DOI number: 10.5027/jnrd.v5i0.03

JOURNAL OF
NATURAL RESOURCES
AND DEVELOPMENT

Integrating agricultural and environmental sustainability across generations: the never-ending quest for the golden fleece

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Article history

Received 16.04.2013
Accepted 30.10.2014
Published 12.03.2015

Keywords

Sustainability
Resilience
Adaptability
Energy efficiency
Input efficiency
Precision farming
Best agricultural practices

Abstract

Dynamic agricultural sustainability strongly depends on a reliable energy resource that is capable of maintaining order in an open (agro-eco-) system at the expense of the order of the environment. In this article, the integrative and complex challenges of combining efficient farming with environmental upgrading are analysed. Farming should be practiced within an appropriate, though moving agro-climax, the impact of which has become more important than that of the remaining natural ecosystems. Efficient use of resources and energy is not only important during the concentration phase of farming, but even more important during the dilution phase. The best way of improving the eco-capacity of farming systems is to increase the vitality of the agrosphere i.e. assimilation capacity of abiotic inputs necessary for crop intensification. This will require hands-on guidelines for the farmer amongst which integrated plant nutrition and the integration of organic and inorganic fertilisation will allow both sustainable and intensive production systems. The intergenerational adoption of the latter will be proof of their sustainable character.

World agriculture faces new challenges today, among which are:

1) a growing population that needs to be fed,

2) a decrease in the availability of prime agricultural land,

3) competition for key resources such as labour, water, and land with other economic sectors such as cities and mining,

4) competing uses for agricultural products, for example fuel,

5) growing awareness of the general public regarding sustainability of agriculture production and hence,

6) necessary improvements to the biodiversity and ecosystem functions in agriculture.

1. Farming towards the right agro-climax

Man-made agro-climax is of greater concern than natural eco-climax

Agroclimax: Ecosystems are very complex and composed of many individuals of multiple species of organisms which interact with each other and their abiotic environment to produce complex structures, dynamics and energy flows. While evolving, agricultural systems are assumed to take advantage of all their potential for intrinsic development and for interactions with natural communities to increase total energy flow within the system. The systems in a state of agroclimax try to maximise production as well as bio-capital generation such as biodiversity, biomass and fertility, by taking care to preserve future productive capacity in the long term.

Human kind remains at the centre of whatever sustainability concept we may imagine. By taking the best of nature, farmers produce food and other useful products under different farming systems which will evolve into both a profitable and a moving equilibrium between plants, environment, labour intensity and economic situation. Dairy farming is a case in point. Fifty years ago there was little maize silage as feed in Europe. Since the seventies most of the feed is now maize silage which appears to be one of the most efficient ways of converting gullies into biomass, meat and milk, of controlling nitrate leakage in the soils, and of capturing subsidies. Nowadays, subsidies have been reduced and dairy farmers try to survive i.e. to optimise their agro-climax, by diversifying into so-called “fancy” combinations like e.g. milk and strawberries. In Brazil, traditional cashew growing was rain fed and combined with extensive cattle grazing and honey making. Nowadays, modern cashew plantations use high yield selected clones under drip irrigation. During the last fifty years, millions of hectares were converted into zero-tillage with the help of cheap, patent-free herbicides. A lack of adaptation to a new economic environment will be punished. Australian cattle ranchers enjoyed golden years during the Vietnam War. Thereafter market conditions changed dramatically whereas many ranchers failed to adapt as they remained dreaming of past highs. Each new development stage settles around a new agro-climax equilibrium. This has very similar characteristics to those of an eco-agro-climax. The eco-climax equilibrium conditions hold also for farming systems at agro-climax stage (Janssens *et al.*) **[4]**. At equilibrium, netto primary production equals total litterfall as the biomass increase becomes negligible. Gross apparent yearly photosynthesis (P_b) takes into consideration neither the root production nor the root respiration.

If $P_b = R + NPP = R + \Delta BM + L_t$

Where ΔBM = yearly biomass increase ~ = 0 at eco-climax
NPP = yearly netto primary production = $\Delta BM + L_t$
L_t = yearly total aboveground litterfall
R = yearly total respiration

Then, at equilibrium $NPP \sim= L_t$

In the case of agro-climax, L_t encompasses “spontaneous” litterfall as well as pruning residues and weeding clippings, which will all be recycled *in situ*. However, most of the fruit (or other harvest produce) will be removed at harvest. This agro-climax stage will be achieved with the help of energy consuming inputs and cultivation practices. Agro-climax will be reached at the optimal combination of environmental efficiency, input efficiency and capital (market) efficiency. Unfortunately, the first of the three efficiency terms is difficult to parameterise. The second difficulty is the speed of adaptability in the face of constantly varying economic and environmental conditions. With seasonal vegetable crops, annual field crops, or poultry it is easy to adapt quickly, whereas it becomes more cumbersome with perennial crops or larger animals.

Farming is an alternate concentration vs. dilution of energy and resources

Agricultural systems as concentrators and dilutors of resources: Agriculture dilutes previously concentrated resources across farm land (Janssens et al.) **[5]**. This dilution process is prone to dissipative energy losses. African countries like Egypt and Morocco are making great efforts at saving water through better irrigation management including drip irrigation, laser levelling of irrigated fields, and drainage control including water recycling. Morocco managed to control the major Sebou River and to reduce flooding of the rich Gharb irrigation perimeter. Hence, diluted irrigation water in the field is likely to reach plants more efficiently and reduce energy dissipation. Towards the drier parts of North Africa multi-layered oasis-style agriculture offsets part of the evaporative losses.

South of the Tropic of Cancer there is a real problem of diluting resources across the field. Irrigation is underutilised and fertiliser application techniques are poorly differentiated as a function of specific soil quality and specific crops. Some cotton-producing countries are using just one fertiliser formula for the whole country. Synergistic effects from water-fertiliser-x-pesticide combinations are poor due to inadequate logistics and untimely supply of all three production components. In Benin tree crops are playing an increasing role, among them cashew and teak. This is to be understood as a way of better diluting both labour efforts and production inputs whilst improving the overall environment.

Northwest African agriculture is a good example of periodic concentration and dilution processes. North of the Sahara and in oasis-style agriculture, man is able to concentrate natural resources (water, manure, plastic tunnels, etc.) in a very efficient way and subsequently diluting them over the field in the same efficient way. South of the Sahara the efficiency of the agricultural concentration-dilution dialectic process is poor, resulting in a mining type of agriculture with frequent bush fires and poor interaction between crop farming and animal husbandry.

