NEW CONCEPTS FOR SUSTAINABLE MANAGEMENT OF CULTIVATED SOILS THROUGH DIRECT SEEDING MULCH BASED CROPPING SYSTEMS: THE CIRAD EXPERIENCE, PARTNERSHIP AND NETWORKS"

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I- Introduction

Conservation-oriented direct seeding techniques include various soil and organic matter management strategies. In most no-till cropping systems in USA and southern Brazil—two regions that account for the greatest area under direct seeding—seeds are mainly sown in crop residue without using any additional cover crops, apart from the commercial crop. Paraná state is the unique situation in this region of Brazil where oats, cropped in pure stands or intercropped with vetch, and ray grass are sown to enhance the biomass production and the soil cover over about a quarter of the cropping area every winter.

In Europe, TCS (*Techniques Culturales Simplifiées*) are often wrongly assimilated with direct seeding. TCS often involves light tillage of the soil surface, whereas this top horizon remains intact in real direct seeding systems, serving a crucial role as an interface for exchanges between the soil and the atmosphere or crops. It is also where organic matter accumulates and various decomposing organisms are active but which are destroyed when the soil is even superficially tilled. Tillage can—depending on humidity conditions when it is performed—also disrupt the physical continuity of the soil profile to the detriment of the crop.

In the humid tropics, the climate is especially harsh, frequently soils are chemically deficient and very susceptible to erosion, and organic matter mineralisation rates are unusually high. In this context, to promote sustainable agriculture, CIRAD had to implement novel organic matter management concepts directly modelled on stable functioning of natural forest ecosystems. The direct seeding principle has thus been bolstered by the concept of direct seeding mulch based cropping systems (DMC). In such cropping systems, the soil is never tilled and must be totally protected by permanent plant cover. Biomass derived from various crop sequences has become increasingly hight over the last 20 years as these systems are continuously improved.

II- Mimicking the functioning of a natural forest ecosystem

The action research undertaken by CIRAD and partners[1], based on the development-oriented research carried out between 1986 and 1992 in frontier farming areas of humid tropical central western Brazil, confirmed the following points (Séguy *et al.,* 1998; Séguy *et al.*, 2001):

- The transfer of tillage techniques from temperate countries to tropical regions does not ensure sustainable management of agrosystems or make them cost-effective. Large monocultures (soybean, cotton) cultivated with disc ploughs have induced catastrophic soil erosion, with the loss of 30-50% of soil organic matter reserves within 10 years. Soil erosion is continuing, and despite the increased use of chemical inputs and implementation

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[1] **CIRAD** team: L. Séguy and S. Bouzinac and Brazilian partners for development-oriented research in permanent collaboration with farmers (*including Mr Munefume Matsubara, the pioneer*), **CNPAF**, the federal rice and beans research center of **EMBRAPA, EMPAER-MT**, the research center of Mato Grosso state between 1986 and 1989; and in partnership with **RHODIA** (Brazilian branch of Rhône Poulenc) and the **COOPERLUCAS** cooperative at Lucas do Rio Verde from 1990 to 1995, and more recently with the **Prefecture of SINOP**, and the group **MAEDA, COODETEC** and the private research company **AGRONORTE** between 1995 and 2002

of crop rotations involving soybean and high-biomass cereals (rainfed rice, maize), the yield capacity of these soils has relentlessly declined with time.

- Direct seeding techniques developed in southern Brazil since the early 1970s, and based solely on seeding in commercial crop harvest residue, are insufficient under hot humid climatic conditions for restoring and maintaining the production capacity of the soil:
  - The decomposition of crop residue, even when there is a high cellulose and lignin content, occurs very quickly and the soil cover can disappear within a few weeks, thus exposing the soil to climatic stress, compaction by heavy machinery, and facilitating weed invasion;
  - Highly active soil organic matter mineralisation processes consume more humus than cropping systems are able to restore, even when grasses account for 50% of the crop rotations (Séguy & Bouzinac, 2001b) ;
  - Root systems of commercial crops are insufficient for restructuring the pore space to enable optimal sustainable development of crops in rotations.

