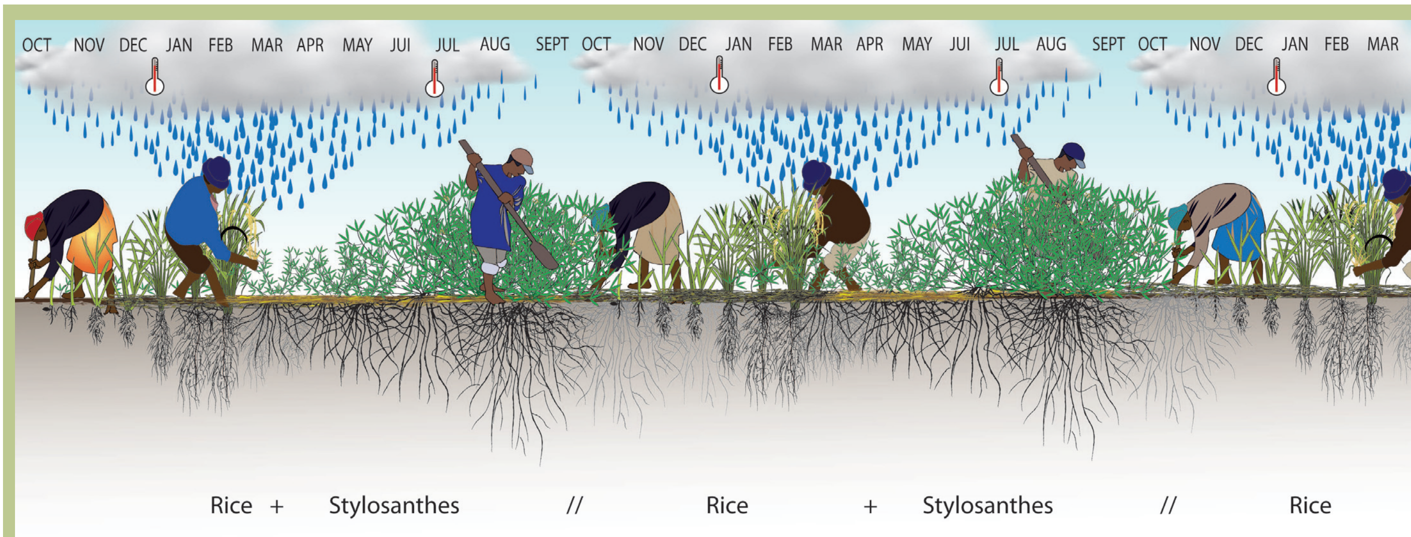
This can be achieved:

* by succeeding in the same year several annual plants, choosing cycles that provide the best coverage of the best soils throughout the year and recycle nutrients as much as possible («biological pumps» in crop succession). We can thus cultivate up to three cycles of crops/cover plants per year;



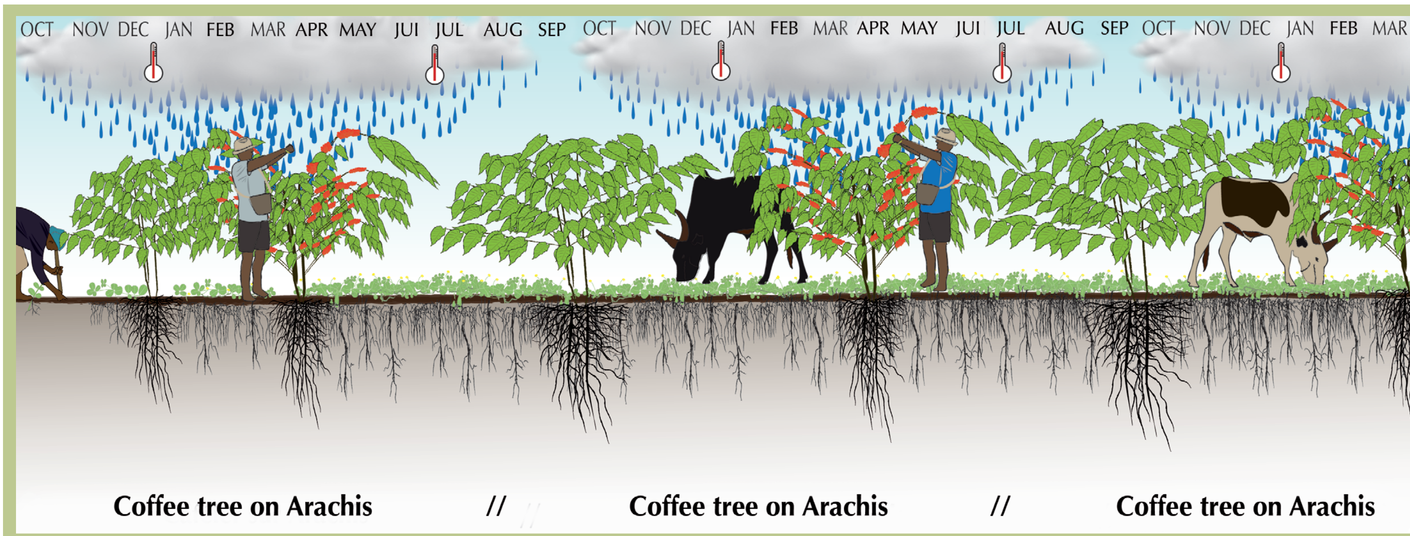
Example of intra-annual crop sequence and intercropping in humid tropical climate

* by associating an annual crop with perennial cover plants that will produce all year (and that we can keep alive or control for the implementation of the next crop);



Example of intercropping of crop and perennial cover plant in humid tropical climate

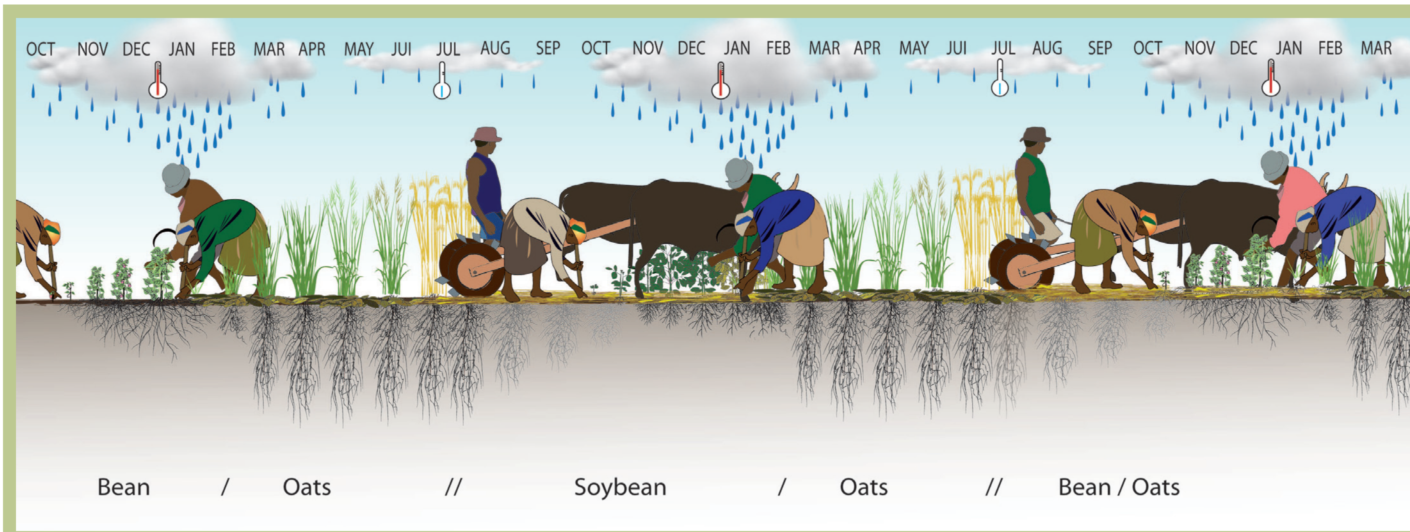
or
* by cropping perennial plants associated with perennial covers, such as coffee on a cover of *Arachis pintoi.*



Example of production of perennial plant on living mulch in a humid tropical climate

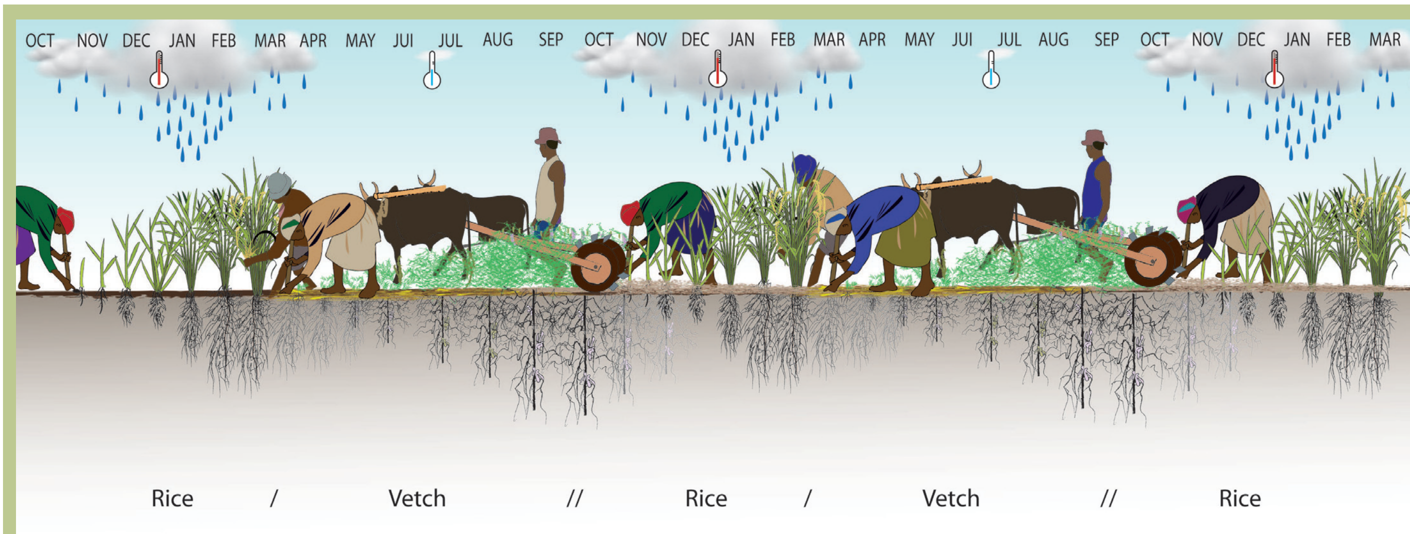
With a shorter rainy season and/or a cold season, the mineralization is slower but the period of biomass production can be shorter. Successions can be done only with:

* a short cycle crop, such as beans (followed by oats, for example);



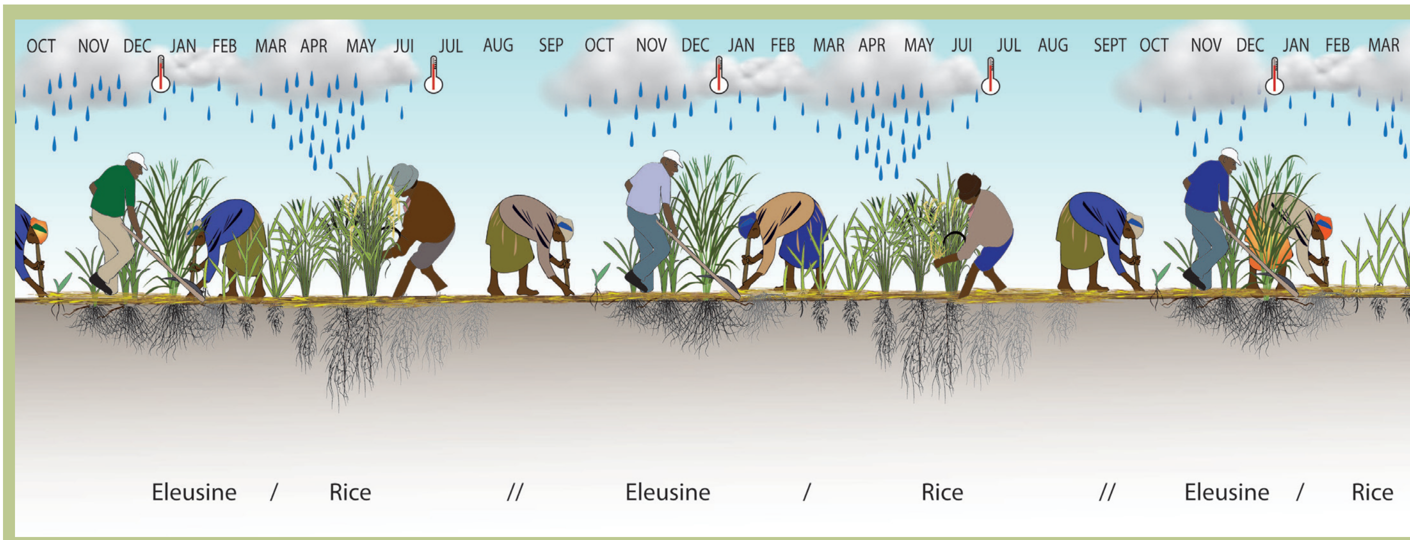
Example of intra-annual succession of crops with a very short cycle