Improving fire management of sugarcane in Mexico will increase the sustainability of sugarcane growing (Janssens et al.) **[6]**. Sugarcane growing and subsequent processing are a good example of how farmers/millers concentrate the final product and of how much energy will be required to achieve this all the way through. In this concentration process they even prefer burning the sugarcane twice in order to increase the crowding intensity within the eco-volume. Eventually, it leads to an environmental regression of the system.

2. Energy requirements for sustainable agriculture

Agriculture as consumer and producer of energy: Agriculture plays a key role in the process of transition toward more sustainable energy use patterns. First, the agricultural sector is itself a user of energy, not only in primary production of commodities, but also in food processing and distribution of agricultural products. Secondly, the agricultural sector substantially contributes to energy supply, in particular through the production of biomass, including fire wood, agricultural by-products, animal waste, charcoal, other derived fuels and increasingly through production of energy crops (Lansink *et al.*) **[7]**. Agriculture is essentially an energy conversion process, transforming solar energy, fossil fuel products and electricity into food, feed, fuel and fibre for human beings. Primitive agriculture involved little more than scattering seeds on the land and accepting meagre yields. Modern agriculture, however, combines petroleum-based fuels to power tractors and self-propelled machines with energy-intensive fertilisers and pesticides, resulting in greatly increased yields. Various parts of the world are at different stages of agricultural development; therefore, energy-use practices and its efficiency vary widely (Peart) **[18]**.

Some agricultural systems can end up producing more phytomass than neighbouring natural systems as was the case with horticulture in the municipality of Teresópolis. However, the same horticultural systems use much more energy to produce the same quantity of energy as that produced by ecological systems, indicating a lower efficiency for energy conversion. Increasing energy use, climate change and the expected increases in the cost of energy underline the need to improve energy use efficiency.

Use rates of renewable resources: Renewable resources should be used at rates less than or equal to the natural rate of generation, and the assimilation of waste and pollutants should be at rates less than or equal to the **assimilative capacity of the environment**.

The interface: Agriculture operates at the interface between nature and the human economy and combines natural resources and economic inputs to produce food. Typically, high quality, non-renewable energies from the human economy are used to capture and concentrate lower quality, renewable energies. Intensive agricultural methods rely more on resources purchased from the economy, while less intensive and indigenous methods typically rely more on natural inputs.

Some important indicators of agricultural sustainability: Agriculture as an open ecosystem needs energy inputs to stabilise its internal system. In order to evaluate its sustainability it is very important to take into account the quality and quantity of the inputs. Thermodynamics allows us to calculate for example the *Energy Yield Ratio*, the *Environmental Load Ratio* and the percentage of the total energy driving a process that is derived from *Renewable Sources*. In the long run, only processes with high renewable sources are sustainable, as advocated by Raviv **[21]** for organic horticulture. The percentage of renewable energy tells us a lot about the sustainable use of resources and quality of inputs in the systems. This can be illustrated by the comparison of different farming systems in the Atlantic rainforest of Brazil (**Figure 1**, **Table 1**): Intensive production brought a high dependence on inputs from non-renewable resources; and the energy transformation ratio is very low. The value of energy yield ratio (EYR) for the vegetable systems is closest to unity (1.19, 1.21, 1.25); it means that the natural contribution is low when compared to resources from the economy; thus, this system is not able to deliver too much net energy to consumer systems because most of its inputs are not renewable (e.g.: herbicide, fuel, fertilisers, pesticides, etc.). For the citrus system the value is slightly higher (2.78). This system does not have high economy inputs, and natural resources are bigger. The ecological system has strong internal recycling which gives economic benefit to the farmer and ecological benefit to environment. Leaf vegetables, fruit and mixed systems produce great environmental damage (Environmental loading ratio, ELR: 7.28, 5.66 and 6.52). Cattle systems, silvopastoral systems and citrus systems (ELR: 1.41, 1.44 and 1.35) generate a high environmental impact. Ecological agriculture, instead, has a lower value (ELR: 0.51), which confirms greater use of natural renewable resources by ecological and organic production techniques. The greater environmental loading ratios for intensive vegetable systems and cattle systems compared to the ecological system reflect the environmental cost of using more purchased resources. Due to the large amount of non-renewable inputs relative to renewable inputs, the vegetable system has the lowest fraction of renewable inputs (12%) compared to the citrus system (43%) and to the ecological system (66%). This indicates that the ecological system depended on renewable resources for over 66% of its inputs meaning that from an ecological point of view it is the most sustainable. Hence, the percentage of renewable energy and resources in a system should be retained as a major indicator of sustainability.

Energy efficiency as prime choice: Sustainable agriculture meets

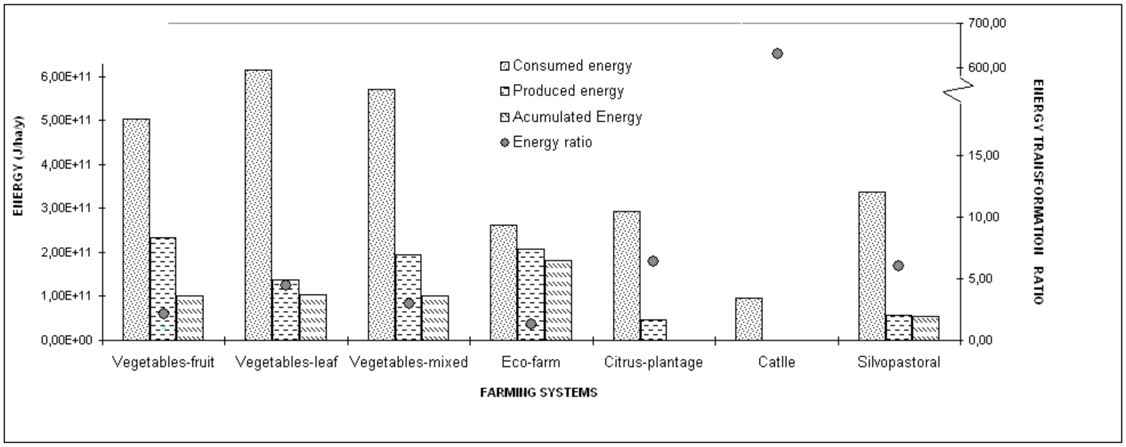

Figure 1: Production, consumption, accumulation and energy ratio of different farming systems in RJ-Brazil (Torrico and Janssens) **[24]**.