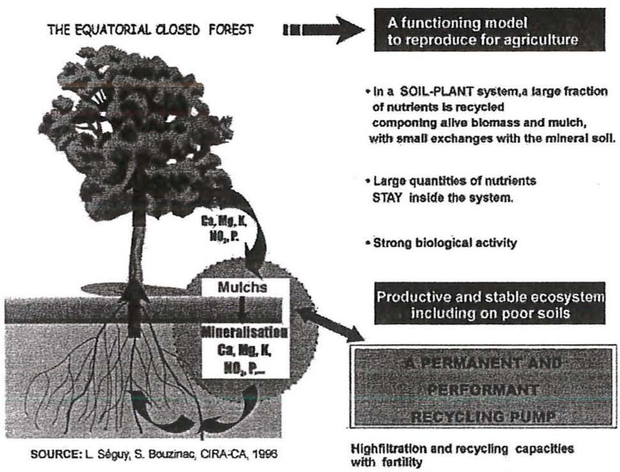


***Figure 1** : The tropical forest ecosystem characteristics : a model to reproduce.*

As an alternative strategy for cultivating tropical soils, CIRAD-CA has developed and implemented new direct seeding techniques based on the natural forest ecosystem model [*Fig. 1*], which is naturally efficient and sustainable in this region. The key features of this natural forest ecosystem are:

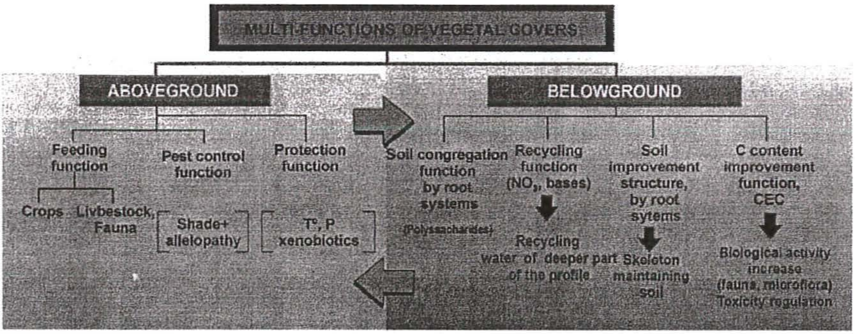
- Total physical protection of the soil by permanent plant cover;
- The possibility of achieving very high primary biomass productivity by making optimal use of soil resources, even on a very chemically depleted and acidic substrate, and by optimising climatic resources (plants growing every time the climate allows it)
- The ability to retain most nutrients in the biomass, not in the soil, through the presence of deep root systems that minimise nutrient loss through their recycling action, and tend to close the soil-crop system;
- Differentiation of the protected surface horizon (0-5 cm), where intense biological activity occurs (micorrhiza and high microbial biomass), and which supplies most nutrients to the roots of commercial crops (Stark & Jordan, 1978).

Under other conditions, natural ecosystems have already served as a model for designing new sustainable cropping systems (Altieri, 2002), but these have generally been perennial cropping systems, involving either trees in agroforestry systems (Ewel, 1999) or forage crop systems in natural grassland regions (Soule & Piper, 1992). The main challenge here was to apply these concepts in annual grain production systems.

III- "Nutrient pump" and "multiple function of cover crops" concepts: steps for the gradual improvement of DMC systems

In practice, we tried—from an advanced degradation stage— to create fundamental transformation dynamics on and within a cropped soil, in order to recover gradually its original functioning mode under natural forest cover, while developing a higher yielding, cost-effective, diversified, sustainable and clean farming system.
This operational reconversion required several steps. It was gradually constructed in direct seeding cropping systems through the insertion of supplementary biomass-generating crops, which are intercropped before or after the commercial crops or in relay. These cover crops have a key role in mimicking the natural forest ecosystem, i.e. they produce biomass during periods when no commercial crops are utilising available resources and they recycle—through their strong and well developed root system—a major share of nutrients which would otherwise be leached away. They have therefore been called "nutrient pumps" (Séguy *et al.*, 1998). The additional biomass that they produce is enough to keep the soil permanently covered, even under humid tropical conditions. Implementation of this "nutrient pump" concept was therefore an essential first step towards the sustainable management of grain cropping systems in these regions.