* a long cycle cover plant, planted after a crop and capable of supporting the dry and/or cold season to grow quickly from the first rain/heat, such as vetch on the Highlands or in the Lake Alaotra;



Example of intra-annual succession of crop/cover plant of long cycle (production during marginal period)

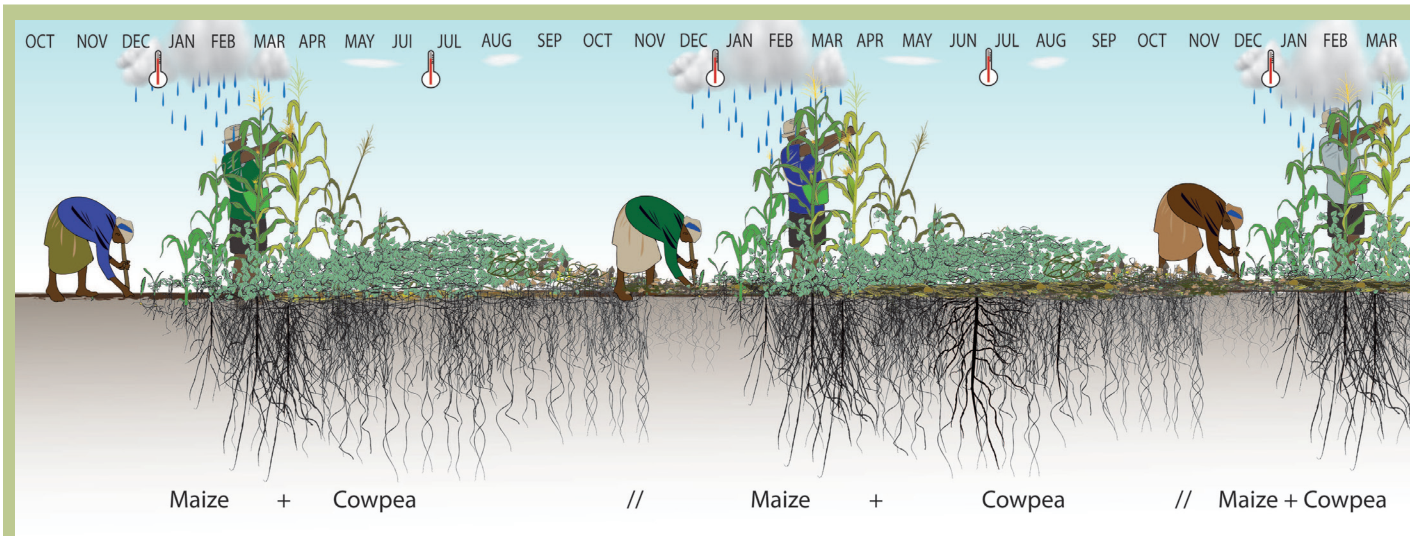
* a cover plant capable of producing, very quickly, a high biomass, such as eleusine, millet, sorghum or brachiaria (or a mixture of these species), established at the beginning of the rainy season or during the short rainy season in a bimodal climate (the small rainy season being too short to allow the crop to complete its cycle).



Example of intra-annual sequence of fast growing cover plant/crop

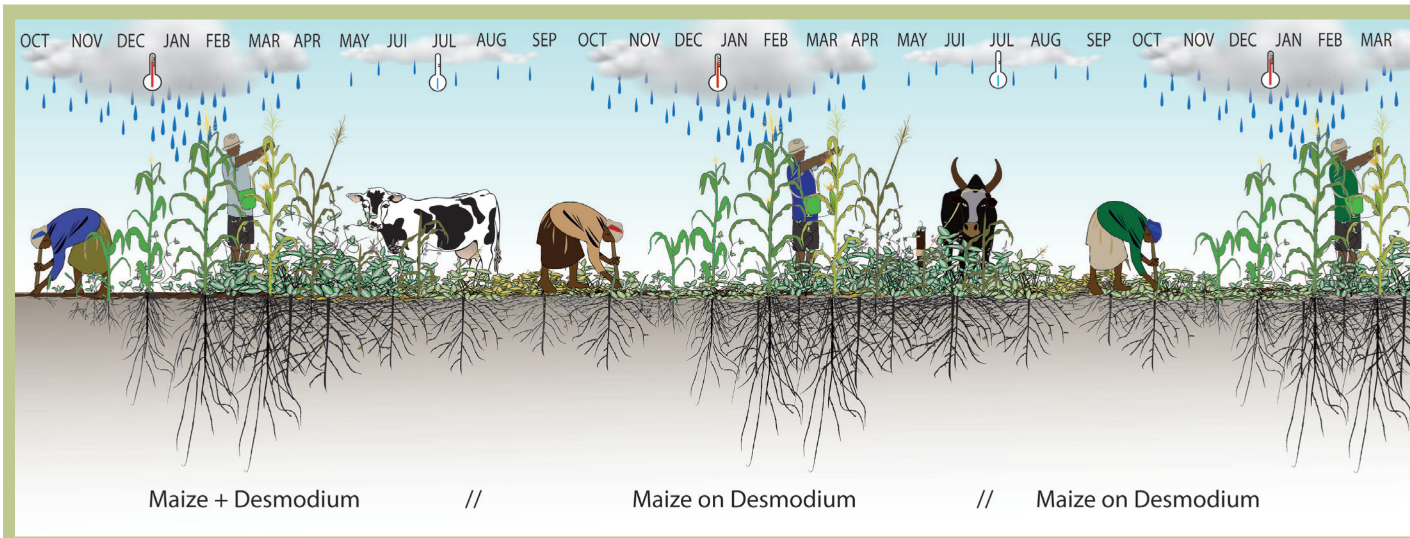
When the rainy season is too short, these successions are not possible, even with plants with a very short cycles (except in special environmental conditions, with a more favourable water regime: lower parts of the toposequence, irrigated fields). It is then necessary , in order to maximize biomass production, to have plants capable of producing during marginal periods:

* plants established during the rainy season intercropped with the culture, and that extend their growth as much as possible during the dry season, by taping deep water from the soil. To properly install itself before the arrival of the dry season and to be able to develop, the associated plant must be planted early enough. However, it might compete with the crop (especially as the water is a very limiting factor) and must be managed by a suitable density, a good arrangement in the space, localized inputs of fertilizer and/or use of cover plants with root systems different from crops. The shorter the rainy season and the lower the amount of rainfall, the more difficult the management of these intercropping and the more they require a specific operational sequence;



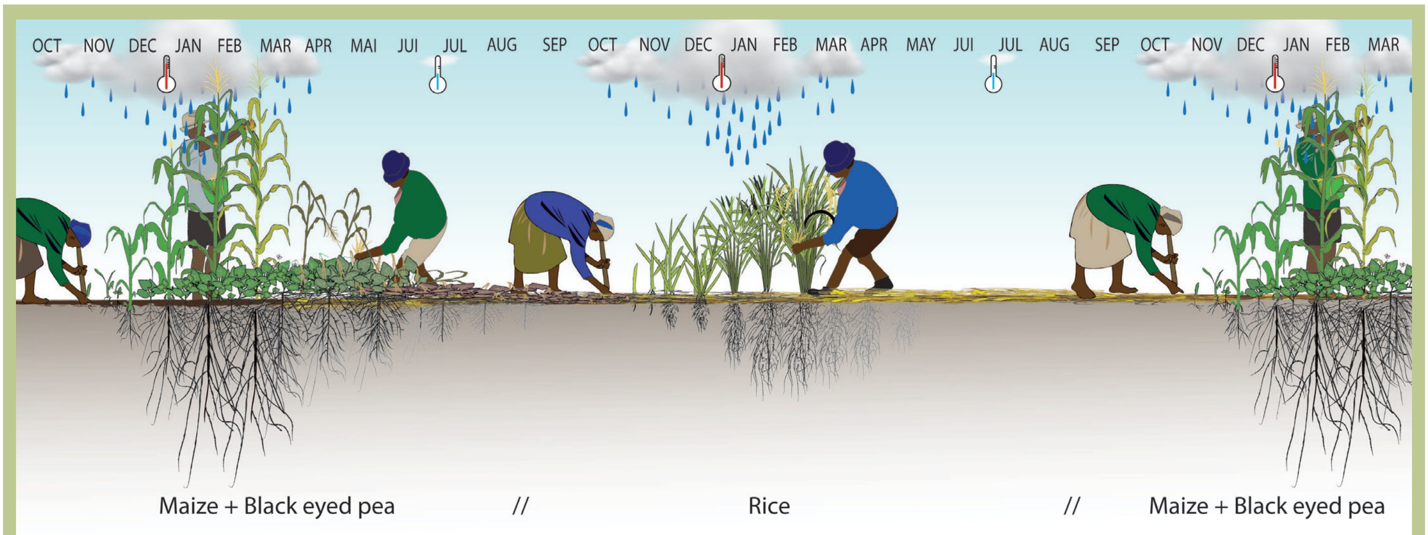
Example of intercropping crop+ cover plant of long cycle (production during marginal period) or

* perennial cover plants used as living mulch (Desmodium, Kikuyu, etc).



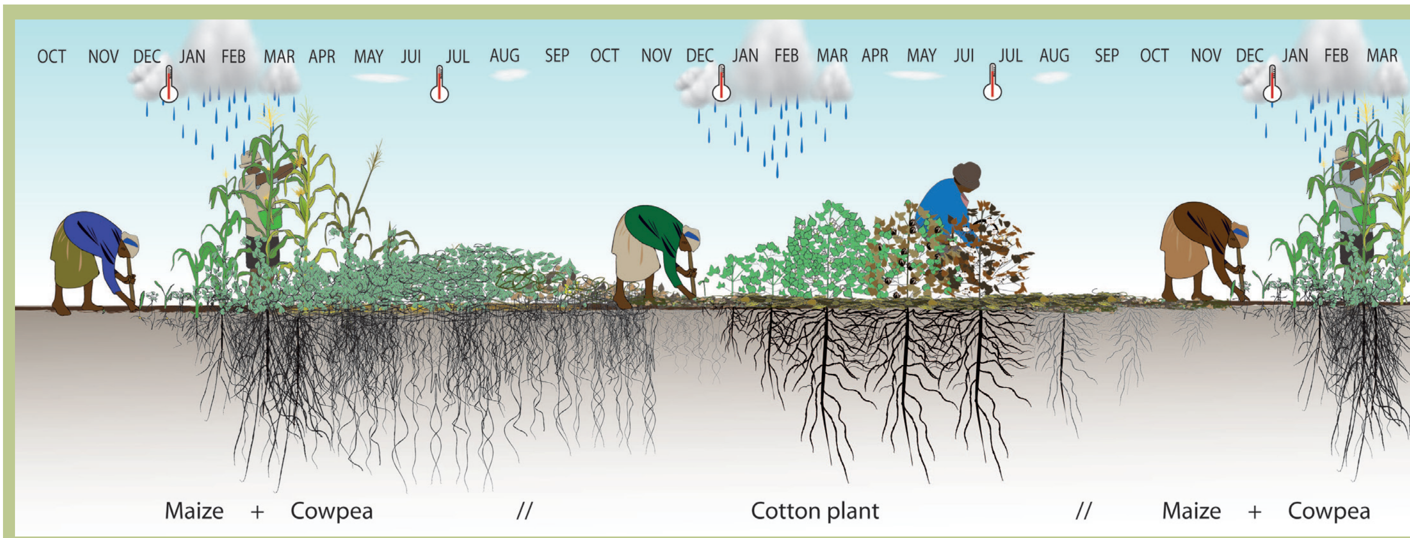
Example of system on living mulch

When it is difficult to conduct intra-annual crop sequences or intercropping with a long cycle crop and/or allowing little light penetration, inter-annual crop sequences become of paramount importance. They ensure over time the diversity of cultivated plants on a plot, the production of sufficient biomass and avoid depleting the soil, by cultivating only species with similar needs. We will seek to maximize biomass production in the first year to «initiate the pump» of direct seeding, as in the maize + black eyed pea system (or cowpea or Vigna umbellata) // rice very interesting in Lake Alaotra (medium altitude and pronounced dry season).