Table 1: Computed transformities and energy indices for farming systems in Córrego Sujo (Teresópolis) and comparison with literature (Torrico and Janssens **[25]**; Torrico & Callado **[26]**)

Emergy indices from farming systems in Teresópolis	Indices $T^{(1)}$	$\%R^{(2)}$	$EYR^{(3)}$	$EIR^{(4)}$	$ELR^{(5)}$	$EER^{(6)}$
Ecofarm	4.8E4	66	5.34	0.23	0.51	1.23
Cattle	6.3E7	41	22.56	0.05	1.41	0.47
Sylvopastoral	2.3E5	41	19.16	0.06	1.44	0.43
Fruit vegetables	3.1E5	15	1.25	4.02	5.66	0.61
Leaf vegetables	6.7E5	12	1.19	5.26	7.28	0.92
Mixed vegetables	4.3E5	13	1.21	4.68	6.52	0.61
Citrus	3.4E5	43	2.78	0.56	1.35	1.91
Córrego Sujo (average of all farming systems)						
Emergy indices for different farming systems (literature)						
Ecological soybean [(a)]	8.8E4	92	1.09	1.19	0.46	1.45
Organic Soybean [(a)]	8.1E4	78	1.27	1.40	0.42	1.35
Chemical Soybean [(a)]	1.0E5	74	1.35	3.40	0.23	2.51
Herbicide Soybean [(a)]	1.1E5	31	3.25	3.70	0.21	2.69
Ecological farming system [(b)]	2.0E5	69	3.36	0.4	0.82	0.02
Ecofarm integrated system [(c)]	2.8E5	75	11.90	0.09	-	5.52
Sitio Santa Helena [(c)]	8.5E5	27	2.52	0.66	-	2.33
Sitio Três lagos [(c)]	2.3E6	25	7.82	0.15	-	9.91
Bovine meat (sej kg^{-1}) [(d)]	2.1E12*	8	7.83	-	11.0	-
Danish agriculture [(e)]	-	-	1.17	5.91	9.67	-

* sej kg-1

(a)Ortega **[12]**, (b)Unicamp **[27]**, (c)Roosevelt-Agostinho **[22]**, (d)Serrano et al. **[23]**, (e)Haden **[2]**. (1)Transformity; (2) Renewability; (3)Energy yield ratio; (4)Energy investment ratio; (5)Environmental loading ratio; (6)Emergy exchange ratio

human needs for food, enhances quality of life of people, protects the integrity of natural systems, and last but not least, is financially profitable. Making a transition to agricultural sustainability involves difficult choices and an understanding of the complex trade-offs and synergies associated with different agricultural pathways. The choice of a particular production system will thus have significant consequences for the energy yields that can be obtained. Improved energy efficiency reduces the vulnerability of producers and consumers to energy price shocks (Outlaw *et al.* **[17]**), it reduces the adverse impacts of long-term real energy price increases and reduces potential environmental impacts of fossil fuel consumption. Fossil energy use efficiency is higher in ecological (low-input) crop production systems than in vegetables (high-input), and cattle systems. This is caused by the fact that in low-input systems, a relatively large amount of the phosphorus and nitrogen originates from non-fossil resources. Fertilisation is a major source of energy expenditure and hence a key agronomic management factor that needs to be revised and improved; in general, nutrient use efficiency is low and far from its potential.

Nitrogen is "the" agricultural energy nightmare. Under intensive cropping, nitrogen often approaches 40-50% of total energy requirements. For example, nitrogen use efficiency (NUE) is approximately 40%, while its potential is close to 70%. On the other hand, fertilisation has been regarded only from a chemical standpoint, often forgetting about the importance of biological and physical soil fertility.

During orchard formation and production the most important development in terms of soil fertilisation has been the fertilisers with nitrification inhibitors (NI); these products are composed by an ammonium (NH_4^+) source (ammonium sulphate) and a NI molecule

(DMPP, DCD or others) which slows down NH_4^+ oxidation to nitrite (NO_2^-) through the inhibition of the enzyme ammonium mono oxigenase (AMO) present in the bacteria of the genus *Nitrosomonas*, which are responsible for this oxidation process (equation1).

$$NH_4^+ \xrightarrow{nitrosomonas} NO_2^- \xrightarrow{nitrobacter} NO_3^- \quad \text{(eq. 1)}$$

The presence of the NI causes slower NH_4^+ nitrification, allowing it to be stable in the soil for a longer time, avoiding its loss by leaching or denitrification. The plant is able to absorb either NH_4^+ or NO_3^- (nitrate), achieving better NUE in the presence of NI, and provoking important nutritional side-effects such as higher P absorption, which stimulates root growth, which in turn translates into better nutrient absorption. The use of N fertilisers with NI reduces N rates up to 50%, depending on the soil, and also decreases P rates (Molina and Ortega **[10]**). A recent long-term study of table grapes (Ortega and Molina **[16]**), under drip irrigation, evaluating a product made of ammonium sulphate and DMPP, demonstrated that using 50% of the N rate applied as urea produced the same results in terms of yield, and better grape quality. All the nutritional effects described in the literature were observed, particularly an increment in P levels in leaves and larger nutrient uptake.

3. Improving the eco-capacity [24]

The resilience index R_i (**Figure 2**) has been defined as

$$R_i = V_{bio} / V_{eco\text{-}max}$$

Where

V_{bio} = actual bio-volume of a plant (crop) community

$V_{eco\text{-}max}$ = eco-volume of nearby natural eco-climax vegetation.

In most cases, there is no eco-climax vegetation left and one has to estimate the potential eco-climax in that particular site. The resilience index is a valuable indicator of the vegetation regression towards its potential natural eco-climax. The higher the index, the closer the crop or vegetation lies to its eco-climax predecessor.

Resilience: The environmental services of biodiversity are certainly significant, probably much more so than the direct benefits of biodiversity in the form of material goods. Biological diversity in general, as well as agro-diversity, appears to enhance the resilience of desirable ecosystem states, which is required to secure the production of essential ecosystem services. Species that directly or indirectly influence the ability of the ecosystem to function will enhance resilience, to the detriment of sets of species that do not have a significant role in altering the states of the ecosystem. The resilience index, R_i, measures the resilience of the systems by comparing the actual bio-volume (V_{bio}) with the potential eco-volume ($V_{eco\text{-}max}$). The bio-volume represents the current state of the systems, and V_{pot} represents the equilibrium state of the ecosystems, which is in contrast to $V_{eco\text{-}max}$ not the natural eco-climax. The systems with indices between 0.3 and 0.5 possess high resilience capacity. Above 0.5, the systems are approaching the climax stage. Indices between 0.1 and 0.2 represent systems with average resilience capability, while those lower than 0.1 are indicative of low resilience. When agricultural systems, like cattle and vegetable systems, are predominant in the landscape, the natural systems cannot guarantee the provision of the same goods and benefits as in the previous equilibrium state and thus, they have very low resilience. The lower the natural capacity to adapt to changes, the higher is the risk to decline. Moreover, the resilience index is highly correlated with the number of botanical species in a landscape (**Figure 2**).