The performances of these systems were then improved through the "multiple function" concept, which can be applied to additional cover crops (Séguy *et al.*, 2001). In addition to their main features of "nutrient pumps", cover crops can fulfil other agronomic and ecological functions that supplement the action of commercial crops, thus enhancing the efficiency of the whole system [*Fig. 2*].



SOURCE: L. Séguy, S. Bouzinac, CIRAD-CA; A. C. Maronezzi, AGRONORTE, Sinop/MT - 1978/2000

Figure 2: Multi-functions of the cover crops in DMC systems

Some of the main functions include:

- **Aboveground:**
  - **Total permanent protection** of the soil surface against harsh climatic conditions and other stresses: the mulch layer provides a water and temperature regulating shield, a protective screen for fauna and against pesticide compounds, and a buffer to avoid compaction under the weight of heavy equipment or animals;
  - **Increasing water supplies available for crops in the system**: the mulch that these crops will produce plays a key role in reducing runoff and direct evaporation from the soil. The extent of these effects vary according to the crop residue type and quantity (Scopel *et al.*, 1998);

- **A nutritional function** for the main crop (nutrient return to the system via mulch mineralisation, regulated by the C/N and lignin contents of the aboveground and root parts of the crops), for livestock (integration of livestock production, forage value of cover crops) and for fauna and soil microflora (recovery of biodiversity);
- **Weed control function** through shade and/or allelopathic effects (e.g. control of *Cyperus rotondus* via sorghum cover, Séguy *et al.*, 1999).

- **Belowground:**
  - **"Congregating the soil"**: Within the top few centimetres, the well developed root system provides support for the soil, stabilises it and avoids compaction;
  - **Restructuring the soil through the high aggregation potential of crop root systems**: these root systems enhance soil porosity to boost filtration, aeration, and ensure quick drying of the soil profile (rapid drainage of excess water) and a high water retention capacity (microporosity). The soil thus becomes highly resistant to compaction due to the movement of heavy machinery and animals. The soil porosity is efficiently maintained via many galleries left by decomposing roots and the production of highly efficient aggregation substances such as polysaccharides secreted by the roots and vesiculo-arbuscular endomicorrhiza (Doss *et al.,* 1989) which enhance structural stability. *Eleusine coracana, Brachiaria ruziziensis, B. decumbens* and *B. humidicola* are ideal species in this respect, and their roots are highly sheathed in a protective microaggregate sleeve;
  - **Tapping deep ground water**, below the horizon used by commercial crops, as occurs in forest ecosystems during the dry season. This capacity to tap deep ground water reserves enables green biomass production during the dry season, continuous carbon supplies into the deep soil layers because of an important roots production, and maintenance of sustained biological activity throughout most of the year.
  - **Recycling of nutrients leached to deep soil horizons**: closing the "soil-crop" system. Nutrients are drawn up to the surface through very strong root systems, which grow to deep horizons and have a high nutrient and organic molecule capturing potential. This especially involves nitrates, K, Ca, and Mg, along with minerals such as Si and Al, which are critical with respect to the soil mineral composition (Lucas *et al.*, 1993)
  - **Fertility mobilising capacity**: nutrient extraction by the root system, even in very poor and acid soils, and then providing crops access to these nutrients via dry matter mineralisation. For instance, *Eleusine* and *Brachiaria* grass species fix nitrogen in their rhizospheres by utilising non-symbiotic bacteria, and are capable with vesiculo-arbuscular endomicorrhisation to mobilise insoluble phosphorus molecules (Doss *et al.*, 1989). *Cajanus, Crotalaria* and *Stylosanthes* legume species symbiotically fix airborne free nitrogen. These grass and legume crops can be mixed to obtain multiple function "nutrient pumps".
  - **Development of high biological activity**: The high biomass input of DMC systems, derived from both aboveground and belowground plant organs, provide ideal cropping environments, i.e. the soil is protected with very little cultivation, thus favouring the development and activity of soil fauna and microflora. This activity promotes the quality of nutrients recovered in the system and enhances soil porosity.
  - **Disintoxication potential** (bioremediation) against polluting pesticide compounds: a mixed sorghum + *Crotalaria* cover was found to be highly efficient for recycling the compound Sulfentrazone (Séguy & Maeda, unpublished data). Some covers can mitigate aluminium toxicity problems (*Cassia, Brachiaria* and *Stylosanthes* species) or excessive salinity: various organic acids released during cover biomass mineralisation have a high neutralising and complex-forming potential (Miyazawa *et al.*, 2000).