Example of crop associations and inter-annual successions (climate with a long dry season)

In semi-arid climates, where the total biomass production and mineralization are limited by water, we will seek to ensure, at least one year over two, a high production of biomass, that will cover the needs of two years (as the maize + cowpea intercropping, preceding cotton plant).



Example of a system with very high biomass production one year in two (semi-arid climate)

In all cases, intercropping and crop sequence will be chosen to minimize the period without biomass production and to ensure a good permanent soil cover (and particularly just before seeding the main crop). Systems are therefore organized over several years and the establishment of a cover plant is made several months before the crop, which requires careful planning.

Management of intercropping and crop sequence

The management of intercropping and crop sequence is made by ensuring the production of the main crop, while adjusting in parallel the associated plants and the parameters of their establishment to maximize their production without damaging the crop. Besides the possibilities of «playing» with the varieties (the characteristics of a species may vary considerably from one variety to another, especially regarding their cycle), the operational sequence allows controlling the eventual competition of cover plants with crops. We can thus adapt seeding dates, density and layout of plants in the space, and/or the manner and depth of seeding, provide localized fertilizer, or control cover plants by mowing, application of selective herbicide or even urea application or irrigation. The choice of systems, and the adjustment of operational sequences that allow us to manage intercropping/cover plants are, therefore, primarily a matter of knowledge and control of the adapted plant material, and of common sense.

Rice + black eyed pea intercropping
Rice sown in double rows on agricultural controlled burning. Black eyed pea sown one month after rice

Mixtures of cover plant species

The mixture of species to achieve the plant cover is very interesting. Increased biodiversity in systems can simultaneously benefit many functions and ecosystem services provided by these plants. Depending on the main constraints to be released in priority, various plants can be mixed:

* plants with tape root systems (cajanus, crotalaria, etc) with plants with fasciculated and strong root systems (Brachiaria, eleusine) to quickly rebuild the soil's macroporosity and microporosity;

* legumes for nitrogen fixation;

* C4 plants for high biomass production;

* plants with high capacity to recycle nutrients leached in depth (root system developing rapidly and in depth) such as eleusine, millet, sorghum, brachiaria;

* plants capable of dissolving (in interaction with the microflora) less available nutrients (lupine, stylosanthes, amaranth, etc);

* plants with strong allelopathic effects (oats, sorghum, etc) for weed control;

* repellent plants or with insecticidal effects (forage radish, vetch, Desmodium, several aromatic plants, etc) for insect pest control;

* plants attractive to entomopathogens (fungi, nematodes, etc) or to predators of pests (vetch, etc); and/or

* any plant capable of performing a function or render a particular ecosystem service, mostly by promoting the development of specific microorganisms: detoxification of the soil against pollutants with sorghum, complexation of aluminium toxicity with Brachiaria, suppression of fungal diseases as rice blast with the eleusine + crotalaria mixture, and numerous other functions yet to be discovered.

DMC and «underground» crops

DMC systems do not exclude the cultivation of "underground" crops such as tubers (potato, sweet potato, etc), tuberous roots (cassava, etc) or legumes buried seeds (groundnuts, bambara groundnuts, etc), which often play an important role in small scale farming.

On one hand, the good soil structure in DMC systems does not need the use of ridging or mounding of roots and tubers. Instead, it must be avoided in order to leave the soil flat and to allow direct seeding afterwards. On the other hand, mulching is never an impediment to penetration of legumes gynophores.

Furthermore, tuberous roots, tubers or seeds of these plants cultivated under crop cover grow mainly on the surface, just under the mulch, so their harvesting disturbs the soil relatively little (and is much faster than in conventional systems).

However, these crops produce little biomass, so it is preferable to intercrop them (cassava+ stylosanthes or potato + oats, for example) or to conduct them with a living cover (such as peanuts or Bambara groundnuts on living cynodon), which allows the crop cover to quickly re-cover the areas disturbed by harvesting. If these crops are not intercropped, it is necessary to reconstruct the crop cover quickly, by installing a system with a very high biomass production.

Such mixtures also allow a very varied biomass quality, with a differential rate of decomposition. The mineralization of this phytomass leads to a regular and continuous release of nutrients for subsequent crops.
The composition of these mixtures aims to use the complementary ecosystems of these plants, to ensure the different agronomic functions and to eliminate primarily the main inhibiting factors.
This composition must also allow an easy management of the cover and maximum economic profitability. For this, the mixture of cover crops must be able to intercrop with the main crop, without harming it. For the planting of cover in succession to a main crop, it is very interesting to integrate a crop with commercial interest (maize, sorghum, etc) that covers the costs of the cover and its control before seeding the main crop.
The use of this mixture must be easy to achieve. Plants with small seeds (eleusine, millet, stylosanthes, amaranth, etc) are very interesting for this. They can be sown broadcast which requires only a few kilograms of seeds per hectare. They can be produced in a small area (the use of mixtures does not allow the collection of seeds in the cover and requires the production of seeds separately). Cycles of different mixed species must be compatible, especially for mixtures of annual species controlled by mowing or rolling after flowering. They must all be handled the same way (either chemically or mechanically), and controlled simultaneously to facilitate their use and to reduce costs.

Mixture of varieties

The combination of varieties of a cultivated species can allow the reduction of risks and can obtain a more stable and higher production (the varieties most adapted to the climatic conditions of the growing year ensure production). It also allows a reduction in the incidence of disease by integrating resistant varieties, which allow production in the event of strong pressure from pests, and reducing the transmission to less resistant varieties (physical barrier to the transport of pathogenic organisms).

The choice of varieties is done in order to introduce:

* varieties resistant to the main diseases (each variety must be resistant to several diseases, not necessarily the same from one variety to another) that can have a high impact in the growing area; and

* varieties with high potential under the existing growing conditions (level of fertility, water regime, etc).

When harvesting is mechanized, the different mixed varieties must have a similar production cycle in order that the harvesting can be done at the same level of maturity. In small plots harvested manually, using varieties with different cycles (like the seeding shift) reduces climate risks. It avoids that an accident (cyclone, strong wind, drought, hail, etc) occurs during a sensitive stage (such as flowering) for all varieties. However, such a practice significantly increases the harvest time because it must be done in several stages.

Mixture of cover plants : oats + vetch + lupine + fodder radish

Replacing missing plants

It is important to systematically replace missing plants (due, for example, to poor germination, a climatic accident, an insect attack, etc) in order to:

* maximize biomass production and to cover the soil;

* not to leave space for weeds that could then multiply and infest plots.

This replacement is particularly necessary when «holes» were formed in the vegetation due to many missing plants. It can be done with the same species, if it is still possible, or with another species (better adapted to the new production period).

Using the right varieties

The characteristics and performance (particularly biomass production) of the same species can vary greatly:
* from one variety to another;

* depending on the cropping system.

It is therefore essential to carefully choose not only species but also varieties to be used when deciding to install the DMC system.
The work of creating DMC systems must be accompanied by the selection of the best performing varieties within these systems.
Subsequently, the dissemination of DMC systems requires the provision of the best performing varieties at the terroir and farm level.

Fertility and biomass production

Fertility directly influences biomass production, which determines the beneficial effects of DMC. Unfortunately, in many situations, the initial fertility is very low.

One of the main difficulties in the transition from conventional to DMC systems is how to obtain a high biomass production in the early years, starting from a low fertility. Once obtained, this high phytomass restored to the soil allows an increase in the fertility level, and is used to nourish plants in the following cycles.

Many cover crops used in DMC were selected for their ability to produce biomass in conditions of low fertility. However, the lower the initial fertility (and the more the climate is a constraint), the more time is required for these plants to produce sufficient biomass. Fertilizer input (mineral or organic fertilizer, controlled burning) significantly reduces the time for obtaining a high biomass, enabling a rapid establishment of DMC systems.

Maize + black eyed pea on poor soil
Marked effect of fertilization (right side) on production.
Lake Alaotra

Gain of biomass production compared to conventional systems

«Dressing» of farming systems
Establishment of oat following maize
Malagasy highlands

Climate and soil fertility largely determine the systems' potential for biomass production.
The potential gain in biomass production of DMC systems compared to traditional systems depends on the factors previously described, but also the pressure on the land use (and thus on the cropping intensity). In environments with low land use (low population density), systems based on crop sequence, or even rotations alternating crop and cover plants that improve the soil are possible, and the gain of biomass compared to the traditional system is very high. Conversely, in environments with very high intensity of land use (with two or three crops per year), only intercropping cover plants in the crops (in intra-annual crop sequence) is possible to increase biomass production (as the entire possible production period is already being used). But they require compliance with a specific operational sequence (especially seeding dates) and allow only limited additional production, which must be well managed to avoid over-exploitation (stray animals).

However, the management of these biomasses may be largely improved by DMC compared to conventional systems which, in general, render little to the soil, either:

* because it is used for another purpose (animal feed, firewood, building materials), use that the DMC systems must consider when suggesting a replacement; either

* because it is a hindrance to their practices (difficult to till, slow decomposition of straws when they are deeply buried, fear of disease transmission, etc). The straw is then often burned. These situations have the potential to easily increase the amount of biomass returned to the soil, simply by changing the management of DMC systems.

1.2. Biomass management in DMC systems

The climate and the soil largely determine the biomass needs to appropriately supply direct seeding systems, by influencing the coefficient of organic matter mineralization (also influenced by the mode of soil management) and the humification coefficient of cover crops (which also depends on the type of residue).

Thus, below a certain level of biomass restitution to the soil, the systems do not maintain the rate of soil organic matter and fertility (or improve them, when starting from very low levels). The low production and or restitution of biomass (aerial and/or root) also creates constraints that can lead to low profitability or even yield loss (poor weed control due to insufficient mulching, etc).

Conversely, when restitutions are above this threshold, the soil gradually becomes richer, and even faster when the amount of biomass restitution is higher.

In practice, this has four major effects on DMC biomass management:

* In temperate or very dry climates, the potential for biomass production is limited (by temperature or water), but the biomass needed to maintain soil organic matter is lower than in hot and humid climates where mineralization is high (but production potential is very high). Similarly, it is more difficult to produce biomass starting from a degraded soil, poor in organic matter, but biomass needed to improve its characteristics is lower than on a soil rich in organic matter, because the losses by mineralization are lower in the former;

* Depending on climate, soil, intensity of land use (and thus, potential for additional biomass production) and the pressure on this biomass (fodder needs, etc) the implementation of DMC systems is more or less difficult. The higher the pressure and/or the lower the production potential, the harder it is to operate DMC systems in good conditions and the less attractive they are without the use of additional mineral or organic fertilizers, which can "boost" biomass production. These fertilizers might be subsidized, as they can be considered as an investment in the "soil capital" just as irrigation works. Conversely, when the pressure on biomass is low or production potential is high, these systems are simple to implement and particularly effective;

* In case of insufficient biomass production in the early years (or of high export to animals, by an uncontrolled fire, etc), making it impossible to cover losses by mineralization and to increase soil organic matter rate, it is necessary to «recharge» the plot in biomass, in order to reach a threshold that will allow soil improvement. If no plant biomass is available around the plot, it is preferable to concentrate available biomass on only one part of the plot, in order to allow its improvement, and to restart a year of DMC preparation (with soil tillage) on the area where biomass has been removed.

The Henin-Dupuis model (1945)

The model Henin-Dupuis is a simple model with two components (stable humus and fresh organic matter) of organic matter dynamic, which allows the prediction of its evolution over time (dC/dt), that depends on:

* the amount of fresh organic matter provided (A);
* its conversion rate into stable humus (K_1, humification coefficient which depends mainly on climate, on fresh organic matter quality, and on soil);
* soil carbon (C) initial stock; and
* its mineralization rate (K_2, mineralization coefficient that depends primarily on climate, soil and its management).

Thus, the variation of carbon rate (organic matter) in the soil $dC/dt = K_1A$ (inputs) - K_2C (losses by mineralization).

To maintain the soil organic matter rate (thus no variation $dC/dt = 0$) inputs must cover the losses ($K_1A = K_2C$). Thus, the higher the initial soil carbon stock and the faster the mineralization (high K1 in hot and humid climates and/or systems with tillage) the greater the amount of fresh organic matter to input is high.

If $K_1A < K_2C$, contributions do not make up for the losses and the system «soil» loses organic matter and deteriorates. Conversely if $K_1A > K_2C$, the system accumulates organic matter, along with all the benefits associated with it.

