Food and Agriculture
Organization of the
United Nations

FROM NATURE-NEGATIVE TO NATURE-POSITIVE PRODUCTION

A CONCEPTUAL AND PRACTICAL FRAMEWORK FOR AGRICULTURE BASED ON THERMODYNAMICS

FROM NATURE-NEGATIVE TO NATURE-POSITIVE PRODUCTION

A CONCEPTUAL AND PRACTICAL FRAMEWORK FOR AGRICULTURE BASED ON THERMODYNAMICS

by

Michelangelo Ferri

and

Marta Arnés García

FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS
BUDAPEST, 2023

REQUIRED CITATION:
Ferri, M. & Arnés García, M. 2023. *From nature-negative to nature-positive production – A conceptual and practical framework for agriculture based on thermodynamics*. Budapest, FAO. https://doi.org/10.4060/cc7414en

The designations employed and the presentation of material in this information product do not imply the expression of any opinion whatsoever on the part of the Food and Agriculture Organization of the United Nations (FAO) concerning the legal or development status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. The mention of specific companies or products of manufacturers, whether or not these have been patented, does not imply that these have been endorsed or recommended by FAO in preference to others of a similar nature that are not mentioned.

The views expressed in this information product are those of the author(s) and do not necessarily reflect the views or policies of FAO.

ISBN 978-92-5-138089-5
© FAO, 2023

Some rights reserved. This work is made available under the Creative Commons Attribution-NonCommercial-ShareAlike 3.0 IGO licence
(CC BY-NC-SA 3.0 IGO; https://creativecommons.org/licenses/by-nc-sa/3.0/igo/legalcode).

Under the terms of this licence, this work may be copied, redistributed and adapted for non-commercial purposes, provided that the work is appropriately cited. In any use of this work, there should be no suggestion that FAO endorses any specific organization, products or services. The use of the FAO logo is not permitted. If the work is adapted, then it must be licensed under the same or equivalent Creative Commons licence. If a translation of this work is created, it must include the following disclaimer along with the required citation: “This translation was not created by the Food and Agriculture Organization of the United Nations (FAO). FAO is not responsible for the content or accuracy of this translation. The original English edition shall be the authoritative edition."

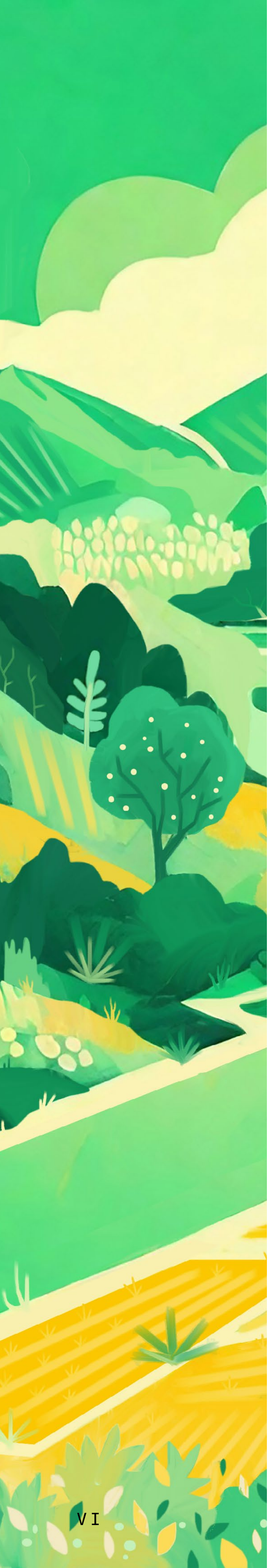
Disputes arising under the licence that cannot be settled amicably will be resolved by mediation and arbitration as described in Article 8 of the licence except as otherwise provided herein. The applicable mediation rules will be the mediation rules of the World Intellectual Property Organization http://www.wipo.int/amc/en/mediation/rules and any arbitration will be conducted in accordance with the Arbitration Rules of the United Nations Commission on International Trade Law (UNCITRAL).

Third-party materials. Users wishing to reuse material from this work that is attributed to a third party, such as tables, figures or images, are responsible for determining whether permission is needed for that reuse and for obtaining permission from the copyright holder. The risk of claims resulting from infringement of any third-party-owned component in the work rests solely with the user.

Sales, rights and licensing. FAO information products are available on the FAO website (www.fao.org/publications) and can be purchased through publications-sales@fao.org. Requests for commercial use should be submitted via: www.fao.org/contact-us/licence-request. Queries regarding rights and licensing should be submitted to: copyright@fao.org.

Cover illustration and graphic design: ©Nina Barrois

CONTENTS



BOX AND FIGURES

BOX

FIGURES

FOREWORD

The concept of nature-positive production in the area of food and agriculture was coined at the first United Nations Food Systems Pre-Summit and Summit (UNFSS) in July and September 2021. The imperative need to steer the world's food systems towards sustainability in its three aspects – environmental, social and economic – was thus framed through five action tracks: ensure access to safe and nutritious food; shift to sustainable consumption; boosting nature-positive production; advance equitable livelihoods; and build resilience to shocks and stress.

The Food and Agriculture Organization of the United Nations (FAO), as the lead United Nations agency for technical expertise in food security, agriculture, forestry, fisheries and rural development, pursues Sustainable Development Goal (SDG) 2 – as custodian agency of ten of its 13 indicators – to end hunger and malnutrition in all its forms. The sustainability of agrifood systems is at the heart of this agenda and is a priority for achieving SDG 2.

However, there are many SDGs relevant to the achievement of this goal, including those aimed at nature protection (SDG 14 and SDG 15). This remind us of the key message that nature must be our ally and that agricultural production must add to, not subtract from, environmental sustainability.

The FAO Strategic Framework 2022–2031 frames all the above with aspirations for better nutrition, better production, better environment and a better life. The transformation of agrifood systems leads to sustainability, and to achieve this we must make peace with nature. This is a lesson well known in the work of FAO, which also leads the United Nation's technical expertise for the long-term sustainable management of essential natural resources.

During the UNFSS, Rome-based United Nations agencies were tasked with leading the follow-up efforts resulting from the summit, as well as mobilizing all United Nations agencies and key partners for the provision of concrete and timely policy and technical assistance support to Members. With this commitment, FAO continues to move forward to catalyse impacts together with Members and other United Nations agencies, providing technical expertise and leveraging tools and processes to support national transformation plans.

To this end, this work contributes to the body of knowledge on nature-positive production initiated during the preparation for the UNFSS. It provides an in-depth conceptual framework in the analysis of the processes that regulate the sustainable production of agroecosystems, tools for their assessment, and key priorities and techniques for their enhancement. It forges new insights by integrating scientific evidence with defined and approved frameworks within FAO to facilitate the path towards nature-positive agriculture.

This work has been carried out by the FAO Regional Office for Europe and Central Asia. This is the first work proposed by FAO directly aimed at strengthening the concept of nature-positive production agriculture and proposing a basis for evaluation and implementation priorities. However, it is primarily oriented towards FAO's strategic work in the Europe and Central Asia region, and therefore it focuses its vision on one of the top priorities set out in the outcomes of the UNFSS for Europe and Central Asia: more rational, sustainable and coordinated use of finite natural resources such as land, soil and water (FAO, 2023c).