Nutrient pumps, in addition to their multiple agronomic and ecological functions, must meet technical and economic criteria to facilitate their cost-effective and large-scale adoption and duplication by farmers (Séguy *et al.*, 1996):

- user-friendly: sowing, technical control in cropping systems, harvesting;

- high added value: bumper forage and grain crops for livestock feed during the dry season, and also for human consumption (complement for wheat flour, beer brewing, alcohol making, etc.).

All cover crops do not fulfil these different functions with the same degree of efficiency. The most suitable systems are ultimately those that, through the different crops in the rotations, best meet the constraints and production objectives of farmers in a given region. Various options are often identified and tested on farms by the farmers. Through the "nutrient pump" and "multiple function of cover crops" concepts, many DMC systems have been gradually developed under highly diversified ecological conditions as new essential functions are identified, along with the species capable of efficiently fulfilling these functions.

IV- DMC systems with "multiple function nutrient pumps": operational examples

These "multiple function nutrient pump" crops are usually planted at the onset of the rainy season, or they are dried before regeneration to form a mulch layer for the commercial crops, or after harvesting these crops, at the end of the rainy season, when they are harvested and utilised by farmers as an attractive added value crop. These nutrient pumps are chosen on the basis of their ability to tap available runoff water at the beginning of the rains and deep ground water at the end of the rainy season, often under extremely variable rainfall conditions. High biomass production at both the beginning and end of the rainy season is always the main goal (Séguy *et al.*, 1996; Séguy *et al.*, 1998). At the end of the rainy season, when rainfall conditions are suitable and to better tap deep ground water, two high biomass producing species can be intercropped: one is a commercial grass (sowing staggered according to the period of the rainy season and the associated risk, i.e.maize, then sorghum, then millet) the other is a very deep rooting perennial forage species that continues to produce biomass throughout the dry season (*Brachiaria, Stylosanthes* and *Cajanus* species), which can be grazed, thus generating supplementary income for farmers (Séguy & Bouzinac, 2001a). These tree species will begin growing again immediately after an accidental fire, quickly ensuring complete soil coverage.