Adaptation of systems to the environment and to the pressure on land and biomass

Type of Environment			Intensity of land use and fodder requirements		
			Low	Medium	High
Length of growing season (Rainfall + water regime) x Temperature	Long (> 9 months)	Without cold season: East Coast	Intra-annual and inter-annual crop sequence (and intercropping) **Easy to manage**	Intra-annual and inter-annual crop sequence (and intercropping) **Relatively easy to manage**	Intercropping, intra-annual and inter-annual crop sequence **Quite difficult to manage***
		With cold season: Highlands	Inter-annual crop sequence, intercropping (and intra-annual crop sequence) **Relatively easy to manage**	Intercropping, inter-annual crop sequence (and intra-annual) **Quite difficult to manage***	Intercropping, inter-annual crop sequence (and intra-annual) **Difficult to manage***
	Medium (5-9 months)	Middle West and Lake Alaotra	Inter-annual crop sequence and intercropping **Easy to manage**	Intercropping and inter-annual crop sequence **Relatively easy to manage**	Intercropping and inter-annual crop sequence **Quite difficult to manage***
	Short (≤ 5 months)	South West and Deep South	Inter-annual crop sequence (and intercropping) **Relatively easy to manage**	Intercropping and inter-annual crop sequence **Quite difficult to manage***	Intercropping and inter-annual crop sequence **Difficult to manage***

* «Quite difficult or difficult to manage»: their implementation requires good technical skills. Improvements by DMC system are slow (even more when soils are degraded). Dissemination of DMC systems under these conditions requires farmers' support over several years (training time for farmers and DMC implementation), biomass protective measures (cessation of common grazing, fencing, etc) and eventual fertilizer subsidies in order to reduce the DMC systems implementation time.

Biomass management principle

Biomass management principle in DMC is simple: to accumulate a maximum of biomass (aerial parts and roots) in the first years, to increase soil fertility rapidly and to ensure various functions.

Once fertility (accumulated in the biomass and in the soil) has reached a level considered adequate, biomass restitution to the soil can be reduced to a level sufficient to compensate losses by mineralization and to ensure weed control. The biomass produced (in quantity, in soils become fertile) can be partly exported to feed animals or as a biomass «recharge» in DMC plots.

High root biomass of grasses (Brachiaria brizantha)

Root biomass

The contribution of biomass by roots is difficult to measure, especially when the contribution of the very small roots (which are quickly renewed), and of the rhizodeposition products is high.

In all cases, biomass production by the roots is considerable. It often represents more than 50% of total production and may exceed 5 to 10 t/ha/year of dry matter in grasses.

This root biomass is protected in the soil, where it is protected from livestock (and is thus entirely returned to the soil), and slowly mineralized.

High biomass of stylosanthes

Biomass management must also be done on a landscape scale, by using, as far as possible, non-cropped areas (uncultivated land, borders of plots, earth banks, etc) in order to increase the total biomass production. The improvement of natural pastures also allows the increase in the total biomass production at the terroir level.
This biomass can be used to «strengthen» the plots' cover that would need it for good management under DMC, to feed animals (thus reducing the pressure on biomass of cropped plots) or even for fuel for an eventual controlled burning.
When, in contrast, biomass production is very significant, it can hinder the establishment of crops (such as Brachiaria biomass of more than 15-20 t/ha), especially in mechanized systems. It is then a question of managing it, in order to make the seeding easier. We can particularly mow it and export it for animals, or even burn it, in extreme situations (the fire destroys only the most tender parts, with low C/N, such as leaves, but largely spares the stalks, more or less lignified with high C/N ratio, i.e., the dominant dry matter that will participate in humus formation).

The needs in biomass to compensate losses

For an effective management of soil fertility, it is useful to estimate the amount of biomass needed for restitution in order to compensate for losses by mineralization. These requirements depend primarily on :

* the climate, that largely determines the mineralization coefficient K2;
* the type of biomass, through the humification coefficient K1;
* the initial stock of soil organic matter (C).

If biomass inputs (aerial parts + roots) are made of a mixture of grasses and legumes with a medium C/N ratio (and thus with a medium humification coefficient), and in a plot with a «medium» organic matter content within the area in question, we can estimate that:

* on the Malagasy highlands, where low temperatures limit mineralization, biomass requirements to compensate losses in soil carbon (3 to 4% of organic matter) are 7 to 9 t/ha/year of dry matter in direct-seeding without tillage (whereas it needs more than 12 t/ha with tillage, which leads to higher losses by mineralization and erosion). The restitution of more than 9 t/ha to the soil allows the accumulation of carbon and soil improvement. Conversely, a restitution less than 7 to 9 t/ ha/year (direct seeding) or 12 t/ ha/year (with tillage) leads to losses of soil organic matter and even faster when the amount returned is low;

* this threshold is quite close in the semi-arid climates of the South and Southwest, where mineralization is limited by the long dry season and where soil organic matter rate is rather low (2 to 2.5%);

* it is higher at medium altitude, as in Lake Alaotra (10 to 12 t/ha/year, without soil disturbance, with 2 to 2.5% of organic matter at the beginning) and especially in Southeast Madagascar's hot and humid climate, where from 13 to 17 t/ha/year of biomass are needed to maintain the soil carbon stock, initially high (4 to 5% of organic matter).

If we start from a highly degraded soil (less than 1% of organic matter), the inputs required to maintain their level of organic matter are much lower (less than 2 t/ha of dry matter can be sufficient to maintain a very low level of organic matter, where the stable fraction dominates). However, it is unsatisfactory to simply maintain such levels of organic matter, which do not allow agricultural production. The intake levels mentioned above are thus interesting to increase these soils' fertility.

2. Fertility management in DMC

2.1. Restoring fertility

In the mode of functioning of the soil in direct seeding mulch-based cropping systems, nutrients are concentrated in the biomass/litter/soil surface, stored in organic form and regularly released by mineralization in a living soil. Fertility management and biomass management go hand in hand.
In the early years of transition, from traditional techniques towards direct seeding, it is necessary to restore, as quickly as possible, soil fertility and to produce biomass that will form the litter and will enrich the soil in organic matter.

Fertility can be restored by:

* mobilization of fertile elements present in the soil (or air) but naturally not very accessible to crops;

* input of nutrients to the plot.

Mobilization of the fertile elements in the soil (in connection with biological activity) can be done:

* quickly, by high oxidation during a controlled burning, which consists of a slow combustion at low temperature, of part of the soil organic matter (organic matter is very acid and not very active, which immobilizes mineral elements);

* gradually, through the use of "biological pumps", i.e., plants capable of:
  - rooting deeply and recycling leached nutrients beyond the reach of crop roots;
  - mobilizing nutrients fixed in the soil in scarcely soluble forms (in interaction with microflora);
  - fixing atmospheric nitrogen in symbiosis with bacteria associated in nodules (legumes) or free (as in eleusine). The use of legumes in cropping systems is fundamental in the early years, when the organic matter level is still low and the biological activity is weak. In these cases, the feeding of these crops depends largely on nitrogen fixation by these plants, which also promote biological activity (especially mycorrhizae that enhances plants' absorptive capacity).

The use of «biological pumps» is done at a very low cost/work, but it requires time. Conversely, soil smouldering (controlled burning) has an immediate marked effect, but requires significant work and the availability of a large amount of biomass for combustion. It should be valorized by high-value added crops (like potatoes).
Nutrient input to the plot may be done by:

* In the form of organic inputs: biomass removed from outside the plot or manure/slurry input, generally at low cost, but unfortunately not always available;

* In the form of mineral fertilizers (and trace elements, if necessary), with an immediate effect, very clear, but at a significant cost, and therefore a risk to be considered.

The different methods to restore fertility can/should be combined according to the available means (capacity of investment in capital and labour, possibility of not using the land, without food production, etc), the tolerable risks, the crops to be planted and the initial soil fertility.

Low pressure on land use gives the «biological pumps» the time required for the production of high biomass and greatly simplifies the introduction of DMC. Conversely, a high pressure on land use does not allow the resting of plots for their regeneration.

The needs in biomass to increase the organic matter in the soil

A differential «biomass input - losses by mineralization» of 1 t/ha of dry matter (i.e., 450 kg of C) gains less than 100 kg/ha of soil carbon (for a relatively high humification coefficient of 0.22).

To increase the soil organic matter rate of 1% on the first 20 cm of soil (which represent about 2000 tonnes of land per hectare) 20 t/ha of soil organic matter must be provided, or 11.6 t/ha of carbon (1kg of carbon is equivalent to about 1.72 kg of organic matter), which corresponds to a contribution of more than 50 to 100 t/ha of carbon within biomass (for a high humification coefficient of 0.22, or low of 0.11, respectively), i.e., more than 100 to 200 t/ha of dry matter (in addition to what is needed to compensate losses by mineralization).

Relatively efficient DMC systems that sequester more than one tonne of carbon/ha/year carry out this work in ten years (4 to 5 years for the most efficient systems, with very high biomass production).

In this case:

* «biological pumps» must be associated with undemanding crops in order to allow a gradual recovery of fertility, which requires a careful management of systems; or
* fertility must be quickly lifted up by the use of fertilizers and/or by controlled burning, with the risks that go along with such an investment.

Restoration of soil fertility as a function of soil degradation state and available means

<table>
<tr><th colspan="2" rowspan="2">Available means</th><th colspan="3">Soil degradation state</th></tr>
<tr><th>Little degradation,
quite fertile</th><th>Degraded</th><th>Very degraded</th></tr>
<tr><td rowspan="4">Space /
time
available
(low land
pressure)</td><td>Investments
with risks
possible</td><td>Fertilizer input
«Biological pumps»
(controlled burning)
All crops
Very easy to manage</td><td>“Biological pumps”
Fertilizer input
Controlled burning
All crops
Easy to manage</td><td>«Biological pumps»
(Fertilizer input)
Cultivation
after several years
Quite difficult to manage*</td></tr>
<tr><td>Investments
without risks
possible</td><td>Fertilizer input
«Biological pumps»
(controlled burning)
All crops
Very easy to manage</td><td>«Biological pumps»
(Fertilizer input)
Controlled burning
All crops
Easy to manage</td><td rowspan="3">«Biological pumps»
Cultivation
after numerous years

Difficult to manage*</td></tr>
<tr><td>Investment in
labour
possible</td><td>«Biological pumps»
Controlled burning
All crops
Easy to manage</td><td>Controlled burning
«Biological pumps»
All crops
Relatively easy
to manage</td></tr>
<tr><td>Investments
impossible</td><td>«Biological pumps»
All crops
Easy to manage</td><td>«Biological pumps»
Undemanding crops
Relatively easy
to manage</td></tr>
<tr><td rowspan="4">Space /
Time
not available
(strong
pressure
on land)</td><td>Investment
with risks
possible</td><td>Fertilizer input
Controlled burning
«Biological pumps»
All crops
Very easy to manage</td><td>Fertilizer input
Controlled burning
«Biological pumps»
All crops
Relatively easy
to manage</td><td>«Biological pumps»
Undemanding crops
Unprofitable in the short
term
Very difficult to manage*</td></tr>
<tr><td>Investments
without risks
possible</td><td>Fertilizer input
Controlled burning
«Biological pumps»
All crops
Easy to manage</td><td>Controlled burning
«Biological pumps»
(Fertilizer input)
All crops
Quite difficult to manage*</td><td rowspan="3">Unprofitable in the short
term
Long-term investment
Protection of downstream
zones

Impossible without
subsidies</td></tr>
<tr><td>Investment in
labor
possible</td><td>Controlled burning
«Biological pumps»
All crops
Relatively easy
to manager</td><td>Controlled burning
«Biological pumps»
All crops
Quite difficult to manage*</td></tr>
<tr><td>Investments
impossible</td><td>«Biological pumps»
All crops
Relatively easy
to manage</td><td>«Biological pumps»
Undemanding crops
Difficult to manage*</td></tr>
</table>

* «Quite difficult, difficult or very difficult to manage» without significant manure correction at the beginning. DMC adoption is difficult without subsidized fertilizer during the first year.

In all cases, the investment in the restoration of soil fertility should guarantee a high biomass production, in order to prepare for direct seeding in subsequent years. This requires that associated plants and cover crops are adapted to the level of soil fertility (initial fertility level compensated by inputs). On a very degraded soil, fertilization of «biological pumps» may be necessary. On moderately degraded soils, the cultivation of demanding plants (such as rice or maize) should be done only after restoration by other plants or with large amounts of fertilizer inputs (and therefore expensive and risky). An insufficient supply of mineral fertilizers (including trace elements), allowing only a partial recovery of fertility for growing a demanding plant can have disastrous consequences for the farmer. In the short term, these considerable costs may not yield any profit, and biomass production may be insufficient for easy DMC management in the following year (not allowing profit in medium term of the investment). On medium or low fertile soils, cultivation of demanding plants imposes the need for a significant level of fertilization in the first year. However, once direct seeding is properly functioning, with high biomass production, fertilizer inputs can be reduced. From an agronomic point of view (and economic, in the medium-term), the best solution is to concentrate fertilizer inputs in the first year, to produce a high biomass, and then to reduce fertilizer application in subsequent years.