Vladimir Rakhmanin
FAO Assistant Director-General and
Regional Representative for Europe and Central Asia

ACKNOWLEDGEMENTS

This publication was prepared by the FAO Regional Office for Europe and Central Asia under Regional Initiative 3 to manage natural resources sustainably and preserve biodiversity under a changing climate. The driving force and framework of some of the new insight provided in this work to the concept of nature-positive production agriculture draw on the exhaustive work carried out by:

- the Research project on Agroecological Landscapes and Food Systems (AGROLAND PID2021-123129NB-C41), coordinated among the Food Action Research Observatory at the University of Barcelona;
- the Metropolitan Laboratory of Ecology and Territory of Barcelona at the Institut Metròpoli in the Autonomous University of Barcelona; and
- the Agro-ecosystems History Laboratory at the Pablo de Olavide University in Seville, Spain.

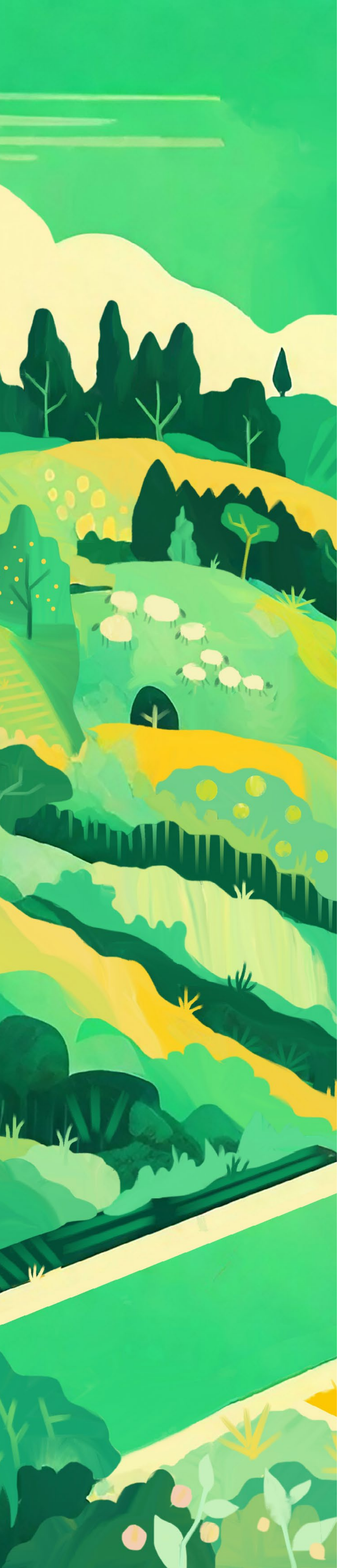
We send them special thanks and recognition for their commendable scientific contribution.

This publication was prepared under the direction of Raimund Jehle, Regional Programme Leader with the FAO Regional Office for Europe and Central Asia. The overall coordination was carried out by Tania Santivañez, agricultural officer and Regional Initiative 3 leader manager with the FAO Regional Office for Europe and Central Asia. Santivañez was the trigger and the spark of this project, not only dreaming up scenarios but managing to put in place the resources and the right foundations to make them happen.

Contribution during the initial stages of the publication concept and comments and publication review are gratefully acknowledged from Martina Duncan, International Climate Change Specialist, FAO; Virag Nagypal, Climate Change and Natural Resource Management Junior Technical Officer, FAO; and the Regional Initiative 3 technical team with the FAO Regional Office for Europe and Central Asia.

The authors of this report would like to acknowledge the valuable peer review comments provided by Anna Kanshieva, Biodiversity and Science and Innovation Specialist, FAO; Antonio Mele, Ecosystem Services Consultant, FAO; Enric Tello, Professor of History and Economic Institutions, Universitat de Barcelona; and Ni Jia, Green Cities Initiative and City Region Food Systems Consultant, FAO. Appreciation is also expressed to Jeremy Schlickenrieder, Natural Resources Officer, FAO; and Yurie Naito, Technical Officer, FAO.

Thanks also are due to Matthew D. Anderson for his editing work and to Nina Barrois, who provided graphic design and layout support.



ACRONYMS AND ABBREVIATIONS

BR	biomass reused
EI	external inputs
ELIA	energy-landscape integrated analysis
EROI	energy return on input
FAO	Food and Agriculture Organization of the United Nations
FEROI	final energy return on input
GIAHS	Globally Important Agricultural Heritage Systems
IPCC	Intergovernmental Panel on Climate Change
ITPS	Intergovernmental Technical Panel on Soils
MEFA	material and energy flow accounting
NBS	nature-based solutions
NPPA	nature-positive production agriculture
NPPACT	actual net primary production
NPPPOT	potential net primary production
SDG	Sustainable Development Goal
TAPE	Tool for Agroecology Performance Evaluation
TIC	total inputs consumed
UNFSS	United Nations Food Systems Summit
UPH	unharvested phytomass

EXECUTIVE SUMMARY

This paper aims to provide more elements to better frame nature-positive production agriculture from a theoretical viewpoint, assess its feasibility and possible limits, and introduce tools for its implementation and monitoring.

The Scientific Group of the UNFSS 2021 set the foundation for boosting nature-positive production in line with the ten principles of agroecology defined by FAO (2023a), the three pillars of nature-based solutions (Eggermont *et al*., 2015; Cohen-Shacham *et al*., 2016), and landscape as the key intervention scale (Hodson *et al*., 2020). Further contextualization and analyses underline the societal necessities that nature-positive production agriculture can tackle in the current international context – the strategic lines but also the challenges (agronomic, economic and social) faced by its implementation (Hodson De Jaramillo *et al*., 2023). Because nature-positive production agriculture is a recent conception, further work is required to define it and make it operational.

This paper is divided into three parts. The first consists of a theoretical framework resulting from a search for answers to two questions: "What does nature-positive mean?" and "What features characterize a nature-positive production system?" The second part presents tools for assessing the nature positivity of agroecosystems, and the third chapter touches ground with a list of proposed priority agroecological, nature-based practices that can help increase the nature positivity of agricultural systems.

The theoretical analysis approaches are the theory of thermodynamics of living systems, its application to agroecosystems and their components, social metabolism, and the analysis of the energy/material profiles and balances that characterize agroecosystems. The resulting framework at the core of this work is the foundation that underpins the following chapters. This theoretical framework is composed of the main characteristics affecting the productivity of agricultural systems: energy storage capacity, energy mobilization capacity and structural complexity. The ecosystem components critical for nature-positive production agriculture systems are:

- above- and below-ground biomass for energy storage;
- soil biota, soil fertility and trophic levels for energy mobilization; and
- biodiversity and landscape patch diversity for structural complexity.

After breaking down the mechanisms through which agroecosystems sustain themselves and their productivity, the second chapter suggests tools for assessing the nature positivity of agroecosystems at the territorial scale. The material and energy flow accounting methodology is proposed as the most effective way to track and analyse the energy profile of an agroecosystem. The energy-landscape integrated analysis methodology further complements the material and energy flow accounting methodology by incorporating landscape complexity metrics. With these tools, we can assess the energy return on investment ratio, which defines how efficient a system is in providing energy rather than consuming it and understand the relationship between landscape and biodiversity. Finally, the Tool for Agroecology Performance Evaluation can provide more accessible analytic tools for assessing some of the features defined in the nature-positive production agriculture framework from a participative approach.