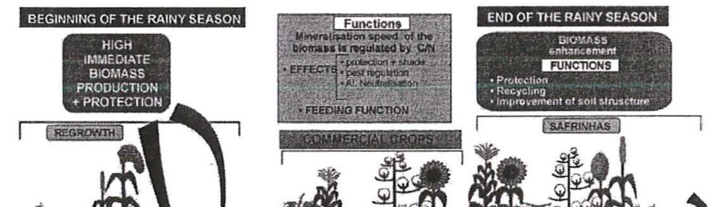


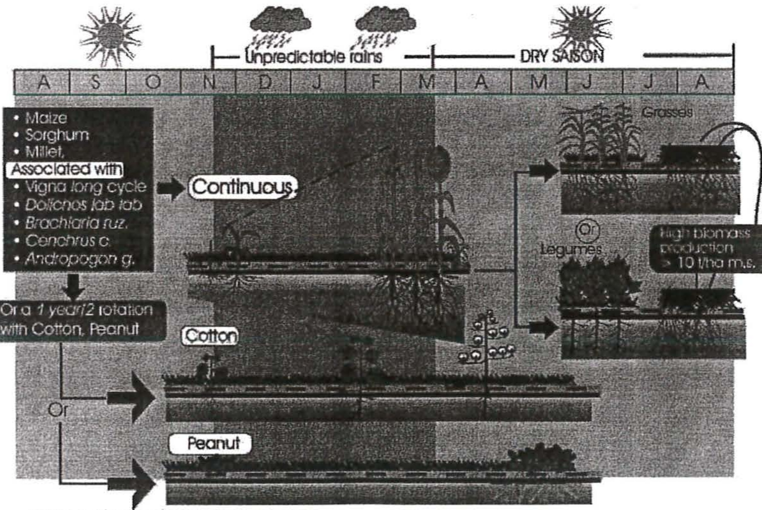
Figure 3 : Some exemples of DMC systems and principles of functionning for the humid Tropics

"Nutrient pump" cover crops can also be perennial species that produce runners and rhizomes (*Arachis, Stylosanthe* and *Pueraria* legume species and *Cynodon, Paspalum, Stenotaphrum* and *Pennisetum* grass species), that form living perennial forage covers whose growth is controlled with very low dosage non-polluting herbicide treatments to keep them from competing with the commercial

crops. They recover full vegetative growth after the commercial crop is harvested and can be grazed during the dry season (Séguy & Bouzinac, 2001a). All perennial species used as live cover are exclusive of annual weeds, thus simplifying the job for farmers, who only have to manage the living cover and the commercial crop in the cropping system.
Intercropped "nutrient pumps" that become functional at the end of the rainy season and during the dry season, like living perennial covers, can produce abundant biomass throughout the year when they are well managed in cropping systems. During the dry season, which is cooler under Brazilian *cerrados* conditions, organic matter mineralisation is minimal and the high biomass production aboveground and underground (surface and deep horizons) enables maximal carbon accumulation and powerful recycling of leached base compounds and nitrates (Séguy *et al.*, 2001; Séguy & Bouzinac, 2001a).
"Nutrient pumps" can be planted in cropping systems either by broadcast seeding under the cover of the commercial crop, or by direct seeding (pure or mixed crops), depending on the target objectives.

A few examples of DMC systems developed on the basis of these principles in large markedly different ecoregions are described below:

1) **In a humid tropical zone (HTZ) on ferralitic soils,** in the central northern region of Mato Grosso state of Brazil (south of the Amazon, with 1600 to more than 2000 mm rainfall/year), conversion of a degraded soil into "forest environment" soil is illustrated in *Fig. 3*. In our experimental conditions, dry biomass production increased from 6-8 t/ha with soybean monocultures on tilled soils in 1986 to 18–22 t/ha under DMC with a two annual crop sequence in 1992, and then to 26–32 t/ha under DMC with a three annual crop sequence in 2001. In this latter situation, production was continuous throughout the year by optimising the use of crops grown under DMC and thanks to much higher available water reserves, as occurs in forest ecosystems. These DMC systems are being adapted in HTZ of Asia (Laos, Vietnam) and in the eastern coastal region of Madagascar, on manually cultivated or minimally mechanised smallholdings.