Use of «biological pumps»

The use of «biological pumps» is an effective and very inexpensive way to restore soil fertility. By their ability to extract the less available soil nutrients and/or to recycle those leached in depth, these plants are able to produce a high biomass even on soils unsuitable for many crops.

Once extracted from the soil and concentrated in the biomass, these elements are mineralized and become available to crops.

The management of fertility recovered in this way, is however, fundamental. If the biomass produced is not returned to the soil or if exports by crops (and forages) are not compensated by fertilizer inputs (organic or mineral), the system's fertility cannot be maintained. Such a «mining» use of «biological pumps» has catastrophic consequences. It leads to the total exhaustion of the soil, where fertility level falls so low that even the «biological pumps» can no longer be used.

This risk is particularly high in dairy farming areas, where these plants are also excellent fodder, and are often seen primarily as an opportunity to increase forage production at lower cost. The medium-term effects of this overexploitation practice must be absolutely well understood to allow a good fertility management in these situations

Localized input of manure and mineral fertilizer in planting holes

This practice is much more efficient than medium fertilization during several years, which does not achieve the «critical» biomass needed for a quick entry in a proper functioning DMC system. It is therefore preferable to provide, for example, 300 kg/ha of NPK in the first year and 100 kg/ha in the following three years, rather than 150 kg/ha in four consecutive years. If the available resources do not provide the initial investment required on degraded soils, it is better to grow less demanding plants (bean, with eventually a low fertilization, Bambara groundnuts or cassava), associated with «biological pumps» that will produce a high biomass. Plots are thus prepared for direct seeding in good conditions, making possible the cultivation of demanding plants, with limited resources, in the following year.

Investment profitability

The short-term profitability of DMC practices depends largely on the level of soil degradation. Little or no degraded soil, allows a high biomass production with low inputs, and quickly valorises a possible investment in fertilizers, with demanding crops but with high value. The transition from traditional to direct seeding is quick and easy. Conversely, degraded soils require greater investment in fertility, with a more uncertain yield (and thus a significantly higher risk).
Beyond a certain level of soil degradation, fertility restoration requires time and huge investments that cannot be recouped in the short term. Investment in soil fertility must be considered (and managed) as a long term investment plan which allows, thereafter, maintaining sustainable production. The adoption of DMC practices under these conditions is much more complicated and depends on the mastering of production factors on a scale larger than the plot. It is much easier to make the transition to the DMC system before this level of degradation is reached.

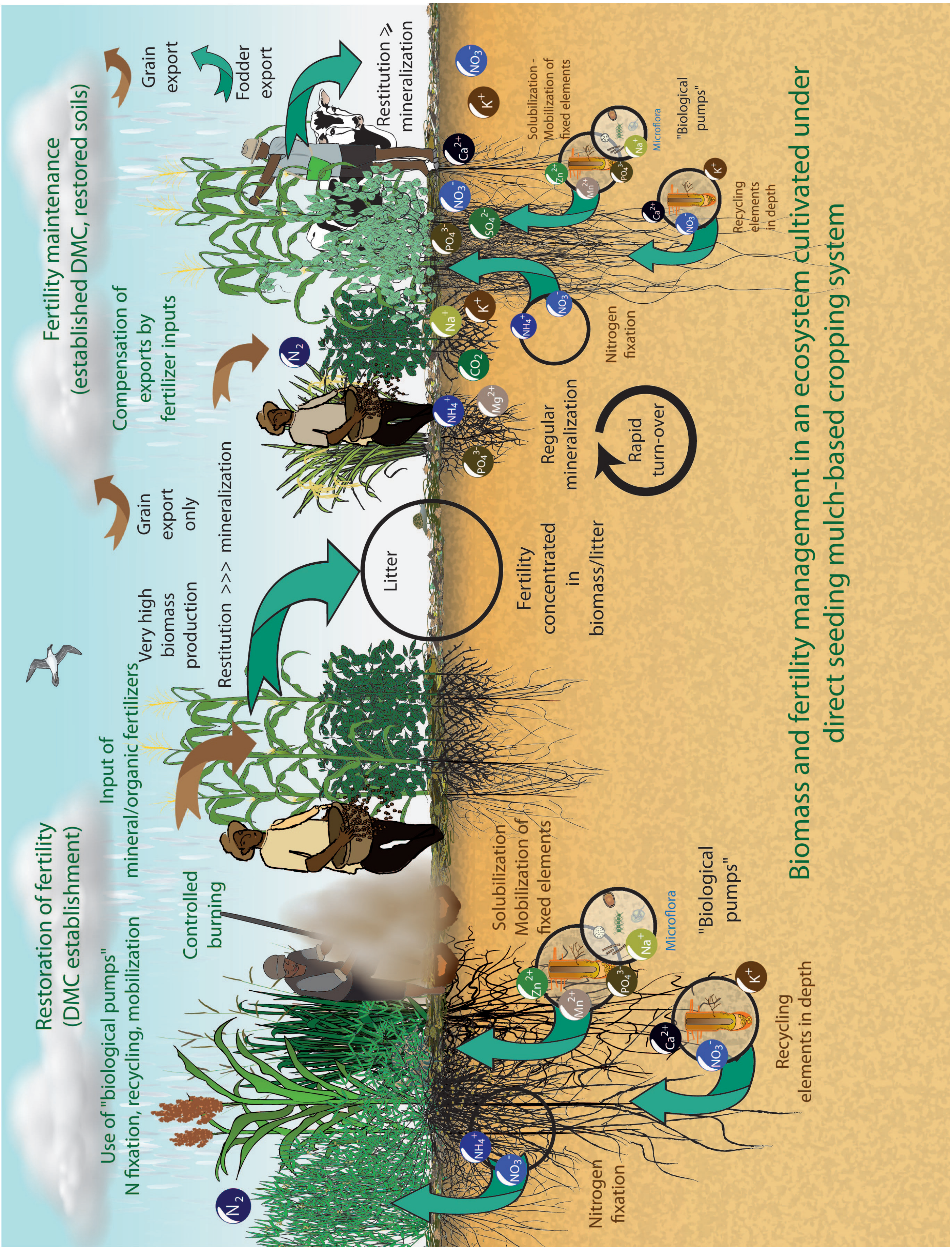
2.2. Maintaining fertility once established by DMC systems

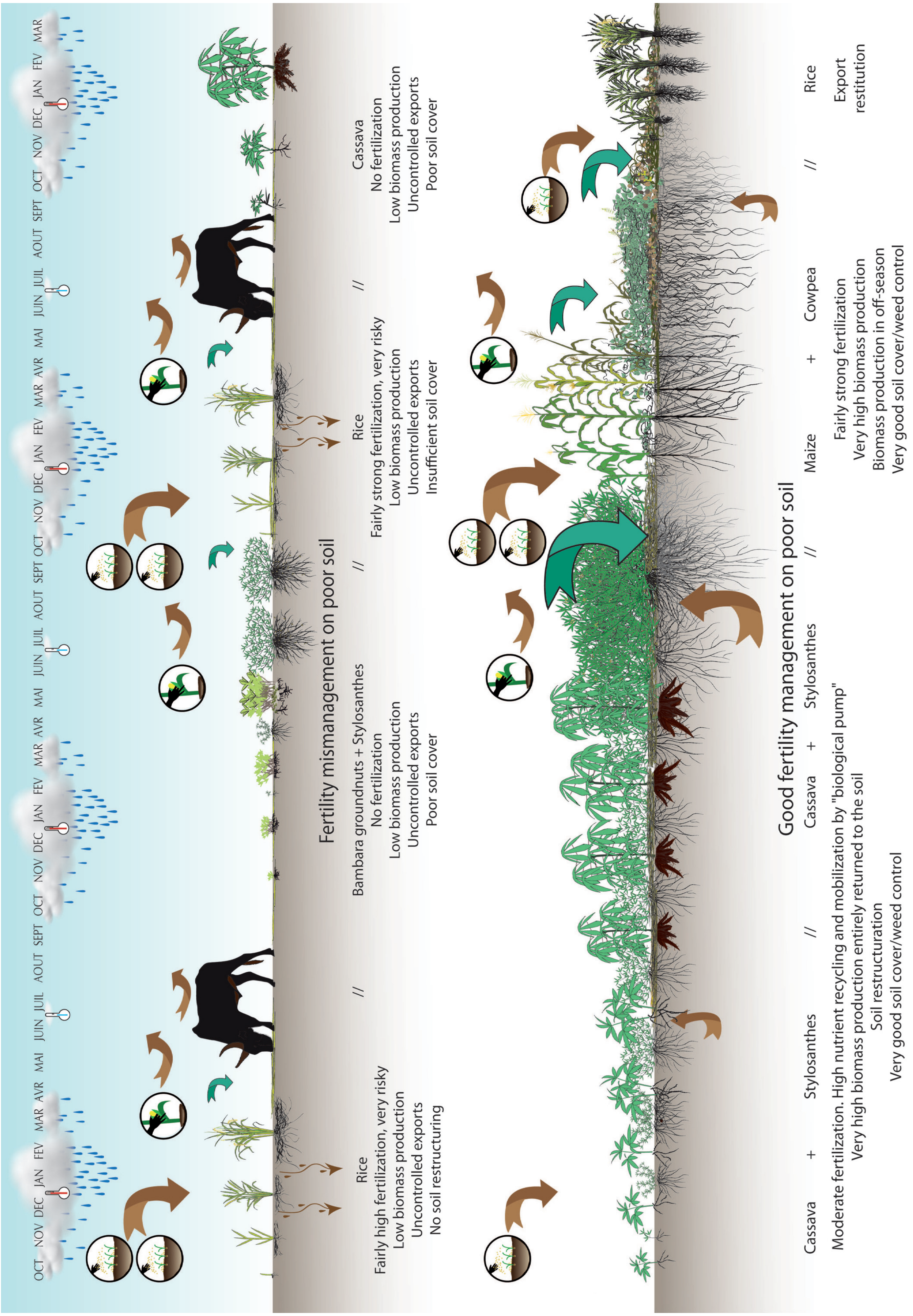
Once fertility is accumulated in the biomass, litter and superficial soil layers, soil fertility management in DMC systems is reduced to maintain fertility and to ensure a rapid turn-over of organic matter (by a regular biomass production of varying quality).
This fertility maintenance is done by:

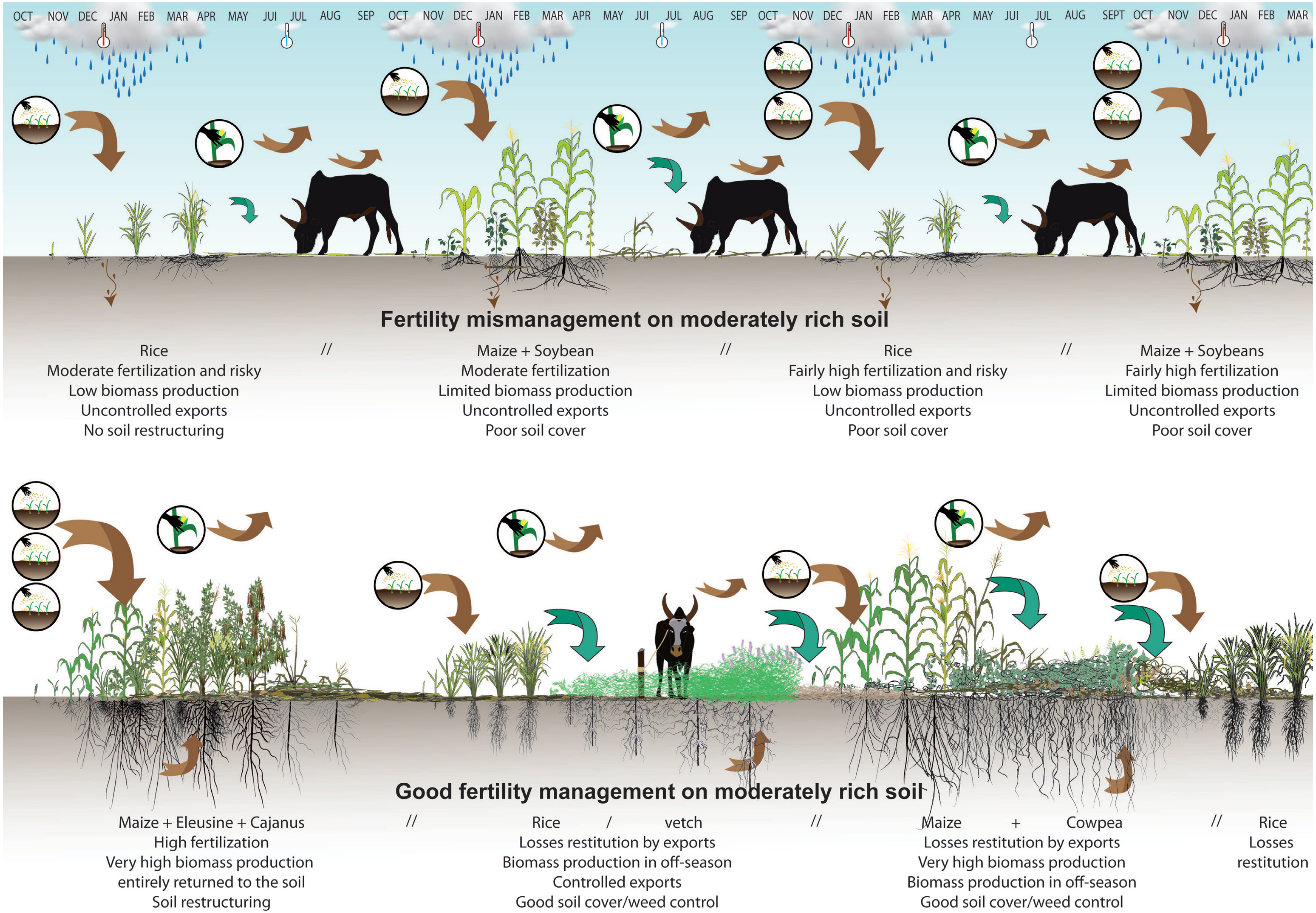
* using in the cropping system, nitrogen-fixing plants and/or promoters of mycorrhizal development;
* using «biological pumps» to limit losses by leaching (especially during sensitive periods) and to solubilise the elements that could be immobilized within the soil; and
* loss compensation (mainly exports by grains, tubers or fibres, and possibly straw), by mineral and/or organic fertilizers inputs.