The third chapter proposes five priority areas in which to frame the measures and practices to increase the nature positivity of agricultural systems at the farm level. Mostly drawing from the nature-positive production agriculture theoretical framework, the principles of nature-based solutions, agroecology, permaculture and soil as the key element for energy storing and mobilization, these priority areas are: soil and water conservation; soil improvement; evolutionary populations; integrating crops, forestry, livestock and aquaculture; and integrated pest management. This work argues that the key to sustainable, nature-positive production agriculture lies in understanding, respecting and mimicking how ecosystems build up their own sustainability.

Therefore, in order to be nature positive, a system should be net energy positive and build its own endogenous sustainability through actively promoting complexity, energy storage and energy mobilization. It should prioritize reducing the need for external inputs and enhancing the overall biomass production with nature-based solutions, acknowledging at the same time that productivity cannot exceed the system's natural carrying capacity, which is not a fixed value but develops with ecological successions and systemic complexity.


© Paolo Nicolello

© Chema

INTRODUCTION

The challenge for the future of agriculture is how to feed a growing population, expected to reach around 10 billion by 2060 (United Nations, 2022), with the finite resources available within planetary boundaries. At the beginning of the twenty-first century, estimates suggested that global food production must increase by 70 percent by 2050 in order to feed the world population (FAO, 2009). In recent years, many institutions and authors have approached this productivity challenge from a "sustainable intensification" perspective, meaning that technological and management advances would allow us to reach this goal without needing to expand the agricultural frontier to farm new areas.

Action Track 3 from the 2021 UNFSS – "boost nature-positive production" – adds a new element to the ongoing debate on food systems: Future agriculture not only needs to be environmentally sustainable, but it should also assist our efforts of ecosystems recovery (Hodson *et al*., 2020). In other words, the ideal system we should be aiming at is expected not only to avoid the depletion of natural resources but also to actively improve the capacity of the biosphere to sustain terrestrial and marine habitats while providing food for everyone. Therefore, nature-positive food systems are characterized by a regenerative, non-depleting and non-destructive use of natural resources (Hodson De Jaramillo *et al*., 2023), in line with the agroecological approach. Moreover, following a similar categorization of nature-based solutions (Cohen-Shacham *et al*., 2016), nature-positive production agriculture should be centred on three main objectives:

- protect natural habitats and prevent the expansion of agriculture in protected areas;
- sustainably manage existing food systems; and
- restore degraded productive systems and bring them back within the boundaries of long-term sustainability.

While modern industrial agricultural systems have managed to increase crop productivity considerably, they also have been found to be less efficient than ancient organic farming in their energy input–output ratio, as a result of dramatic increases in the external inputs applied (Marull *et al*., 2019a; Tello *et al*., 2016, 2008). Natural ecosystems, on the contrary, spontaneously tend to maximize their energy efficiency through developing increasingly more complex nutrient recycling chains that circulate larger and larger amounts of energy within the system (Schneider and Kay, 1994). As a result, developing ecosystems gradually increase biomass productivity, which is their main energy storage structure. A relevant role in ecosystem productivity is played by biodiversity, which increases the variety of physical structures and timeframes in which energy is kept circling within the system (Altieri, 1999; Flombaum and


© Ashutosh Chaudhari

Sala, 2008; Mori *et al*., 2021). Complexity thus emerges as one of the key features for ecosystem sustainability (Capra, 2005; Mayer, 2020; Prigogine, 1986). **We argue that any productive system that aims at becoming regenerative for nature, or "nature positive," should follow the way of complexity and diversification (Figure 1).**

When addressing nature-positive production agriculture, it is important to clarify what productivity is from an ecological perspective. According to the thermodynamic approach adopted in this paper, productivity should be assessed in an integral way that goes beyond crop yield and food productivity (hence Figure 1 compares crop output with biomass output); biomass productivity develops hand in hand with ecological successions and is directly linked with nutrient recycling feedbacks, even in agroecosystems with the main aim of producing food. Unharvested biomass should therefore be considered an important energy carrier that maintains and stabilizes soil fertility and other ecological services provided by above- and below-ground biodiversity.

A nature-positive approach should therefore aim at maximizing the overall biomass productivity in a given territory, rather than only food productivity, in order to keep ecosystem services running and support overall natural functioning. This approach is similar to pre-green-revolution organic farming, which used to achieve sustainability through the exchange of energy and matter among different land uses (farmland, forestry, pastures and natural areas), with a territorial management focus. Unfortunately, these systems are also known to require an extra land cost – also called land cost of agrarian sustainability – for the same food output to be produced, in comparison to modern agro-industrial systems (Guzmán Casado and González De Molina, 2009; Guzmán, González De Molina and Alonso, 2011). The land cost of agrarian sustainability is an inherent feature of any territorialized and independent agroecosystem; whether sustainable intensification practices will be able to reduce it remains to be seen.

By referring to both natural functioning and food production, nature-positive production requires a multidisciplinary approach that can bring together ecology and agronomy. **This paper tries to build this bridge by applying the thermodynamic perspective to the question of agricultural production**. Hence, the core of the proposed framework is the analysis of agroecosystems as both energy-consuming and energy-capturing structures whose functioning and productivity are directly correlated with structural complexity and the capacity to store and recycle incoming energy flows.

As a result of this conceptualization, **this paper also argues that food production and environmental stewardship (including biodiversity conservation) are not necessarily conflicting but possibly complementary.** Agriculture needs biodiversity, while biodiversity can benefit in return from the increased primary production that nature-positive production agriculture can spark. This stance is still seen with scepticism from many actors and practitioners, so the paper showcases scientific evidence in an attempt to support it.

METHODOLOGY

This study has been established through a desk review of the materials resulting from the 2021 UNFSS in relation to Action Track 3 on boosting nature-positive production and a wide range of scientific literature from academia, United Nations agencies, the European Commission and non-governmental organizations.

For the theoretical framework established in Chapter 1, this work analyses the linkages among ecological productivity, the sustainability of ecosystems and social metabolism, extracting key concepts and theories connected with this nexus from the following investigation lines:

- the sustainability and thermodynamics of living systems;
- complexity theory;
- the relationship between biodiversity and productivity;
- ecological successions;
- disturbance ecology;
- the energy efficiency of agroecosystems;
- agricultural sustainability; and
- traditional agriculture.