This resilience index, R_i, allows us to define the eco-capacity C_{eco} of a plant or crop community as follows:

$$C_{eco} = R_i \cdot V_{eco}$$

Agricultural systems	Resilience (%)	Richness
Grass system	0.005	8
Citrus	0.006	8
Fruit Vegetables	0.012	19
Mixed Vegetables	0.013	21
Leaf Vegetables	0.014	19
Silvopastoral systems	0.029	34
Ecological systems	0.124	96
Coffee Chiapas-Mexico	0.142	99
Cocoa Agroforest	0.22	120
Coffee Northeast-Brazil	0.411	122
Caatinga Teresina-Brazil	0.052	16
Water plants	0.054	6
Regeneration forest (3 y)	0.088	30
Forest Uganda	0.154	43
Forest fragment Chiapas	0.198	64
Fragments Atlantic Forest	0.365	110
Forest Atlantic Forest	0.63	263

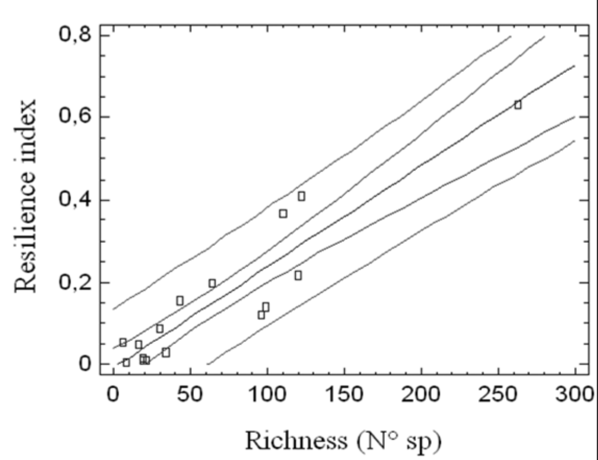

Figure 2: Simple Regression-Resilience index vs. Richness (number of species). The output shows the results of fitting a linear model to describe the relationship between the Resilience index and Richness. The equation of the fitted model is Resilience index = –0.0075 + 0.0024 * Richness. Correlation Coefficient = 0.934. R^2 = 87.3 per cent (Torrico & Janssens **[24]**)

Where

V_{eco} = field surface x average crop height at canopy closure (in m^3)

If there is no canopy closure, the total V_{eco} = sum of the individually measured eco volumes i.e. Sum of canopy basal area x height. For ease of comparison we normally express all observations on a hectare basis. If we compare a young oil palm plantation to a soybean field under humid tropical conditions within the equatorial belt with rapeseed production under a temperate climate and with sunflower under semi-arid conditions, we obtain very clear differences as to the eco-capacity of the four different oil crops (**Table 2**).

Table 2: Comparing the eco-capacity (C_{eco}) of four oil producing crops

	Oil palm	Soybean	Rapeseed	Sunflower
Height (m)	7	0.8	1.3	1.8
Basal area at soil (m^2/u)	0.6^2 x π/4=0.2826	0.000	0.000	0.002
Population/ ha	150	300000	300000	50000
Bio-volume V_{bio} (m^3/ha)	7x0.2826x150 = 296.73	18.85	122.46	176.62
Eco-volume V_{eco} (m^3/ha)	10000x7 = 70000	8000	13000	18000
Eco-volume at climax $V_{eco-max}$ (m^3/ha)	50x10000= 500000	500000	250000	120000
Resilience index (R_i)	296.73/500000= 0.00059346	0.000	0.000	0.001
Eco-capacity C_{eco}	0.00059346 x 70000 = 41.54	0.3	6.37	26.49

Furthermore, this oil palm will yield 5 t of palm oil with far less inputs than needed for the production of 0.3-0.5 t of soybean oil, or 1 t of rapeseed oil, or 0.8-1.0 t sunflower oil. It can be concluded that eco-capacity is a good indicator of environmental efficiency of a plant (crop) community and that under tropical humid conditions soybean cannot compete with the productivity of an oil palm, particularly when looking at the input requirements (**Table 3**).

Table 3: Input analysis of intensive oil seeds and oil palm cultivation (adapted from Corley and Tinker **[1]**)

Item (units/t of oil)	Soybean	Sunflower	Rapeseed	Oil palm
Nitrogen (N kg)	315	96	99	47
Phosphate (P_2O_5 kg)	77	72	42	8
Pesticides/herbicides (kg)	29	28	11	2
Others (kg)	117	150	124	88
Energy (GJ)	2.9	0.2	0.7	0.5

4. The vitality of the agrosphere and its organic matter is the best protection against the environmental load of abiotic inputs

If we want to intensify farming systems throughout the world we do need the help of agrochemicals. What input levels can be tolerated without threatening farming and the neighbouring environment?

This question holds for both organic types of agriculture and also for conventional types of agriculture. The eco-capacity of a plant (crop) community will also be a good indicator of its vitality, which in turn will determine its capability to withstand and neutralise both biotic and abiotic stresses. The latter type includes critical agrochemicals such as fertilisers, pesticides, fungicides and herbicides. The correct idea is not to polarise between organic and inorganic fertilisers, but rather to estimate the neutralising potential of a farm system towards agrochemicals. In essence, how much soil litter and how much soil organic matter is needed to neutralise what quantity of agrochemicals within a certain period of time? What is the *assimilative capacity* of the agro-environment?

a. "Hic et nunc" implementation of sustainable agriculture by farmers

Learning and teaching sustainability together with the farmer – challenges of Better Management Practices and the Traffic Light System. Together with farmers, agricultural students and scientists, over the last ten years we have been elaborating the principles of Better Agricultural Practices (BMP) and the Traffic Light System (TLS). The aim of this participatory methodology is to instil farming husbandry in the use of sustainability principles which encompass productive, competitive and efficient cropping practices combined with active ecological management and social responsibility.