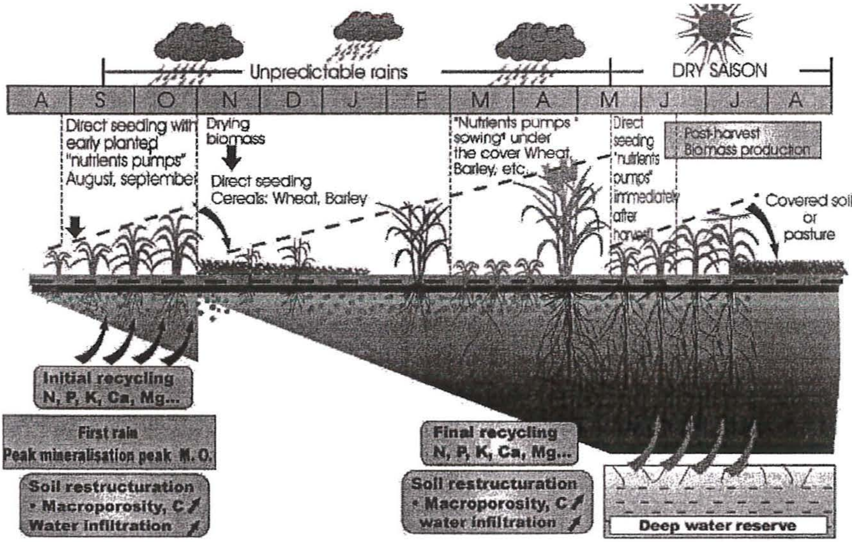
SOURCE: L. Séguy, TAFA/CIRAD-GEC team, 2002

Figure 4: Some DMC systems for the South Western Malagasy (300-600 mm/year)

2) **In contrast, under semiarid to Sahelian climatic conditions:**
   - **On tropical ferruginous soils in southwestern Madagascar,** on manually cultivated smallholdings, DMC systems provide permanent soil cover despite the uncertain low rainfall conditions (300-600 mm/year) through the use of powerful nutrient pumps adapted

to these specific soil-climate conditions: maize, sorghum, millet, intercropped with long-cycle legume food crops that do not substantially compete with grasses (e.g. *Vigna unguiculata, Dolichos lablab*) or forage crops (e.g. *Macroptilium atropurpureum, Stylosanthes hamata*) or even forage grasses (e.g. *Brachiaria, Cenchrus* and *Andropogon* species). Annual aboveground biomass production is much greater than 12–15 t/ha dry matter [*Fig. 4*]. These DMC systems are being adapted to conditions in northern Cameroon and Mali, on manually cultivated, animal draught or minimally mechanised smallholdings.

- **On brown clayey-lime soils in Tunisia, in the Mediterranean Basin,** the low winter rainfall levels (400-500 mm/year) lead to low irregular yields of wheat, barley and sheep grazings (rangelands). DMC systems are currently being developed on the basis of the "opportunity farming" principle, whereby all heavy rainfalls (above 40-50 mm) are exploited to produce supplementary biomass with "nutrient pumps" adapted to these specific soil-climate conditions (*Cenchrus, Trifolium, Medicago, Brachiaria, Andropogon, Melilotus* and *Pennisetum* species, etc.), either before the winter cereal crops are planted or under the cover of these crops in early spring so that biomass production will be extended as long as possible into the dry season, both aboveground and belowground (congregating and restructuring the soil to promote efficient water infiltration) [*Fig. 5*].