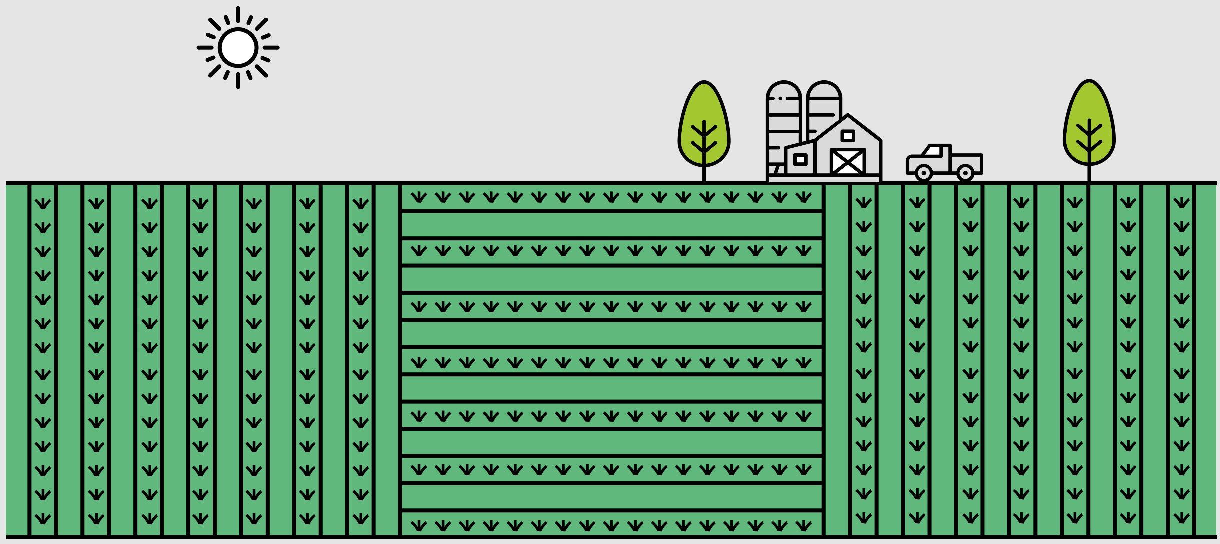
Chapter 2 on measuring and monitoring nature-positive production is based on methodologies provided by FAO (the Tool for Agroecology Performance Evaluation) and by a multidisciplinary research group at the University of Barcelona and the Pablo de Olavide University, among others.

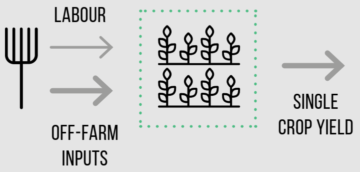
Finally, the priority intervention areas defined in Chapter 3 stem from the matching of the previous chapters' results with the main principles of agroecology, developed by FAO, and permaculture.

LIMITATIONS OF THIS STUDY

While this study provides a list of practices and techniques that can assist the reintegration of agricultural practice, nature and biodiversity management, said list is not exhaustive of such a complex social–ecological nexus. This study also doesn't tackle the institutional, economic and systemic obstacles that need to be overcome to allow for the large-scale implementation of nature-positive production agriculture (well identified in Hodson *et al.*, 2020).

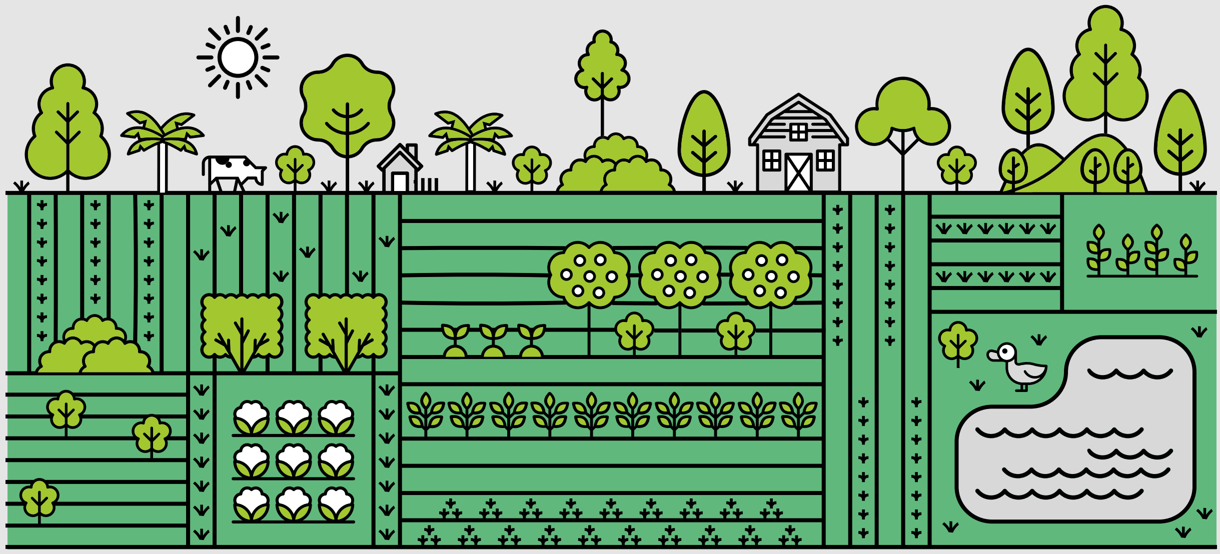
FIGURE 1. ENERGY FLOW COMPLEXITY IN MONOCULTURAL SYSTEMS AND DIVERSIFIED/INTEGRATED SYSTEMS

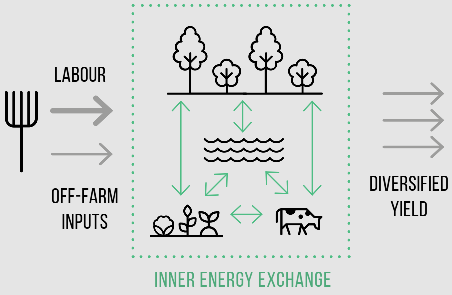




MONOCULTURAL SYSTEMS

- 🔴 high nutrient extraction rate
- 🟢 high average crop output
- 🟡 intermediate output stability
- 🔴 low energy efficiency
- 🟢 high labour efficiency





DIVERSIFIED/INTEGRATED SYSTEMS

- 🟡 intermediate nutrient extraction rate
- 🟢 high average biomass output
- 🟢 high output stability
- 🟢 high energy efficiency
- 🔴 low labour efficiency

🔴 unfavourable 🟡 neutral 🟢 favourable

Source: Authors' own elaboration.


© Oziel Gomez

CHAPTER 1. A THEORETICAL FRAMEWORK FOR NATURE-POSITIVE PRODUCTION AGRICULTURE


© GIAHS/Pareto Paysages

The theory draws from the thermodynamics of living systems, including its application to the nexus between biodiversity and productivity, from social metabolism and material and energy flow accounting. This approach has been considered fit for this paper's purpose because:

- It is scientifically sound and long-term tested.
- It provides indicators and quantitative methodologies.
- Because it is suitable for historical analyses, it helps in the analysis of today's picture and the trends and trajectories of our agricultural systems in time.
- It avoids the biases of many other approaches that advocate for sectoral solutions (technological, digital, economic, agronomic, etc.).
- It is applicable to any agricultural system regardless of the geographic location, climate or cultural environment.

Through the thermodynamic perspective, the inherent functioning of ecosystems is analysed and conclusions drawn regarding the interrelations between systemic complexity, sustainability, biomass production, natural resources and biodiversity. These theoretical elements will then set the basis for approaching the goal of ecosystem restoration pursued by nature-positive production agriculture.

1.1. A THERMODYNAMIC APPROACH TO LIFE: ECOSYSTEMS AS LIVING ORGANISMS, COMPLEXITY AND SUSTAINABILITY

The concept of nature-positive production seeks to understand and exploit the possible synergies between food and agriculture production and nature. What does productivity mean in nature? This work argues that the nexus of this synergy lies in the thermodynamic functioning of living systems.

Thermodynamics state that every physical and chemical process is inherently and constantly driven towards increasing entropy. So, how are living systems able to sustain their own life, if the very nature of any process is to dissipate energy and reach thermodynamic equilibrium (in other words, death)? Authors such as Erwin Schrödinger (1944) and Ilya Prigogine (1986) have argued that the answer to this question lies in the capacity that living systems have to offset and "dump" the entropy they produce in the surrounding environment. Living systems can hence be seen as "dissipative structures" that accumulate energy, in the form of high-complexity organic compounds, in order to further increase their capacity to catch energy over time and dump entropy (in the form of lower-complexity biomass). Their sustainability, or their far-from-thermodynamic-equilibrium state, depends on these constant flows of higher-complexity-energy input and lower-complexity-energy output (well exemplified by cellular respiration).