The implementation of BMP and TLS presents a fundamental step for successful sustainable crop production and for ensuring the highest possible standards of all growing and processing activities in harmony with the locally prevailing economic, ecological and social conditions (Pohlan and Salazar **[19]**). On a global scale, over the last 10 years this type of production management has stimulated numerous activities towards the creation of well-adapted agro-ecological growing systems including the following structural baseline aspects:

- Analyse the real situation in productive chains: from territorial zoning to the final products;
- Determine strategies for Better Management Practices in short- and long-term crop development using the principles of traceability and transparency;
- Identify and evaluate the potentials, risks and weaknesses involved in economic, ecological and social sustainability of the present crops;
- Facilitate professional information about the crops and the agro-ecological systems;
- Disseminate practical instructions for farmers adapted to local site conditions, socio-economic traditions, social and ethnics culture and levels;
- Facilitate quality diagnostics, monitoring and auditing of BMP

in all agricultural chains together with the farmers and guide quality control of the farmers' agronomic and post-harvest labour and field management.

This approach was first applied to coffee growing areas and then introduced step by step into cocoa, tropical fruits (pineapple, mango), sugar cane and Jatropha (Oberthür et al. **[11]**; Hallensleben and Pohlan **[3]**; Pohlan and Janssens **[20]**). The methodology presents a total of 13 key pillars of sustainable crop husbandry. The so-called Traffic Light System helps to appraise risks (in terms of control points and compliance criteria) and develop the principles of risk prevention in each growing system. For the BMP in perennial crops a total of 50 equally weighted control points were developed (**Table 4**). Together with the 13 pillars, these 50 indicators will be rated for red Hot Spots (*in casu* "black"), yellow ("grey") risk factors and eventually for the desirable green ("dark grey") approval notes, either for the agronomic methods and techniques, for the site selection or for the final maturity of coffee beans.

Together with the farmers using this new farmer's philosophy it becomes possible to discriminate between red, yellow and green indicators combined with internal control management. As a result it will be possible to receive opportune warnings of hazardous red Hot Spots. Hence, the farmer is now part of a precise, effective and transparent risk control mechanism. He is now fully aware of the importance of avoiding the red-light situation by all means and will realise that the yellow risk points should be swiftly transformed into green comfortable components. **Table 4** and **Figure 3** offer practical guidance for the farmers, well adapted to the local conditions and to the socio-economic environment, enabling a simple, effective and locally specific use of BMP by all categories of farmers.

Figure 3 gives a visual control in the form of 11 red Hot Spots in red (very high risk), 15 yellow light spots warning for high risks and 24 desirable green light spots without risks. The red Hot Spot determines a situation with very high risk, requiring immediate change if economic losses are to be avoided. This evaluation can be summarised in a traffic light diagram (**Figure 3**).

In future farming systems, "*slow release carbon*" should be encouraged just as is the case with fertilisers. Indeed, quick release carbon, such as e.g. herbaceous plants, can normally be fed to animals and converted into proteins. In any case, CO_2 will be produced as the final degradation product. If so, any energy and any components should be extracted during the decay process, and eventually CO_2 will be recycled in the photosynthesis process. Moreover, most of the CO_2 will remain at plant level as it is heavier than air. It is also difficult to understand the rationale behind the Kyoto agreement, whereby CO_2

Table 4: Traffic light system for evaluating sustainability indicators of coffee orchards in Nicaragua (red=hot spot; yellow=high risk; green = ideal situation) (Pohlan et al. **[19]**)

Pillars of sustainability	Hot spots (red light)	High risk (yellow light)	Ideal situation (green)
1. History & subdivision of farm	No maps, no soil analysis		Climate
2. Soil maintenance and conservation		Soil inclination >25°, erosion control	Adequate water holding capacity, soil organic matter
3. Origin and quality of seeds		No certified seeds and no elite plants	Seed quality, polybag size, good varieties
4. Nursery establishment and quality of seedlings/cuttings	Number of nematodes above allowed threshold value	Root system without pruning (wrenching), nursery plants overdue	Sub-optimal nutrition
5. Management of shade trees and coffee transplanting		Pruning without physical protection	Multi-layered diversified shading with pruning, coffee transplanting
6. Pruning of shade trees		Pruning without protection	Pruning management
7. Weed control	Use of E.U. forbidden herbicides		Frequency of weed control
8. Crop nutrition	Inadequate storage conditions, use of dirty recipients		Applied rates, fertiliser choice, according to phenology and crop needs
9.Pest and disease control	Inadequate storage conditions, EU forbidden pesticides, Use of dirty recipients	Overdose applications, no protective clothing	
10. Irrigation, intercropping, diversification		Poor quality irrigation water	Intercropping, diversification
11. Management of plant material		Rejuvenation without physical protection	Rejuvenation, removal of suckers
12. Harvest management	Use of inadequate recipients	In-field transportation conditions	Harvesting fruits at maturity
13. Social environment	Child labour <14 y.	Lack of restoration and dormitories, failing social security	Social empowering, transportation, recreation, incentives

has been promoted as the yard stick in the newly created carbon credit market as a major indicator for environmental pollution. If Kyoto would have chosen a gas like CH_4 as an appropriate indicator of environmental pollution, it would have been closer to the energetic core of the problem. Indeed, it is an energetic nonsense to expel CH_4 without using its energy. This is pure entropy and environmental pollution. If we want our farming systems to be more sustainable, we should try to extract as much as possible energy along the production, processing, and marketing chain from both the main products and from the residues.

b. Integration of organic and inorganic fertilisation

The concept involves the addition of stabilised organic matter (OM), viz. C, as a key element of the fertilisation plan along with moderate nutrient rates, and the use of reduced N rates using fertilisers with NI. The objective of the C applications is to provide an energy substrate for the growth of beneficial soil microorganisms, from which several indirect effects are generated: soil particle aggregation, improvement of the water retention capacity, release of nutrient and other plant-promoting substances (phytohormones), and disease suppression, among others (**Figure 4**).

Organic matter quality is fundamental to achieving the expected effects; composted OM sources are desirable, with low contents of extractable (available) N, and high C levels. They should also have a low C/N ratio (similar to a soil, which means from 10 to 12) and low levels of heavy metals. The use of fresh or composted animal manure, without mixing C-rich materials, is undesirable, since they add considerable amounts of N, negatively affecting fruit quality, while supplying low levels of C. **Table 5** shows the average composition of high-quality composts.

Other excellent sources of OM, particularly for crops under drip irrigation, are the humic substances. They are usually extracted from fossil C sources such as leonardite, using a strong base (usually KOH); however, they can be obtained from any C source, including compost, animal manure, plant residues, etc. The more mature the original material the higher is the proportion of humic acids in relation to the fulvic ones. Any of these products can be used knowing its composition in terms of C content, applying them at a proper rate.