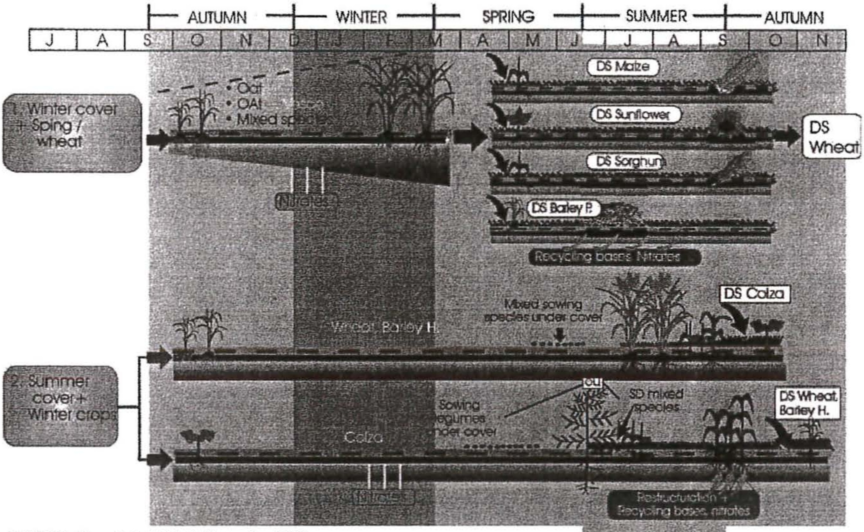


1 - species and mixed species, adapted to marginal rainy conditions
SOURCE: L. Séguy, CIRAD/GEC - 2002

Figure 5 : Some DMC systems in semi-arid zones of Tunisia (150-500 mm/year)

3) **In temperate climatic conditions,** in large cereal cropping regions of central France, on quite fertile soils (brown clayey-lime soils in Berry, Loire valley and Cher), the same DMC development strategies are applied [*Fig. 6*]:
   - **High biomass production in winter** (oats, oats + vetch, mixed species) for direct seeding of spring-summer crops to serve as nutrient pumps (maize, barley, sunflower, sorghum);
   - **Abundant biomass production in summer** in rape/wheat rotations, using diversified nutrient pumps (mixtures of temperate and tropical species).

In all of the large ecoregions, rotations are based on the same forest ecosystem functioning model: maximum aboveground and belowground biomass production, protected untilled soil, increased available water reserves throughout the year, biodiversity recovery through the use of rational rotations and nutrient pumps.



SOURCE: L. Séguy, J. C. Quillet, H. Charpentier, 2002

Figure 6 : Some DMC systems for temperate zones as Center of France

V- An international network:

• ***The agroecology action plan: a CIRAD/AFD/FFEM/MAE collaboration***

In collaboration with many partners[2], CIRAD[3] is developing a large-scale research network geared towards adapting these techniques to a broad range of biophysical conditions: nutrient deficient to highly fertile soils, temperate to subtropical, tropical and equatorial regions, dry regions (450 mm/year rainfall in Tunisia) to humid tropical regions (2000-3000 mm rainfall in the Amazon), sea level to highland areas (highlands of Madagascar), plains (including very infertile and poorly irrigated rice fields) to steep-sloped regions (North Vietnam).

DMC systems are also adapted to different socioeconomic conditions, and different levels of crop intensification: from regions already integrated in the world market (Brazil) to enclaved mountains (Vietnam), with a broad range of population densities or intensive agriculture, with a high capital and supply investment potential, to the poorest, no-input, extensive farming conditions.

Various French funding agencies (AFD – "Agence Française de Développement", FFEM – "Fond Français pour l'Environnement dans le Monde", and MAE – Ministry of Foreign Affairs) have been

[2] **Partners: MAEDA, USP/CENA, EMBRAPA, AGRONORTE, COODETEC, FUNDAÇÃO RIO VERDE, FAZENDA MOURÃO** ***(Brazil)*****; ANAE,FOFIFA and TAFA** ***(Madagascar)*****; VASI** ***(Vietnam)*****; NAFRI** ***(Laos)*** **; SODECOTON** ***(Cameroon)*****; INRAT** ***(Tunisia)***; and many other partners throughout the world which unfortunately cannot be listed here.

[3] **CIRAD-CA/GEC** hosts a web forum on direct seeding on permanent plant cover without soil tillage **(DMC): http://agroecologie.cirad.fr**
It also supports and participates in the **DMC** (Direct seeding, Mulch based systems, and Conservation agriculture) initiative: **http://agroecologie.cirad.fr/dmc/index.php**
Moreover, **CIRAD-CA/GEC** contributes to the international dissemination and application of all sustainable agriculture techniques through the **TWCA** (Towards World-wide comprehensive Conservation Agriculture) project.

jointly supporting the Agroecology Action Plan (PAA) by financing the development-oriented research programme in five pilot countries (Cameroon, Laos, Madagascar, Mali and Tunisia).