All of this also applies to any ecosystem, including agricultural systems (henceforth referred to as "agroecosystems"), whose energetic input is not only solar radiation but also labour and other external inputs injected by human societies, which shape the system in order to achieve a certain amount of food produce output. **This paper looks at agroecosystems as dissipative structures whose functioning and efficiency depend on the overall amount of energy flowing through them as well as their capacity to store it.**

In order for living systems to be able to self-generate, the simple exchange of energy and matter with the environment is not of any use unless it brings to energy accumulation within the system itself: Living systems grow and stabilize thanks to their capacity to turn the energy/matter input from their environment into new structures (new biomass), the function of which is both energy storage and energy mobilization. Organisms store energy in their tissues and mobilize it with their biological processes; ecosystems store energy in the biomass of their organisms and mobilize it through the food chain and the nutrient recycling that happens in the soil. These two functions, energy accumulation and constant circulation, are at the core of life sustainability and are directly correlated with systemic complexity.

This link between complexity and sustainability in ecology recently has been under the spotlight with the ever-more-compelling call for biodiversity protection, which is universally considered one of the most important goals for


© GIAHS/Badal Sarker

preventing further ecosystem degradation (Convention on Biological Diversity, 1992; Agenda 2030; United Nations Decade on Ecosystem Restoration, 2020–2030). Other authors have investigated the role of information and complexity in ecosystems and their analysis under a thermodynamic perspective (Font *et al*., 2020; Marull *et al*., 2016a, 2019a; Ulanowicz, 2001). In general, increasing information and complexity in agroecosystems implies a structural diversification (of land uses, landscape elements, crop species, gene pools, economic activities, etc.): The need to diversify agriculture has been also supported cross-culturally from an environmentally centred, Western perspective (Tamburini *et al*., 2020); a family farming-centred, developing countries perspective (Schneider, 2009; Schneider and Niederle, 2010); and a cultural heritage perspective (Ranaboldo and Leiva, 2013).

From a thermodynamic perspective, the flaw of simplified and monocultural agroecosystems is that they mostly fail in supporting these key energy efficiency mechanisms, whose function is substituted by external, fossil fuel-based, high-embedded-energy inputs. In the long term, the result is the partial loss of the self-regenerating capacities that ecosystems normally develop. Nature-positive production agriculture systems, on the contrary, should be designed first of all to maximize energy storage chances and to keep a large flow of energy constantly cycling through them, just as natural ecosystems do to ensure their capacity to grow and thrive. This can be achieved mostly through increasing the system's **complexity**. The average yearly balance between energy input (labour and farming inputs) and output (harvested produce) should also be close to net zero, or even possibly positive, in order to allow for the replenishment of natural resources and actively promote ecosystem regeneration. Whenever the energy output exceeds the input, some sort of resource depletion is happening within the system, most likely at the expense of soil fertility (Tello *et al*., 2015, 2008).

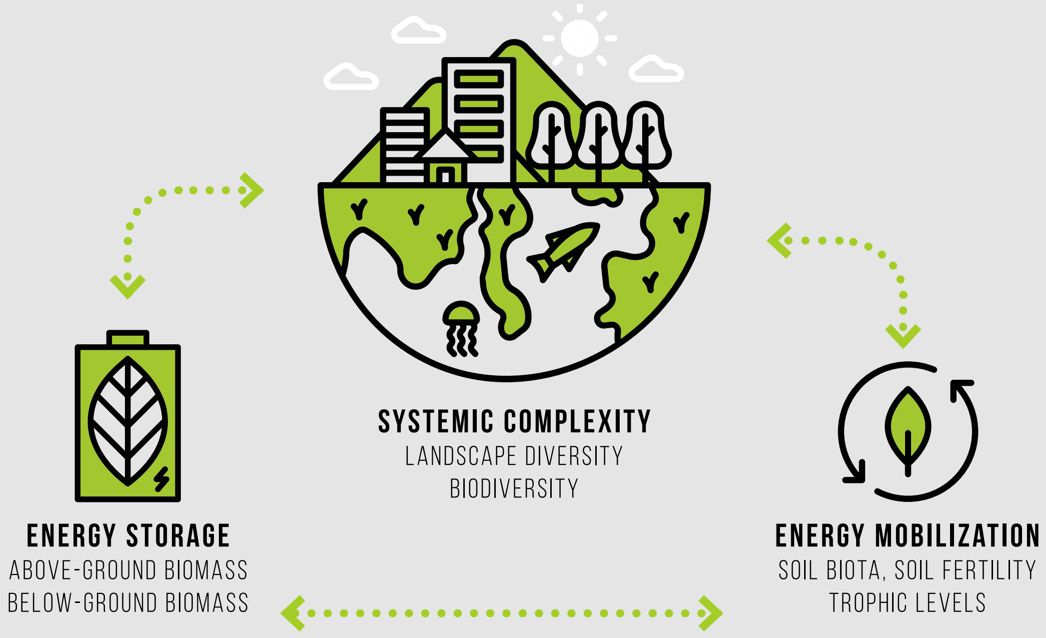
According to the three main features highlighted above, the most critical structures for nature-positive production agriculture systems are:

Above-ground and below-ground biomass for energy storage. More biomass means more energy units available within the system.

Soil biota, soil fertility and trophic levels for energy mobilization. A rich soil and longer food chains ensure more efficient recycling and longer residence time within the system for each energy unit.

Landscape diversity and biodiversity for systemic complexity. Diversity of habitats, species and gene pools increase both energy storage chances and energy recycling rates.