Many of the commercial products are recommended at very low C rates (< 5 kg C/ha); however, research has demonstrated that optimum C rates are usually > 50 kg C/ha/season (Ortega and Fernández **[13]**; Martínez **[9]**). The use of humic substances normally increases soluble C (SC) in soils, stimulating microbial growth and provoking the desired effects as described in **Figure 4**.

A practice currently seeing expansion in the fruit production industry is the use of compost tea. This corresponds to an aerobic fermentation of a compost suspension in water (3 to 4% W/V), which is then injected into the soil through the irrigation system. Compost tea does not correspond to a C source, since its contents are very low; water extracts only the soluble fraction of the OM. Strictly, compost tea is a soil inoculant. Through this, soil is inoculated with beneficial microorganisms extracted from compost that may include: phosphate solubilisers, nitrogen fixers, cellulolytic, proteolytic, and amylolitic micro-organisms, among others, as well as actinomycetes, fungi and yeasts.

It is for this reason that, in order to obtain a good inoculant it is necessary to have high quality compost, this means compost with a high concentration of beneficial microorganisms, and low or null levels of human pathogens such as *Salmonella or E. coli*. **Table 6** shows some values for compost tea samples. On average the concentrations of beneficial microorganisms are well above reference values; however, the variance is very high, meaning that the quality of the compost and the process used are highly variable.

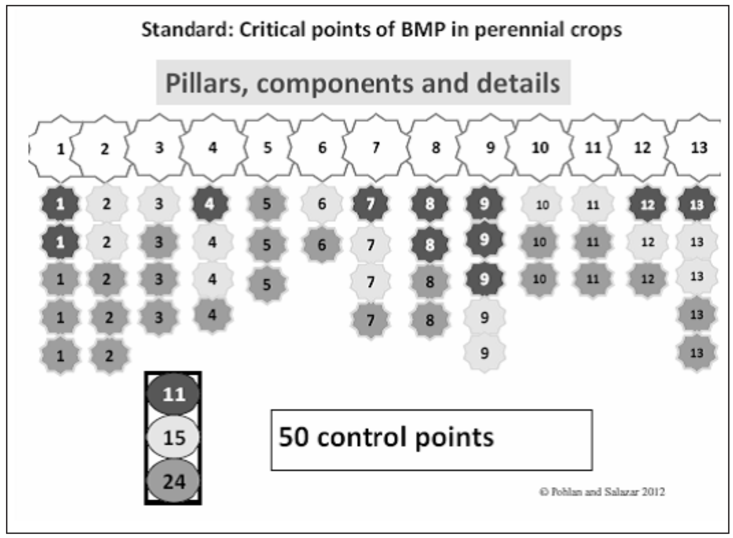

Figure 3: Diagram presenting the pillars and components of the BMP and TLSystem (Black = red; grey = yellow; dark grey = green) (Pohlan et al. **[19]**)

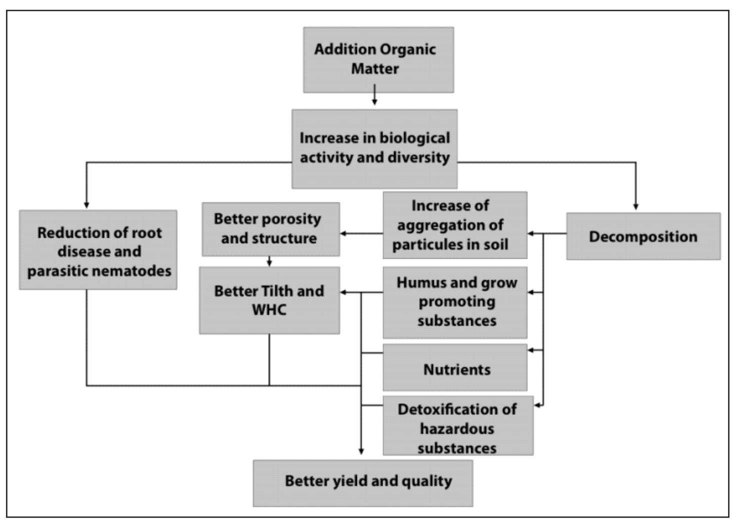

Figure 4: Effects of the application of OM to the soil (Adapted from Magdoff and Van Es, 2000. In: Martinez **[9]**).

Another way of inoculating soils is through the application of commercial products which usually contain a variety of micro organisms which were isolated in several regions of the world, are not necessarily adapted to the local conditions, and are commonly found at concentrations not sufficient to cause the desired effect. It is for these reasons that determining the quality of the inoculant is a key factor in the success of the technology. The development of site-specific inoculant is a logical way of achieving the expected results.

5. Sustainability of intensive production systems: technologies to improve nutrient use efficiency and decrease environmental impact.

Introduction

Agriculture intensification has allowed increasing yields and has closely satisfied growing demand; however, the environmental cost has been high, particularly in terms of soil and water quality. Thus, the new challenge is to produce high yields in a sustainable way, maintaining or improving soil, water and air quality as well as increasing agrodiversity, biodiversity and ecosystem functions. There are a group of old and new technologies that should be implemented together to improve nutrient use efficiency, while achieving high yields and quality. The concept is called integrated plant nutrition (IPN) and it is based on the use of high-quality organic matter, along with proper fertiliser rates. It also includes the use of available tools for diagnosis and follow-up for soil, plant tissue and biological products, the use of modern fertilisers, and site-specific management.

Table 5: Chemical characteristics of compost derived from agricultural residues (n=9).

Statistic	OM (%)	C (%)	C/N ratio	N (%)	pH	Humic Substances (%)
Average	51.5	25.8	12.8	2	8.2	5.2
Standard Dev.	3.6	1.8	1.5	0.2	0.6	1.5

Statistic	Cr	Cu	Ni	Pb	Cd	Zn
	-------------------------mg/kg---------------------					
Average	12.5	32.2	8	4.5	<0.01	47.3
Standard Dev.	0.7	1.8	1.2	0.7	-	10.1

Source: Martínez et al. [8]

Table 6: Concentration of beneficial microorganisms in selected compost tea samples.