A simple calculation based on the quantities harvested, the forage exported and the average contents of elements in various plants, allows the evaluation of exported quantities and to compensate them with an equivalent fertilizer input in the following season.
The main difficulty is the need to anticipate a drop in biomass production, in order to avoid it. Insufficient biomass production, which does not allows the cover of losses, risks to «disarm» DMC systems and complicates their steering in order to restart production.
In the absence of analytical tools (very expensive), the field «pilotage», in order to avoid «undermining» the restored fertility, can be achieved by:

* precise tracking of yield evolution and observation of scarcity signs on the most demanding crops (unexplained yield drop, deficiency symptoms, etc), indicating that the system is trying to «succeed» and that fertilizer provided is not sufficient;
* establishment of «witness» crops in which plant density is greatly increased (doubled). With such a density, plant extracts are more important than in a «normal» plot and signs of deficiency will appear before the crop seeded at a normal density suffers from it. At the onset of deficiency symptoms on the witness crop, it is possible to complete plot fertilization before the crop suffers yield loss (simple prevention technique).


Restoration of fertility
(DMC establishment)
Use of "biological pumps"
N fixation, recycling, mobilization
Controlled burning
Input of mineral/organic fertilizers
Very high biomass production
Restitution >>> mineralization
Litter
Grain export only
Fertility maintenance
(established DMC, restored soils)
Compensation of exports by fertilizer inputs
Grain export
Fodder export
Restitution ≥ mineralization
Nitrogen fixation
Recycling elements in depth
"Biological pumps"
Microflora
Solubilization Mobilization of fixed elements
Fertility concentrated in biomass/litter
Regular mineralization
Rapid turn-over
Nitrogen fixation
Recycling elements in depth
"Biological pumps"
Microflora
Solubilization - Mobilization of fixed elements
N_2
NH_4^+
NO_3^-
Ca^{2+}
K^+
Mn^{2+}
Zn^{2+}
PO_4^{3-}
Na^+
Mg^{2+}
CO_2
SO_4^{2-}
Biomass and fertility management in an ecosystem cultivated under direct seeding mulch-based cropping system


OCT NOV DEC JAN FEV MAR AVR MAI JUIN JUIL AOUT SEPT OCT NOV DEC JAN FEV MAR AVR MAI JUIN JUIL AOUT SEPT OCT NOV DEC JAN FEV MAR AVR MAI JUIN JUIL AOUT SEPT OCT NOV DEC JAN FEV MAR
Fertility mismanagement on poor soil
Rice
Fairly high fertilization, very risky
Low biomass production
Uncontrolled exports
No soil restructuring
//
Bambara groundnuts + Stylosanthes
No fertilization
Low biomass production
Uncontrolled exports
Poor soil cover
//
Rice
Fairly strong fertilization, very risky
Low biomass production
Uncontrolled exports
Insufficient soil cover
//
Cassava
No fertilization
Low biomass production
Uncontrolled exports
Poor soil cover
Good fertility management on poor soil
Cassava + Stylosanthes // Stylosanthes // Cassava + Stylosanthes // Maize + Cowpea // Rice
Moderate fertilization. High nutrient recycling and mobilization by "biological pump"
Very high biomass production entirely returned to the soil
Soil restructuration
Very good soil cover/weed control
Fairly strong fertilization
Very high biomass production
Biomass production in off-season
Very good soil cover/weed control
Export
restitution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Fertility mismanagement on moderately rich soil
Rice
Moderate fertilization and risky
Low biomass production
Uncontrolled exports
No soil restructuring
//
Maize + Soybean
Moderate fertilization
Limited biomass production
Uncontrolled exports
Poor soil cover
//
Rice
Fairly high fertilization and risky
Low biomass production
Uncontrolled exports
Poor soil cover
//
Maize + Soybeans
Fairly high fertilization
Limited biomass production
Uncontrolled exports
Poor soil cover
Good fertility management on moderately rich soil
Maize + Eleusine + Cajanus
High fertilization
Very high biomass production
entirely returned to the soil
Soil restructuring
//
Rice / vetch
Losses restitution by exports
Biomass production in off-season
Controlled exports
Good soil cover/weed control
//
Maize + Cowpea
Losses restitution by exports
Very high biomass production
Biomass production in off-season
Good soil cover/weed control
//
Rice
Losses
restitution

2.3. How to provide mineral and/or organic fertilization

High production of brachiaria fertilized on degraded soil

Crop fertilization or «biological pump» fertilization?

When crops and cover plants are intercropped, putting the fertilizer at the foot of the main crop can help to manage the risks of competition between plants, by favouring the commercial crop. However, generally, crop fertilization, whether localized or distributed over the entire field, also benefits cover crops. These «biological pumps» use the fertilizer appropriately, allowing them to produce a very high biomass, and they contribute back to the good functioning of DMC systems and to supply the subsequent crops, after this biomass mineralization.

When crops and cover plants are grown in crop sequence, the «biological pumps» benefit from the effect of the previous fertilization provided to the main crop. The early years of transition from traditional systems to DMC systems, the fertilization is mainly to the crop (at least 2/3 on crop normal fertilization and 1/3 on the cover plant) and is essential (especially if the soil is poor). By contrast, once DMC systems are established and running on a high quantity of biomass/litter, it is possible to obtain a better use of mineral fertilizers by giving the majority (two thirds) to the «biological pumps».

These «biological pumps» will transform the mineral fertilizer into organic fertilizer which, therefore, will be stored and released gradually to the main crop and that will be supplied in a more regular way. However, the conditions to access credit in the case of a small family farm (interest rates, loans duration, and requested guarantees) are often very restrictive. The implementation of this management principle for the agricultural optimization of mineral fertilization is difficult under these conditions. Moreover, the adjustment of fertilization to the climatic conditions of the country, or to unforeseen events, may only cover that part of the fertilizers that has not yet been applied.

Avoiding nitrogen blockages

On a mulch poor in nitrogen (without legumes), the mineralization process (which in time will release soluble nitrogen) can cause, at first, a significant nitrogen immobilization (used by bacteria). A cereal (or cotton), established in such cover, has a strong risk of «nitrogen hunger» in the beginning of the cycle, which could be very detrimental to its development. To avoid this phenomenon, we can:

* prepare legume-based covers if we wish to establish a cereal or cotton crop;

* control the cover several weeks before crop establishment, which will allow the release of nitrogen at sowing time, which happens while the mineralization process is already occurring. However, it is not always possible to treat such cover on time, and therefore we must:

* apply nitrogen (30 to 50 kg N/ha) when sowing, which is essential for all cereal or cotton crops on a grass mulch that is beginning its decomposition.

High biomass production of stylosanthes

3. Soil structure management in DMC systems

Soil restructuring by powerful root systems and biological activity
Maize on desmodium

On compacted soils, the establishment of efficient DMC systems goes through a rapid soil decompaction. In year "zero" of DMC preparation, the use of mechanical decompaction (sub soiling) requires specific equipment and is very expensive. It can only be considered for crops with high added value. It is better to use cover plants able to perform this function quickly (such as eleusine, brachiaria, cynodon or sorghum) established in year "zero" of DMC preparation (often after tillage). These plants, thanks to their powerful root system and to their ability to promote the development of a high biological activity, enable the soil to quickly re-establish a favourable structure. Their high biomass production equally supplies the organic matter storage and aggregation processes, necessary for the creation of a sustainable and good structure.

Before soil has been de-compacted by restructuring plants, it is preferable to intercrop them only with compaction-tolerant crops, either because of their strong root systems or because they are happy with superficial rooting. The greater constraint is the climate, the greater risk is the implementation in year "zero" of demanding plants such as rice, which require good macro porosity and significant amounts of water.

Subsequently (in established DMC systems), all crops are possible. The strong biological activity, the replenishment of soil carbon and the plant cover (protective role) contribute to the maintenance of good soil structure. However, some intercropping/ crop successions are not always sufficient to sustain a favourable structure. In such a situation, the temptation to use tillage is often strong, but it presents many disadvantages, such as: a rapid loss of several benefits obtained over the years without soil disturbance. It is much more efficient to regularly establish (every 2-5 years) plants with a high re-structuring power in the cropping systems.

4. Weed management in DMC systems

Weed management is crucial in early years, during the transition from conventional practices to DMC systems. When the biomass production is insufficient (especially in the early years, in soils with low fertility) to assure a good soil cover, the temptation to use tillage again is often strong (people lacking experience in managing these systems). It is essential to avoid returning to tillage and to implement those practices (without tillage) that allow good weed control (perennial and annual) during the transitional years. The choice of crops and intercropped plants at the beginning should take into account the flora that is present, and focus on producing a high biomass to control this flora, by possibly using the plant covers' allelopathic properties. In all cases, the first step is to control perennial plants.

4.1. Control of perennial plants in year "zero"

Pre-existent perennial plants are very competitive with annual plants (crops), even if they have been mowed or tilled (in particular, plants with rhizomes and/or runners):

- they start their growth generally faster than annual plants which start from seeds, and thus perennial plants quickly dominate annual crops;
- their root systems are often stronger and deeper than that of annual plants and they become competitive for water and nutrients.

In addition, weeding these perennial plants during cultivation is difficult and their chemical control requires the use of selective specific herbicides (very expensive and/or unavailable in Madagascar). It is therefore essential to control these perennial plants before crop establishment.

When using living cover (bean or black eyed pea on cynodon, for example), the control is usually done with a total herbicide at a reduced dose. The aim is to slow the perennial plant growth for sufficient time (ap-

Establishment of black eyed pea in Cynodon dactylon controlled by herbicide

proximately 45 days) in order to allow the crop to develop and dominate the living cover, but without killing the latter, so that it redevelops naturally after the main crop harvest. For DMC establishment on dead cover (or on living cover systems but with a perennial plant), perennial plants must be completely controlled. This control is done by:

* application of total herbicide at a high-dose (preferably at the end of the preceding rainy season, on active vegetation plants before flowering and which should pass through the dry season);

* tillage in the beginning of the dry season, coupled or not with an application of total herbicides, at a low dose, then once again tillage and pulling out any surviving plants.

For perennial plants particularly resistant (*Cynodon dactylon, Cyperus rotundus, Imperata cylindrica,* etc), control may be completed by the establishment of plants particularly effective in cleaning plots, such as vetch, mucuna or stylosanthes.

Once perennial weeds are eliminated from the plot, re-infestation is prevented by manual control or localized application of total herbicide on possible new shoots (before they can be able to produce seeds). Weed control in DMC systems, therefore, consists mainly in the control of annual weeds.