FIGURE 2. MAIN FEATURES AND ECOSYSTEM COMPONENTS AFFECTING PRODUCTIVITY



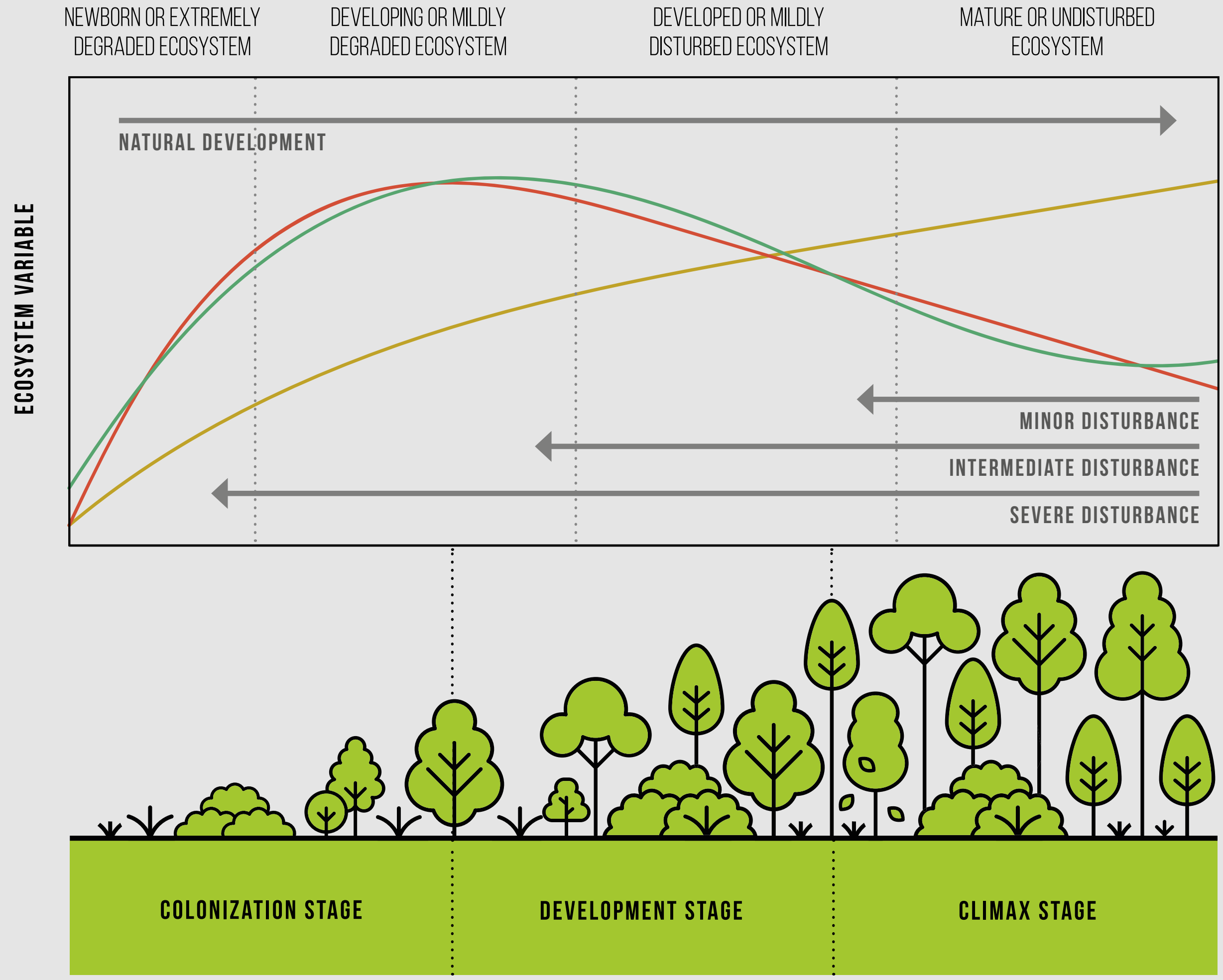
Source: Authors' own elaboration.

1.2. ECOLOGICAL SUCCESSIONS: THE NEXUS BETWEEN PRODUCTIVITY AND BIODIVERSITY

Ecosystems and organisms show similar patterns when it comes to growth and biomass production, although at very different timescales: Their productivity increases with exponential growth in the early development stages, flattens at maturity, and slowly decreases with ageing. However, although the late stage of organisms is usually degenerative until death, ecosystems don't really degenerate; rather, they stabilize, as seen in Figure 2. Moreover, while organisms only follow one growth direction, the evolution path of ecosystems is not linear but dynamic: Depending on the frequency and extent of environmental disturbances, ecosystems shift between maturing stages, where stability gradually increases, and degrading stages, where disturbances alter the established balances and cause the loss of ecological niches and biodiversity. Big fires, heavy storms, volcanic eruptions or landslides can occasionally wipe out a large portion of the above-ground life in an ecosystem and send it back to an earlier stage of development. In the case of agroecosystems, the continuous removal of large portions of biomass in a crop field, either by harvesting, grass removal or both, is also to be considered a severe disturbance that keeps the system at a low-biodiversity, low-productivity early stage.

Newly colonized ecosystems, as well as ecosystems recovering after a severe disturbance, quickly increase biodiversity and productivity until they reach a mature stage at which accumulated biomass stops growing and becomes stationary. From a thermodynamic point of view, the fully mature stage is where the energy storing rate (new biomass) roughly equals the energy dissipation rate that comes from animals' and plants' metabolisms (the so-called "ecosystem respiration," cellular respiration plus photosynthesis). This means that the energy intake equals the energy output, and there is no more accumulation within the system. This late succession stage

FIGURE 3. ECOLOGICAL SUCCESSIONS



Source: Adapted from Guo Qinfeng 2005. *Ecosystem maturity and performance.* Nature 431: 181-184.

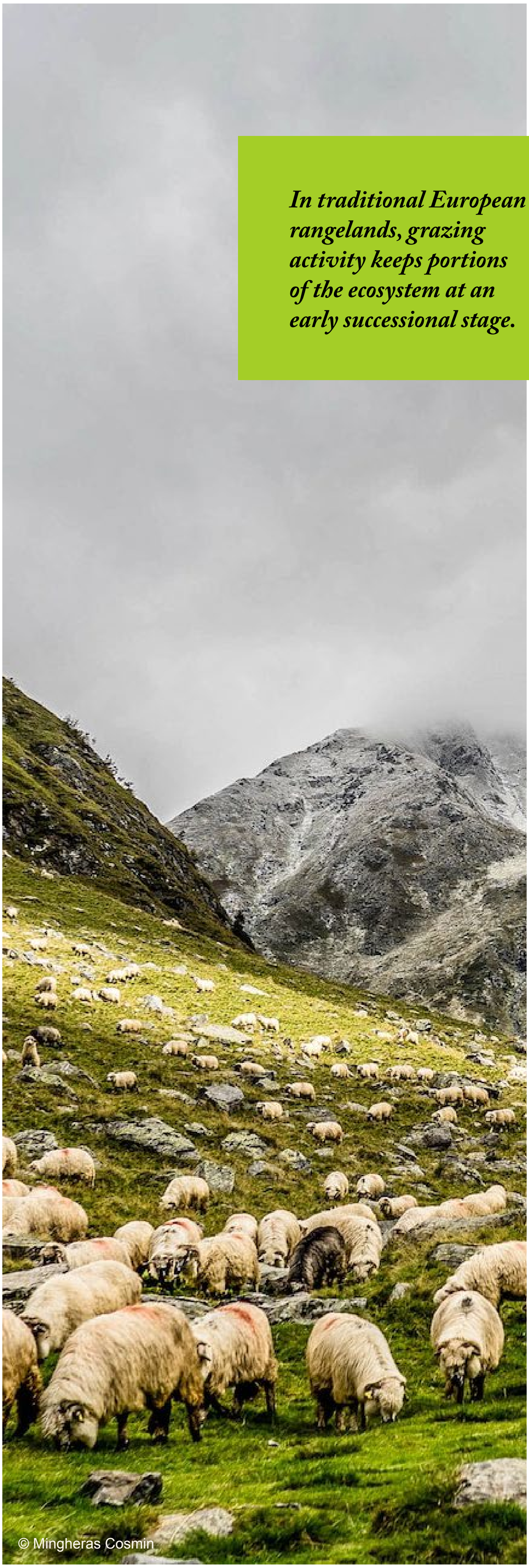
is where all the possible ecological niches have been filled and the system has reached its maximum possible energy storage capacity. As Figure 2 shows, diversity and productivity peak in the developing stage of an ecosystem, which reflects the role that ecological (and/or anthropic) disturbances have in driving both characteristics. High rates of disturbances keep the ecosystem at an "infancy" stage where colonizing species dominate, whereas low disturbance rates keep the ecosystem at a fully developed stage where climax species have a functional advantage. An intermediate level of disturbance is often associated with higher biodiversity and productivity, where colonizing and climax species co-exist in complementary landscape patches (Dasgupta, 2021; Hall *et al*., 2012; Willig and Presley, 2018). Any effect on biodiversity depends on the disturbance's frequency, extent and intensity (ibid.).