Analysis	Units	Average	Std. Dev.	Reference value
Total bacteria (hetero-trophs)	CFU/ml	2.E+7	2.E+7	1.E+6
Fungi and yeast	CFU/ml	5.E+6	6.E+6	1.E+5
Azotobacter (N fixer)	CFU/ml	3.E+5	5.E+5	1.E+3
Bacillus	CFU/ml	7.E+5	1.E+6	1.E+5
Actinomycetes	CFU/ml	6.E+5	1.E+6	1.E+4

Source: Adapted from Martinez [9]

IPN does not aim to transform intensive agriculture into organic agriculture, since productivity needs to be as high as possible; it intends to integrate some aspects of organic production into traditional management, particularly developing biological and physical fertility to improve root systems and nutrient use efficiency. Here, the IPN concept is reviewed and some examples of its use are presented, particularly for intensive fruit production systems in Chile.

Integrated plant nutrition

For many years, the nutrition of intensive crops, particularly fruit and vegetables, contemplated the application of high rates of fertilisers, particularly nitrogen, and its control only through tissue analysis, without considering soil variability and nutrient supply. This resulted in significant nutritional imbalances, reflected in plant physiological problems, such as "spring fever" or "bunch stem necrosis" in table grapes, which ultimately resulted in poor fruit quality. Along with this, particularly in low precipitation areas, excess fertilisation caused salinity problems in the soil, and, in general, adversely impacted the quality of water due to excess nitrate leaching.

The application of organic matter, particularly fresh or stabilised manure from different sources, has been a traditional management tool used by producers to improve the physicochemical properties of the soil and, from here, to recover decayed orchards with weak root systems. However, ignorance of the characteristics of the organic materials used has caused significant problems in the form of nutritional imbalances due to excess nitrogen.

A variety of organic products are available within the farm and on the market, which when properly integrated with inorganic fertilisers in an IPN program would achieve the desired productive objectives. This requires knowledge of their origin and composition and how they act in the soil when applied.

In modern agriculture, which has multiple objectives - agronomic, economic, social and environmental - the design and implementation of proper nutrition programs is essential. IPN, which considers the use of all available tools and the inclusion of organic and inorganic products within the fertilisation program, seems to be the future of this important agronomic management, under intensive crop production systems.

Using nutritional diagnostic tools

Traditionally it had been established as a rule that, for the case of fruit crops, tissue analysis, particularly of leaves, was the only valid tool for diagnosing a plant's nutritional status. However, there is ample evidence that this tool alone does not allow a proper nutritional diagnosis. Nutrient levels are often inadequate in leaves, but can be high or even excessive in the soil itself. From this simple observation, for orchards it is strongly recommended to assess soil fertility levels in the area of greatest concentration of roots (normally at a depth of 30 cm). Soil analysis should be done at least every three years. However, in the case of available nitrogen ($N\text{-}NO_3$+$N\text{-}NH_4$) the analysis should be done annually. The most common analyses are: extractable nutrients (N, P, K, Ca, Mg, Zn, B), pH, electrical conductivity, organic matter (OM) and cation exchange capacity (CEC). To these, soluble nutrients are added (particularly, K, Ca, and Mg) to estimate daily delivery rates and determine the likelihood of a deficiency in the plant, in periods of high demand, even with high levels of nutrients in the soil. In the case of extractable or available N ($N-NO_3$ + $N-NH_4$), the idea is to determine the residual levels prior to bud break, which are often high due to previous fertilisation and mineralisation of the organic matter, and to consider them in the N balance for estimating fertilisation needs. For example, an available N level of only 20 mg / kg, in an orchard watered by furrows, means about 60 kg N / ha in the first 30 cm of soil.

Regarding OM, this is measured as organic carbon (C) in the soil. This value is multiplied by a factor of 1.72 (or 2) to obtain OM content. The 1.72 factor comes from the fact that, on average, the soil organic matter (SOM) contains approximately 58% C. There are several laboratory methods for estimating SOM, including: dry combustion, wet digestion (Walkley and Black **[28]**) and, more recently, the use of near infrared spectroscopy (NIRS). Normally, dry combustion methods yield higher C values than wet digestion, overestimating C levels when the soil has free calcium carbonate (Ortega **[14]**).

With regard to tissue analysis, the main problem is the absence of adequate standards to compare against. Foreign standards are normally used, or those obtained locally by analysing data obtained from tissue samples sent to laboratories. Local standards should ideally be obtained for each site, through the selection of trees or fields that fully meet the agronomic objectives: good yields and fruit quality. The use of precision farming tools can facilitate the process of obtaining these standards.

Precision agriculture and fertilisation management

Variable application of fertilisers is, without any doubt, one of the areas of greatest development inside precision agriculture. However, its impact at the production level has been erratic, with excellent results in some cases and null in others. According to Ortega **[15]** there are several reasons for this:

1. It is normally assumed that soil fertility is the crop yield limiting factor. In most cases, this assumption is not true and the yield reached is a function of other soil limiting factors, usually physical.

2. The recommendation algorithms are inadequate, because, in most cases, they tend to the application of higher fertiliser rates in areas of the field, where yields are lower and vice versa, assuming that these are being limited by soil fertility levels.

Ideally, fertilisation should be performed variably as a function of two criteria: 1) the soil fertility level, which, if it is low, should be increased above the critical levels (CL); in this case chemical soil quality should be optimal; and 2) the potentially reachable yield (yield goal), according to other soil limiting factors.

The correction of soil fertility levels, together with soil chemical and organic aggregates, should be performed prior to plantation using variable rate technology (VRT), as a function of prescription maps. Once the orchard is in production, fertilisation needs should be estimated as a function of yield goal only, maintaining soil quality above the critical levels.

Use of highly efficient fertiliser products

In the search for improved nutrient use efficiency, particularly NUE, there has been an important development of new fertiliser products.

The use of controlled release fertilisers (CRF) at planting is, without any doubt, one the most important developments for fruit production in the last few years. Depending upon the length of the growing season and climatic conditions (temperature), CRF of 3, 6, 9, or 13 months of release time are selected and added to the plantation hole mixed with the soil. Usual rates vary from 30 to 200 g/plant, depending upon the species. CRFs are chemical complexes covered by a semi-permeable plastic coating, which allows water to enter the granule, nutrient dissolution and finally a controlled release into the soil by diffusion. Low electrical conductivity (EC) levels around each granule localise the fertiliser close to the roots, increasing nutrient use efficiency. This finally translates to better plant growth rates in comparison to traditional fertilisation practices.