• ***The DMC network: an international challenge involving partners from developing countries.***
The DMC (Direct Sowing, Mulch-based and Conservation agriculture) is a Global Partnership Program under GFAR. It aims to strengthen the capacity of key stakeholders to develop suitable DMC systems and to accelerate their wide adoption. The GP-DMC features a process of learning and synthesis.
This initiative has been formally launched in January 2000 at a stakeholder meeting attended by representatives of National Agricultural Research Institutes, NGOs, International Agricultural Research Centers, regional networks and other institutions. Since March 2002, the Program has being implemented by a facilitator from IAPAR – the Agricultural Research Institute of the State of Parana, hosted by CIRAD. So far, the main activities are the development of a DMC Website[4] and the implementation of case studies in collaboration with various stakeholders.
The purpose of the case studies is to provide a better understanding of the technical, social-economic and organisational factors that can constrain the adoption of DMC systems, mainly by small farmers. By analyzing and comparing experiences from decentralized initiatives, by synthesizing lessons learned, and by identifying and filling gaps, DMC practices can be harnessed by a wide range of stakeholders
The first case study was carried out in **Bolivia,** in collaboration with ANAPO (the National Association of Oil-Seed Producers) at Santa Cruz de la Sierra. A second case study is now being carried out in **Tanzania** under collaboration between FAO and DMC, under IFAD funding and will be completed by late May. The third case study is being carried out in **Ghana,** under a collaboration between the Sedentary Farming Systems Project, ICRA (The International Centre for Research oriented to development in Agriculture - Wageningen) and DMC.

• ***STAR Soil &Ecosystems: a unifying initiative towards an integrated project on the stability and resiliance of soil and cultivated ecosystems.***
An integrated project, based on the highly promising results already obtained, especially in developing countries, is proposed that within 5 years would be able to:

- Consolidate current experience in the tropics (DMC) aimed at adapting and creating new cropping systems with sustainable production, based on soil protection, production, biomass recycling and on enhancing biological activity and determining the scientific, technological and socioeconomic implications for research.
- Support and develop similar initiatives in Europe, associating farmers and researchers (cf. France, Switzerland, Germany, Spain, Italy, Central Europe, etc.)
- Pool available resources in order to be able to conduct top quality targeted research to benefit all concerned stakeholders.
- Participate in retraining researchers, agronomists and technicians by developing an innovative approach combining agronomic and ecological principles.

VI- Conclusion

The direct seeding mulch based cropping systems (DMC) concept, in addition to the principles described above, could become a key tool for the global development of environment-friendly sustainable agriculture managed like a " biology-driven" farming model.
In all large tropical, subtropical and temperate ecoregions, irrespective of the type of agriculture, DMC systems provide complete erosion control and are always much more profitable than cropping systems with tillage, i.e. spectacular savings in labour, farm machinery and fuel with DMC systems.
These results highlight that DMC systems are more productive, stable, and cleaner, with an increasing share of organic fertilisation to enhance the soil production potential. This type of agriculture, which is based on the "nutrient pump" concept to benefit commercial crops, can act as a CO_2 sink via high biomass inputs into the system.

DMC systems can quickly have beneficial impacts on the biological quality of soils and water. These positive environmental impacts of DMCs can induce civil society to support farmers who utilise these cropping systems for their participation in reducing the greenhouse effect and preserving the landscape, rural infrastructures and wildlife. The use of "carbon credits" could ultimately be a stimulating incentive to foster agricultural development in this direction. These credits could be adjusted according to the carbon sequestering capacity of crop management sequences and cropping systems, thus encouraging farmers to adopt DMC systems.

These scenarios are, however, only realistically possible if the various development stakeholders are able—jointly and *in situ*—to develop future cropping systems that fulfil the sustainable environmental criteria set by society, along with the agronomic, technical and economic criteria set by farmers.

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