The analysis of successional dynamics suggests that the anthropic disturbances that come from agriculture or forestry don't necessarily result in an impoverishment of the agroecosystem. While it is undeniable that extensive land use changes are driving habitat and biodiversity loss all over the world, the limited disturbance created by low-intensity agriculture can keep the agroecosystem in an intermediate developing stage, with relatively higher biodiversity and biomass production rates. Therefore, low-intensity agriculture has the potential to increase the amount of energy (biomass) circling within a given ecosystem, at the expense of its stability. Nature-positive production agriculture systems have the potential to be more productive and diverse than both industrial agriculture and undisturbed nature.

One example of such positive correlation between anthropic disturbances and biodiversity is the traditional European rangeland, where grazing activity keeps portions of the ecosystem at an early successional stage. This results in a higher landscape patch diversity and exceptionally high biodiversity. Eighteen percent of endemic European vascular plants are connected to these seminatural grasslands – almost twice as many as in forests, which cover a much larger land surface – as are more than two-thirds of the butterflies species (Habel *et al*., 2013; Lomba *et al*., 2015). In the Western Balkans, rangelands only cover around 20–30 percent of the total land area, yet up to 70 percent of the important plant areas in the region are associated with these habitats maintained by herders (Kazakova and Stefanova, 2010).

The limited spatial and temporal extent of the grazing disturbance prevents excessive ecosystem degradation. The European Union coined the concept of "high nature value" farming in order to recognize the contribution to biodiversity of low-intensity livestock activities, so much so that high nature value metrics are among the biodiversity indicators used to evaluate the effectiveness of the European

In traditional European rangelands, grazing activity keeps portions of the ecosystem at an early successional stage.



© Mingheras Cosmin


© Amy Humphries

Union Member State Rural Development Programmes (European Commission, 2006). The abandonment of pastoralist activities and the intensification of grazing has in fact become a growing concern for the protection of European biodiversity.

In forestry, natural disturbance-based management is precisely centred on the artificial emulation of natural disturbances, whose role in maintaining ecological structure and function is widely recognized (Attiwill, 1994; Bergeron and Fenton, 2012; Newman, 2019). Natural disturbance-based management is emerging as one of the possible paradigms of sustainable forest management (Kuuluvainen *et al*., 2021).

Even the oases systems,[1] which are artificial and aimed at the production of food, can be seen as examples of the potential that the anthropic action has in enhancing the ecosystem capacity to develop and support biodiversity.

Figure 2 also shows the direct connection that links biodiversity and biomass productivity (also see Liang *et al*., 2016, for a focus on forests), as a result of the former's contribution to systemic complexity.

Biodiversity cannot be observed solely as the number of species present in an ecosystem; it also implies species functional traits and the different functions performed among living organisms and between these and the non-living structures of an ecosystem. This is called functional diversity. All the ecosystem elements connect through the nutrient cycles and the energy flows, creating sustainable and complex energy storage structures that improve the energy "residence time" (that is, the amount of time an energy unit spends in a system before being released out of it) within the system. Microorganisms, plants, lichens, fungi and animals, at all trophic and community levels, perform biological and chemical processes that provide services to human activity in agriculture, including biomass production. Most of these organisms reside in the soil – more than one-quarter of global biodiversity (FAO, 2022) – and from there they carry out such functions as photosynthesis, carbon fixation, decomposition of organic matter, recycling of nutrients, oxygenation and aeration of the soil – which enables water filtration and the displacement of root structures – among many others.

Losing biodiversity implies reducing an agroecosystem's energy storing and energy dissipation capacity. As suggested in The Economics of Biodiversity (Dasgupta, 2021), this is due to reduced efficiency in the capture of biologically essential resources by the organisms (nutrients, water, sunlight, prey),

---

[1] Extraordinary examples of oases have been recognized by FAO with the Globally Important Agricultural Heritage Systems award. For more information, visit https://www.fao.org/giahs/en/.

and consequently decreased biomass production. Accordingly, ecosystem productivity maintains a close functional relationship with biodiversity and biomass, and they go hand in hand throughout all the stages of an ecosystem life cycle.

The rhythmic cycle of nature – from the input of solar energy collected by primary producers to the decomposition of products, going through all the ecosystem functions that allow the flow of matter and energy – makes up self-organized and regenerative ecosystems whose main drivers of stability must be maintained within agrifood systems to ensure long-term productivity and resilience (Dasgupta, 2021).

As already mentioned, biomass is to be considered the main energy storage structure in ecosystems. Nevertheless, the soil subsystem acts as the main recycling structure, where spent energy (dead biomass) is decomposed and made available to build new biomass. Soil also represents the emergency energy storage structure, where seeds, macronutrients and micronutrients are accumulated: If a severe disturbance such as a fire or a landslide wipes out all the above-ground biomass in an ecosystem, the soil acts as the energy reservoir from which the ecosystem rebuilds itself.

The bottom line of this summary of ecosystem functioning is that there are close links among biomass production, soil richness and systemic diversity. To improve agricultural production sustainably, the underlying biophysical conditions that may make it possible should be accounted for; the main condition that needs to be met is having more energy naturally flowing (as opposed to artificially injected, such as via chemical fertilizers in industrial agriculture) through our agroecosystems, with the objective of feeding the soil communities rather than depleting them.

This can be achieved through a more complex landscape mosaic in which farmland interacts more often with woodland and seminatural areas. Productivity should be assessed, managed and maximized at the


© Iswanto Arif

Farmland interacting with woodland and seminatural areas allows for more natural energy flow.

landscape/ecosystem scale in an integrated way, with biomass being exchanged among the different land use patches, from the forests and natural buffer zones in which it naturally accumulates to the farmland and pastures where it's harvested. Living organisms, "the most energy-efficient 'machines' by far" (Ho and Ulanowicz, 2005), should be put back at the centre of our strategies, displacing chemical inputs. The integration among farmland, pollinators, livestock, forestry and natural areas has, in fact, been a key feature of historical organic agroecosystems that have managed to sustain communities for centuries, if not millennia (FAO, 2018a; Guzmán Casado and González de Molina, 2009; Marull *et al*., 2018; Tello *et al*., 2012).

1.3. SOCIAL METABOLISM AND MATERIAL AND ENERGY FLOW ACCOUNTING

Social metabolism (also called "societal metabolism" or "socioeconomic metabolism") entails the application of the biological concept of metabolism to socioeconomic systems. These are modelled into a set of components or substructures that are connected by flows of energy and/or matter. The theory behind social metabolism was developed beginning in the second half of the nineteenth century to reintegrate natural sciences and economics (Hall *et al*., 2001). In opposition to the mechanical interpretation of classical economy, where inputs and outputs are always quantitatively and qualitatively equal, social metabolism allows for the accountancy of entropy and energy dissipation in the economic processes. While this analytical methodology has been mostly applied to industrial systems, this paper will discuss its application to agroecosystems.