4.2. Control of annual weeds

During the year “zero” of DMC preparation, the control of annual weeds is done mainly by tillage and, if necessary, by herbicides. Established intercropping plants must allow the reduction of weed pressure. Nevertheless, they complicate the use of selective herbicides. If, in the year “zero”, the control of the plant cover is insufficient, and if intercropping does not allow the use of selective herbicides, hoeing, or preferably, manual weed control becomes necessary, which requires a considerable amount of work. When weed pressure is high, it is then better to first establish a crop easy to weed (such as corn or sorghum), intercropped with plants that quickly cover the soil (voluble legume, for example) and/or those that have a marked allelopathic effect (such as oats). Operational sequence can also be adjusted to control annual weeds better: high density to quickly cover the soil, very early seeding, short-cycle varieties, etc. Some weeds with particular characteristics and that can be real nuisance plants (such as striga) can be controlled by specific systems.

In the following years, on an established DMC, the control of annual weeds is primarily done by plant cover, which, if sufficient, prevents the re-appearance of most weeds, either by shading effects or by allelopathic effects of the cover plants used. The more the soil plant cover is regularly supplied, and the more the plant cover contains «cleaning» plants (capable of dominating others), the better the control.

In case of some plant re-growth (especially if there is a fallow period permitting this re-growth), the application of a total herbicide at a low dose before crop establishment is sufficient to prepare the plot. The absence of soil tillage means that seed stock is not remounted in favourable conditions for germination. Only weed seeds produced in the plot in the previous cycle, and those transported by the wind or by animals, are able to germinate.

Weeds control by a thick mulch
Photo : K. Naudin

If the cover plants are regularly fed, in sufficient quantities, weed pressure gradually decreases. However, if the cover plants do not adequately cover the soil (DMC systems poorly mastered, crop mishap, very strong economic interest to export biomass, etc), weed control needs the use of selective herbicides (when they are available) or manual pulling out of weeds (before seeding). Hoeing should be avoided, whenever possible, because it disturbs the soil, accelerates mineralization, and, consequently, reduces cover vegetation and has the risk of increasing weed intensity (and also the risk of losing the agronomic benefits of the previous years in DMC). Maintaining a soil cover, as permanently as possible, is therefore a key point in weed control.

4.3. Control of cover plants

To avoid a cover plant becoming an undesirable weed, its management must be adapted to the cropping system. Generally, the cover plants should not produce seeds when we wish to cultivate the plots again, except:

* in the case when we expressly wish that the plant cover, which will be killed in order to establish the crop, can re-install itself naturally without the need of re-seeding. This case is limited to plants with a slow start (such as stylosanthes or vetch), which are therefore unlikely to compete with the next crop;

* if we have a selective herbicide specific to the established crop, that controls the cover plant properly.

In all other cases, the more «aggressive» the cover plant, and the more it is a species similar to the established crop (thus making it very difficult to control with selective herbicides), the harder it is to control it in the next crop and the more important it is to avoid its seed production.

Oats: «cleaning» plant with significant allelopathic effects

5. Bioaggressor management in DMC systems

5.1. Management of nuisance fauna

Managing insects and other noxious animals (slugs, nematodes, etc) in DMC is primarily done through a balanced nutrition (which reduces the accumulation of reducing sugars and free amino acids in the plants, much appreciated by insects) and through integrated pest management principles, by:

* establishing an ecological balance in order to allow the development of auxiliary populations, that are predators of crop pests;

* using plants that are insecticidal, nematicidal and/or repulsive in the cropping systems. The more intense the pest pressure, the more we seek to include in the system plants that will control them;

* creating, via DMC practices, a favourable environment to the development of entomopathogenic organisms (Beauveria sp., Bacillus thuringensis, etc) and possibly by their inoculation.

However, establishing an ecological balance and a balanced nutrition demands time (from several months to several years, depending on the ecosystem degradation state). During the early years, until such equilibrium is reached, pest control is done by:

* using crops that are minimally sensitive to major pests as much as possible (we can start, for example, with leguminous crops in environments infested by Heteronychus sp.);

* a reasonable use of pesticides.

Pesticides (especially those with a wide spectrum), are unfavourable to establish an ecological equilibrium, their use should be kept to a minimum, and used exclusively in case of very high pressure on sensitive crops, and if possible with the least harmful treatments (preferably seed treatment, being the active material, the most selective as possible, in a low dosage). Soil treatments, particularly harmful to the soil fauna and microflora, should be avoided whenever possible.

5.2. Management of virus, bacteria and fungal pathogens

Similarly, the major diseases are controlled in DMC systems by improving plant nutrient status and microflora activity (secretion of elicitors, antibiotics, etc). The time it takes to restore the soil biological activity, disease control (especially fungal diseases) is done, above all, by:

* the use of resistant varieties and species, mixed together;

* the input of staggered organic fertilization, as much as possible, to avoid mineral nitrogen peaks in the soil (and consequently in the plants).

The use of fungicides, as with other pesticides, is limited to a strict minimum, since their impact on microbial activity is extremely negative. If the fungal pressure is such that a treatment is indispensable, it must be done in the least harmful way (seed treatment, at a low dose, with an active ingredient the most selective as possible). Pesticide use in high doses, even with a short-term positive effect, has very negative effects on plant health, in the medium-term, due to its impact on soil biological activity and on plant physiology.

6. Management of work schedule and equipment in DMC systems

Generally, DMC practices and their diversity provide a very flexible management of work schedule. In DMC systems, the three main workloads are the cover treatment before seeding, seeding and harvest.
In manual agriculture, cover treatment can be done relatively early, according to workload constraints. In particular, it can be done during the dry season when a farm's workload is generally lighter. Moreover, the possibility of sowing crops in the dry season, or at the very beginning of the rainy season, allows the split in the workload between plot preparation and sowing. This enables the very early establishment of crops.
The equipment required in small family farms is limited to a backpack sprayer (which can be shared by several farms), useful for phytosanitary or herbicidal treatments.

In mechanized farming, only sowing equipment is specific to DMC systems, because it must allow direct seeding in the mulch. There is a wide range of seed drills (and sprayers): manual, with animal traction, with small and large machinery. The absence of tillage limits the power required (and, therefore, the investment), and significantly reduces equipment wear and fuel expenses. Mechanization cost is consequently much lower in direct seeding compared with conventional mechanized agriculture.

Moreover, the better load-bearing capacity and the rapid surface drying of plots allows entry to the plots with heavy equipment, at almost any time, needing to wait just a few hours after heavy rains. This particularly enables the optimal treatments by applying them at the best moment.

Very healthy rice after stylosanthes
Photo : Rakotondramanana

Finally, it is possible to quickly harvest a crop while broadcast seeding another plant (adapting a seed drill on a harvester), which permits the establishment of crop succession in minimal time, even during the busy harvest period.
Work management (and of equipment) in DMC systems is therefore reduced to spliting high workload periods (cover control, sowing and harvest) by "playing" with species cycle and varieties at the farm level, in order to avoid the overlap of important tasks or competition with other activities.

7. Crop/Livestock integration in DMC systems

Direct seeding mulch-based cropping systems are based on the optimization of production and management of biomass, and they favour organic matter intake. These systems must be, consequently, integrated with livestock farming systems, particularly those of large animals (cattle, sheep, goats, pigs, etc), which are both biomass consumers and organic fertilizer producers, and can also provide the labour force used by cropping systems.

According to each situation, and particularly according to biomass production possibilities and to the importance of livestock farming in the agricultural system, crop-livestock integration can be done easily and it can represent an "entry", or contrarily an obstacle, for the transmission of DMC technology. In all cases, DMC systems must be planned according to the role of livestock on the farm, and at the village territory level. This adaptation is particularly based on the type of livestock farming and on fodder resources community management (or not).

A. pintoï *: a cover crop that tolerates heavy grazing*

7.1. Adaptation of DMC systems to the pressure on biomass (fodder needs)

In environments where the pressure on biomass is relatively low (few animals to feed compared to available areas and production potential), crop-livestock integration does not cause a problem. Feeding animals is not done at the expense of biomass restitution to the soil, and livestock can easily be used on cropping systems, providing workforce and, above all, quality organic fertilizer. Improving integration between agriculture and livestock is done primarily by animal management: facilitating their feeding (possibly through fodder within DMC systems) and stable-manure collection, improvement of animal health (feed and veterinary care), etc.

When animals pressure and the needed fodder increase, crop-livestock integration must be done in order to optimize biomass use. It depends primarily on the possibilities of increasing total biomass production thanks to DMC practices, on the economic interest of livestock versus the economic interest of crops, and on the resources management at the ter-

Weakening of B. ruziziensis *by heavy grazing* ritory level. Many possibilities exist, more or less easy to manage, depending on the situation. They must be locally adapted, on a case-by-case basis.

When stocking rates approach the maximum that can be supported by the environment (without over-exploitation), regardless of its management, crop-livestock integration becomes particularly delicate and depends largely on the comparative interest of crops versus livestock and on resources management at the territory level. Only an optimal management of fodder crops, capable of returning back to the soil a sufficient amount of carbon through their root system, and whose exports are compensated by fertilizer inputs, allow the maintenance of soil fertility. Such management is only possible if resources are handled individually and if livestock is a major source of farm income (as in dairy farming), allowing a certain intensification (restitution of exported nutrients).

Beyond this threshold stocking rate that the environment can withstand, livestock is “mining” , drawing on soil fertility and causing its rapid degradation. Systems cannot be sustainable, regardless of their management.

7.2. Adaptation of DMC systems to fodder resource management

The more stocking increases at the territory level, the more resources management must be refined. Optimization of biomass production, which is done primarily by intercropping/crop sequences and by fertilization management, can only be done if the benefits from these practices return to those that have established them (individually or collectively).
Thus, common grazing, a very frequent practice which allows animals to «roam» on plots after harvest, is a major obstacle, limiting the possibilities of having good biomass management.

This obstacle may be eliminated by:

Cassava + Brachiaria

* modifying the local rules, in order to protect biomass on plots of those that give priority to their crops and want to use the available biomass for soil regeneration, by DMC practices. Such modification of local rules requires an understanding of the interest of maintaining a high soil organic matter rate, and a collective awareness of the impact on soils and crops by excessive biomass exportation. However, some «big» livestock producers might oppose this because they have a large number of animals to feed, and cannot ensure feeding solely from their farms, and often have a strong influence in collective decision-making due to their status given their large stock holding. This option is also very difficult to implement in the case of itinerant livestock;

* implementing, in cover plants, crops for all seasons (such as cassava, for example), which can prevent animals from accessing plots (according to local rules). The «crop», so established, can be extensively managed, with very low density and no investment. Its main interest is to protect biomass rather than to obtain any production (very random when outside of the normal cropping period);

* using cover plants unpalatable to animals, such as crotalaria. This option has the advantage of being applicable in all situations, but severely limits the systems’ possibilities and does not allow a partial export of biomass to feed farmers’ animals.

7.3. Adaptation of DMC systems to the type of livestock farming

Depending on farming vocation, the integration possibilities with DMC systems are more or less varied, and more or less easy to implement.

Intensive commercial livestock farming (dairy or meat)

This type of livestock farming, although having the disadvantage of a strong biomass export, has the advantage of being individually managed and often with animals' confinement, which allows a good fertility management: production of quality manure and incomes (generated from products sale) that permit reinvestment in fertilizers in order to maintain plot fertility (used primarily for fodder production). In these farms, with the dominance of fodder production, pasture regeneration through intercropping in DMC systems, is an interesting option.

Extensive commercial livestock farming (dairy or meat) and crops

For mixed crop-livestock farms DMC systems offer many possibilities. Systems that use intercropping and crop sequences allow (in varying degrees) the increase of available fodder. Fertility management is facilitated by livestock farming incomes and by the operating sequence (stable feeding allowing production of good quality manure). The fodder crops component can be adjusted according to the varying prices of livestock products and crops.

The main difficulty is to obtain a good balance between restitution and use of biomass as fodder, particularly during the early years, when most production must be returned to the soil in order to enhance it. One must also resist the temptation to increase stocking at the expense of soil restitution, and especially when prices of livestock products are comparatively more interesting than agricultural ones.

Livestock farming for animal-draught power

Draught animals are generally low in number but they benefit from a lot of attention in order to assure a good diet and good sanitary conditions. The integration into DMC systems can be done by fodder production, particularly during key periods (before major tasks), and by reducing the needs for draught power. Manure production contributes to restoring exported nutrients.