The effects of integrated plant nutrition

The effects of IPN are summarised in **Figure 4**, showing the effect of C application on dry matter (DM) production. There is an increase in DM with the C rate. However, this increment is greater in the presence of moderated chemical fertilisation (Ortega and Fernández **[13]**). The general mechanism is very simple: adding C and other nutrients stimulates the development of beneficial soil micro-organisms, improving soil quality and stimulating root growth. This allows greater exploration of the soil volume and better use of water and nutrients, which finally results in increased yields and quality, through more balanced and long-lived orchards. **Figure 5** shows the effects of IPN on root development in table grape: increased root density with C rate. The increase was even greater when an inoculant was applied. This compound effect resulted in significant "outliers" with respect to the binomial regression model (**Figure 5**).

Martinez **[9]**, working in table grape var. Thompson seedless in the north of Chile, found a linear increment in exportable yield with the application of humic substances extracted from compost made of grape pomace. The rate of increase was approximately one export box (8.2 kg of grape) per kg C applied.

The effects of integrated plant nutrition are cumulative. Therefore, the follow-up through soil and tissue analysis is fundamental, in order to evaluate changes in time and make the proper adjustments, season by season. Research results by Martinez **[9]** have demonstrated that IPN improves soil quality over time with respect to the baseline. This means that it is feasible to achieve good agronomic and economic results, while maintaining or improving soil quality.

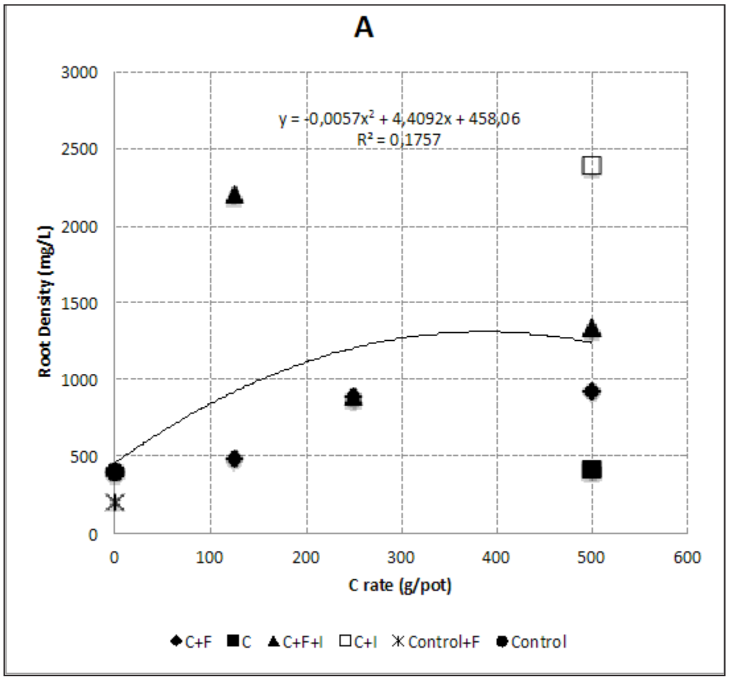

Figure 5: Root density as affected by C rate from compost (C) in the presence or absence of chemical fertilisation (F) and inoculant (I). From: Martínez **[9]**

Proposal for integrated plant nutrition

Integrated plant nutrition should include at least the following elements:

- Use of available diagnostic tools to determine soil fertility and plant nutrition status. To obtain a proper number of samples, according to soil and plant variability, it is fundamental to properly estimate the selected parameters.
- Use of stabilised organic materials, properly characterised in terms of their chemical, physical and biological properties, applied at proper C rates.
- Use of moderate nutrient rates established as a function of soil fertility, crop yield, and the fertiliser source used. Using sources with NI allows decreasing N rates up to 50%, depending on the soil and crop.
- Soil inoculation with high-quality products applied at the proper concentration. Obtaining site-specific inoculants is a logical way of approaching this technology.
- Implementation of site-specific management (SSM) using precision agriculture tools. Detailed soil mapping of production units in terms of physical, chemical, and microbiological properties is the basis for establishing SSM.

6. Conclusions and recommendations (**Figure 6**)

1. There are several old and new technologies on the market that can be integrated into nutritional management in intensive agriculture. These should be managed with the criterion of site-specificity; i.e. by adapting the technologies to the reality of each orchard or field.
2. The use of high-quality organic matter and an adjusted chemical fertilisation are the basis of IPN. For this, it is necessary to know in detail the fundamentals of each technology involved and use the available tools for diagnostics and monitoring for soil, tissues, and organic materials, such as: chemical, biochemical (enzymatic activity), and microbiological analyses.
3. The results of the use of IPN in intensive crops are: increased yield and quality, increased nutrient and water use efficiency, maintenance or improvement of soil quality, and a decrease of the environmental impact.
4. Farming should be practiced within an appropriate, though moving agro-climax, the impact of which has become more important than the remaining natural ecosystems. Efficient use of resources and energy is not only important during the concentration phase of farming, but even more important during the dilution phase.
5. The best way of improving the eco-capacity of farming systems is to increase the vitality of the agrosphere i.e. assimilation capacity of abiotic inputs necessary for crop intensification. Conversely, efficient agricultural systems will reduce the environmental load of the remaining natural systems. This will require hands-on guidelines for the farmer, amongst which integrated plant nutrition and the integration of organic and inorganic fertilisation will allow both sustainable and intensive production systems. The intergenerational adoption of the latter will be proof of their sustainable character.

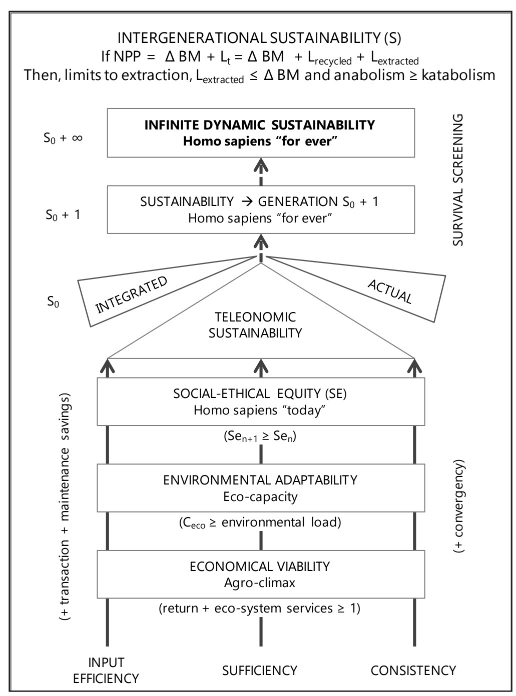

Figure 6: Intergenerational sustainability in agriculture.

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