Livestock farming for «Capitalization»

The social status given by the ownership of animals is very important in many southern countries. Moreover, the saving role of animals is often prominent. Consequently, owning animals is frequently an essential component of capitalization. Frequently, these animals use community resources that are very difficult to manage. Common grazing allows animals to eat most of the year on resources that are not individualized. When stocking at the territory is not very important, fertility can be maintained at this scale. However, when stocking increases, pressure becomes too strong and this kind of production "mines» natural resources. Unfortunately, in a framework where the community use of resources (common grazing), when the environment is very restrictive (se-

Free grazing after harvest
Lake Alaotra

Feeding park of draught cattle

mi-arid climate, for example) or is being degraded, and when crops are not lucrative, farmers very frequently "adopt" this "mining» type of livestock farming to take advantage of common resources.

Thus, very large herds are found in semi-arid environments, where the low potential of biomass production should limit the number of animals. These animals are often forced to travel long distances to feed themselves (itinerant livestock), which further reduces livestock farming systems performance. In such a situation, with severe resource shortages and lack of opportunities to manage these resources, crop-livestock integration is particularly difficult. The only possibility of maintaining a sufficient soil biomass is using cover crops unpalatable to animals.

8. DMC systems and trees

DMC principles, which copy the functioning of a forest ecosystem, allow the integration of trees in diverse ways into the systems, becoming agro-forestry systems (with soil permanent crop cover).

8.1. Soil restructuring before planting

On degraded and heavily compacted soils, restructuring the soil with very powerful grass root systems (such as Brachiaria brizantha cv. Marandu) is a prerequisite for any shrub plantation (reforestation, orchard planting) in good conditions. When using leguminous trees (acacia, etc), nitrogen fixation enhances rapid grass growth and helps to fulfil, even better, its decompaction function.

Acacia plantation after soil restructuring by brachiaria

8.2. Soil protection in orchards and plantations

Soil cover by perennial plants protects and enriches the soil and controls weeds in orchards and plantations. Living covers are preferably established before trees are planted. They must be able to survive in intense shade (as Arachis repens) in order to assure their functions, particularly in dense tree plantations, that allow little light penetration.

Creeping vines (such as *Arachis pintoi, Stenotaphrun secondatum, Axonopus compressus*), once planted, require little maintenance (possibly, their control around trees in case of water deficit). Erect plants (such as *Stylosanthes guianensis* or brachiaria) can be mowed around young trees to avoid competition for light, and possibly controlled (chemically or mechanically) around trees in case of competition for water. Voluble plants (such as pueraria) should not be planted close to trees since their control requires arduous and frequent work.

Leguminous covers, thanks to their atmospheric nitrogen fixation that benefits trees, are particularly advantageous. In dry environments, the establishment of plants capable of remaining green for a long time in the dry season (such as stylosanthes) limits the risk of the spread of fire.
Part of the biomass produced can be used to feed animals after mowing (especially when trees are still young) or grazing (when trees are no longer at risk of being damaged).

8.3. Planting high value-added trees

In DMC systems, intercropping annual plants with trees, before they close their canopy, allows production in the early years after plantation, when trees are not yet producing but still allow light penetration. It also allows the establishment, at a lower cost, of perennial plant cover under the trees. Similarly, planting productive trees in the medium term (fruit, rubber, coconut, etc) intercropped with species with very slow growth but with high-value (teak, dipterocarps, albizia, etc) permits a regular income during the long growth period of these valuable species. Besides the considerable benefits obtained in the long term, intercropping allows us to protect biodiversity by producing these rare species rather than exploiting them in their natural environment.

Peach orchard on clover cover

9. Risk Management and DMC systems

Risk management is a crucial issue in agriculture, and particularly in the context of small family farms. In general, DMC practices in well-installed systems greatly reduce risks and ensure a stable and resilient production:

* climate risk is reduced due to a large amount of usable water, buffered temperatures, calibration of crop cycles in the optimal periods, species mixture and/or variety, etc. It is even possible to manage crops with a limited risk in zones and/or periods where they would not be not possible (or at a very high risk) in conventional agriculture;
* weed and pest pressure is generally reduced;
* production costs (and thus investment) are low once properly installed systems can operate with minimal input;
* production diversity reduces agricultural risks and the economic risk of market fluctuations, etc.

The main risk to manage is consequently the one linked to the transition from conventional to DMC systems, during the first few years, until the ecosystem functions are operational. This period is even more critical since it requires an increase in soil fertility (and therefore an investment in time and/or inputs) and working time to conduct these systems is only significantly reduced once the systems work properly, after accumulating a high amount of biomass. However, once past the first years (always with the temptation to return to soil tillage when a problem occurs), when farmers master direct seeding techniques and reap direct seeding benefits they rarely abandon it.

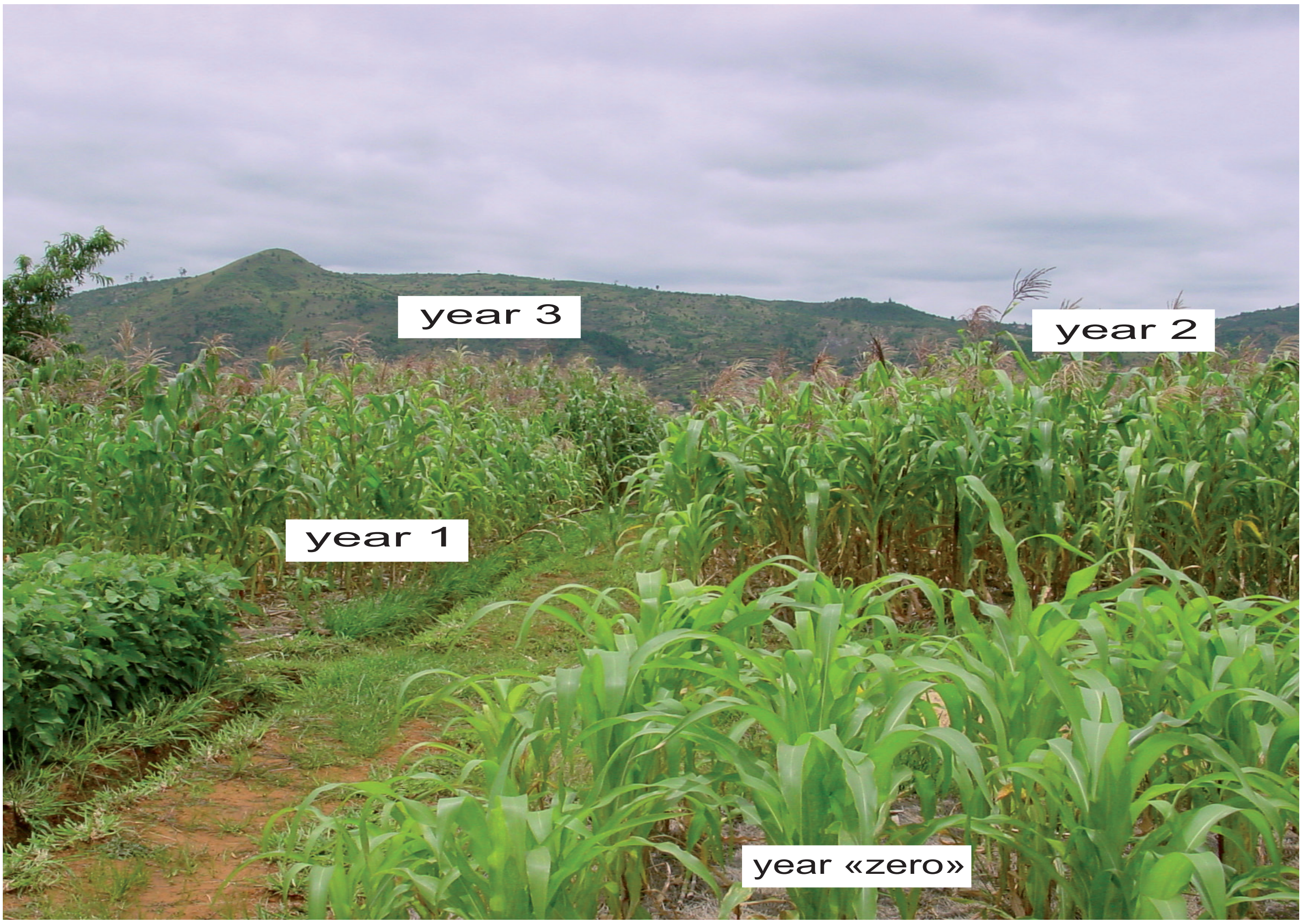
This transition stage is particularly sensitive in small family farms, whose investment means are limited as well as their capacity to take risks. The most risky investment, because of their high cost, is firstly fertilizers. In order to minimize the risk, this expense should only be made when the risk of failure is limited, therefore, when all conditions of success are gathered in time: cropping system adapted to conditions, early sowing in the most favourable period (including, if necessary, avoidance of hail or hurricane risk periods), available methods to control weeds and bioaggressors, etc.

In addition to these agronomic factors, two other factors, more difficult to manage, must be faced:

* production safety. An increased risk of crop theft (unfortunately common in Madagascar) is a significant obstacle to increase agricultural production (regardless of the method). By increasing the risk of not being able to pay back investments, the interest in intensifying production comes down.

* land tenure security. The risk of not being able to benefit, in a medium-term, from the effects of these improved practices reduces the interest to invest in plot fertility in the long-term (unless the investment can be profitable in the short-term, such as controlled burning with potatoes or cassava + brachiaria intercropping, which has profound effects on cassava's yield during the same year).

The higher the risk of failure and the lower the ability of the farmer to bear a failure, the higher the needs to turn towards systems with low investment (and therefore less risk): hardy crops, progressive restoration of fertility by using «biological pumps», etc.



Increasing yields within direct seeding years

10. Complexity and apprenticeship in DMC systems

DMC practices require a certain amount of knowledge, particularly about plant material and control of its management, which is acquired gradually. A learning period is therefore necessary.

On the other hand, among the wide range of DMC systems, there are highly variable levels of complexity. Some systems, such as those based on mulch with Stylosanthes guianensis are extremely simple to implement, offer great flexibility, are applicable in many situations and/ or are little affected by operational sequence changes. Conversely, other systems such as those on live cover (very effective) demand an excellent technical mastery, specific inputs, a calendar, and a very precise operational sequence, etc.

Direct seeding training plot in school

During the learning period (whether that of managers, technicians or farmers), it is best to start with the simplest possible systems, even if their production potential is lower than those of more complex systems. A simple system well-managed is more productive than a mishandled complex system!

Gradually, with an increasing knowledge about plants and systems technical master, it becomes possible to have more complex systems: introducing a greater number of plants in order to diversify ecosystem functions performed by these systems, to have a more refined management, with more specific inputs, etc.

11. Conclusions. Integrated management of DMC systems

DMC systems, by their diversity and the multi-functionality of plants on which they depend, allow us to:

* ensure indispensible functions for the good functioning of the ecosystem;
* deliver many ecosystem services free

These systems operate, above all, as a whole and must be managed in an integrated manner in order to assure its multiple fundamental functions. Thus, fertility management cannot be separated from weed and pest management, and must take into account livestock needs or market conditions, for example.

Besides an overall management of ecosystems cultivated under DMC, it is necessary to consider cropping systems over time, over several years, in order to:

* assure sufficient biomass production for direct seeding, every year. In particular, one must keep permanently a biomass sufficient to control weeds and to maintain fertility, and thus, always anticipate for insuring good conditions for the next season. However, it is possible, for example, to produce plants of great interest for farmers but that produce little biomass, with the condition of producing a great amount of biomass in the previous year and/or to establish a plant in succession which will allow the production of sufficient biomass before next crop;

* manage fertility over time by alternating plants with different functions and needs, starting with plants able to remove major difficulties (compaction, low fertility, acidity, weeds, etc);

* control weeds. The control of perennial plants sometimes must be done several months before establishing the crop in year "zero", at the end of the preceding rainy season. Subsequently, weed control starts primarily by annual weeds thanks to the permanent plant cover, and therefore, it is closely linked to the previous crop.

This integrated management, in space and time, depends primarily on the choice of crops and plants intercropped or in sequence in the cropping system, and partially, on the operational sequence choice. It requires accurate monitoring and refined observations of the plot's changing conditions.

Beans after oats

Maize + Stylosanthes intercropping

The diversity of plants and systems provide opportunities to adapt to the major agronomic constraints (climate, soil, etc) and socio-economic (biomass pressure, available resources, market conditions, etc). However, each constraint reduces the number of possible systems and/or their performance and interest. The more the constraints (level of environmental degradation, pressure on biomass, markets, etc) are numerous and strong, the more difficult and complicated it is to design and implement systems that quickly remove all these constraints. Flexibility is reduced. Therefore, it takes time, and the introduction of these systems is more difficult and slower than in less restrictive environments, that offer a wide range of possibilities.

Principles, functioning and management of ecosystems cultivated under Direct seeding Mulch-based Cropping systems (DMC)

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