Following this theory, agroecosystems can be modelled into three main subsystems: farmland (further dividable into cropland, pastures and woodland); livestock/barnyard; and associated biodiversity, energy and matter flow between these subsystems, in part due to natural processes and in part under the influence of the farming community. The agroecosystem receives its main energy inputs from the sun, as solar radiation, and from the farming community, in the form of labour and other agricultural inputs. The energy output consists of the harvested biomass from all three subsystems, whereas the portion of biomass that is returned to the subsystems can be accounted for as reused biomass.


© FAO

Because of their self-reproductive capacity, the substructures of an agroecosystem need to be considered as funds rather than stocks; funds are defined as "elements that are part of a process, which provide services for a certain period but are never physically incorporated in the product" (Georgescu-Roegen, 1971 in Padró *et al*., 2019). The farmland, livestock/barnyard and associated biodiversity subsystems are conceived as energy reservoirs with their specific input and output but also their inner throughput, which is crucial for their functioning and is affected by the input/output ratio. Analysing the extent and distribution of energy/matter flows allows for a first assessment of the long-term sustainability of a given agroecosystem under a specific management model. In order to be able to be nature positive, these management models need to take into account "the full costs of the agroecosystem's reproduction in biophysical terms" (Padró *et al*., 2019). This implies allowing for the regeneration of the energy storage and energy mobilization structures (above- and below-ground biomass, soil fertility, soil biota, trophic levels, etc.).

The material and energy flow accounting methodology is a tool that can be used to analyse the energy profile of such modelled agroecosystems under a fund flow perspective. The methodology simply aims at accounting for all the energy units that flow in the system and between its subsystems in a defined time span. **Chapter 2.1** will further discuss the application of material and energy flow accounting to agroecosystems, the challenges to overcome, and the useful information that it can yield for effectively measuring the potential for ecosystem support of nature-positive production agriculture.

© Ej Wolfson


© Hai Tran

CHAPTER 2. ASSESSING AND MONITORING NATURE-POSITIVE PRODUCTION AGRICULTURE AT THE TERRITORIAL SCALE

It is now clear that agroecosystems are not isolated systems and that their sustainability is connected to the good management of the structures that ensure their energy efficiency, as well as the human-assisted optimization of the biomass flows among different land uses thanks to agroecological and nature-based management. The need for effectively assessing and monitoring nature-positive production agriculture arises towards enhancing agroecosystems energy efficiency and self-generation, and so the question: how to assess the nature positivity of agroecosystems?

Following the main premise of the theory approach, the first part of this chapter delves into the analysis of the flow of energy and matter in agroecosystems (material and energy flow accounting), as a new contribution of this paper to FAO's ongoing work to analyse agricultural performance and support the transition towards more sustainable and resilient agrifood systems.

Secondly, we bring to the coalition the work done by FAO in the development of a tool capable of assessing agricultural performance in a participatory way across many dimensions to move beyond standard measures of productivity (e.g. yield/ha) and better represent the benefits and trade-offs of different agricultural systems: the Tool for Agroecology Performance Evaluation (TAPE).

2.1. MATERIAL AND ENERGY FLOW ACCOUNTING

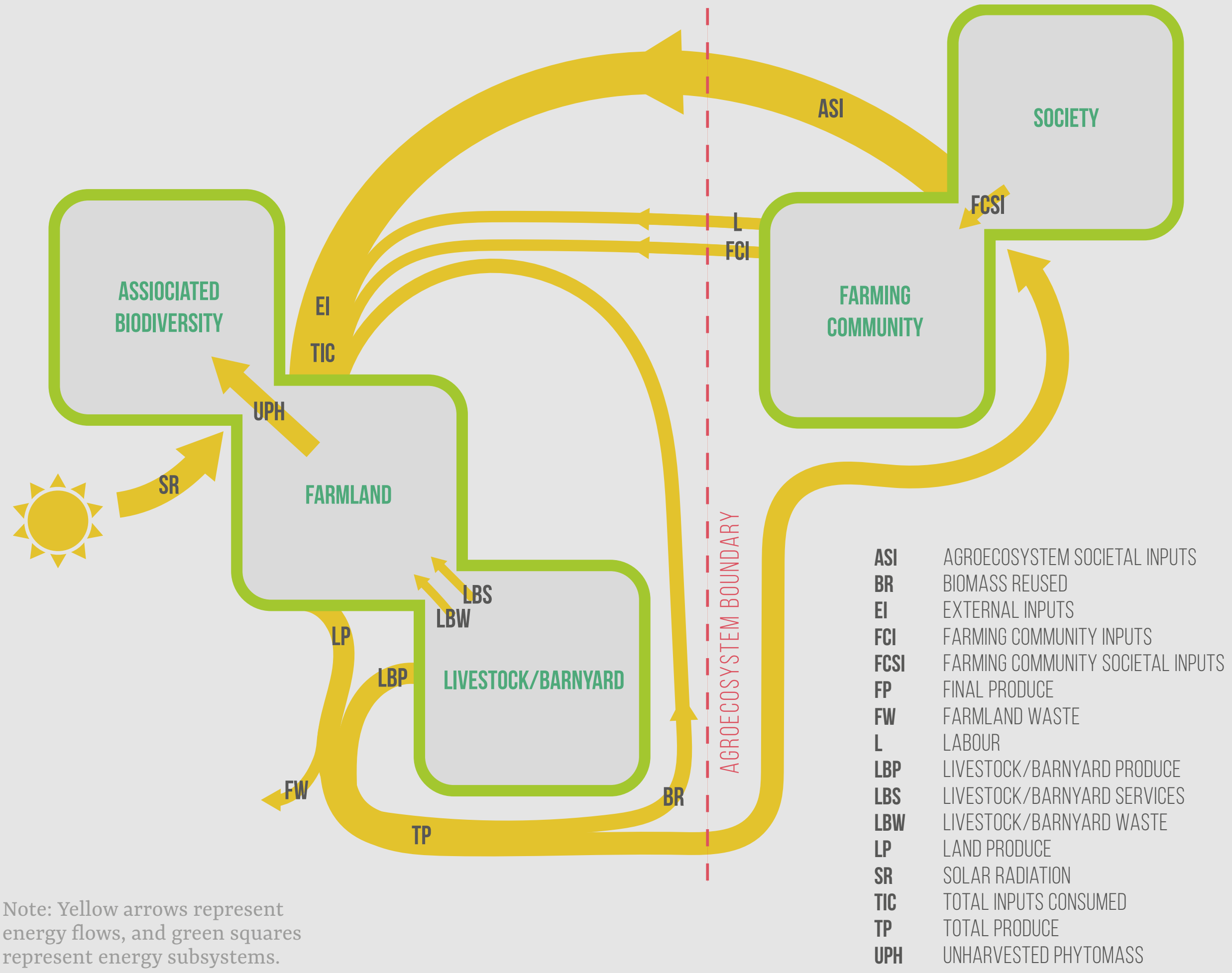
The material and energy flow accounting framework is used to analyse the complex interaction between society and nature by tracing and monitoring the material and energy flows that connect them and by assessing the effects that these flows have on the underlying ecosystems (Haberl *et al*., 2004). Material and energy flow accounting consists of modelling funds and flows in a graph in which the amounts of material and energy can be accounted for in a determined time frame. Compiling datasets for different time frames or scenarios opens up the field to analyses and strategic planning.

Figure 3 shows the modelling of a generic agroecosystem as suggested by Tello *et al*. (2015). The agroecosystem is divided into the three subsystems (farmland, livestock/barnyard, associated biodiversity), while the farming community and the global society act on it from the outside, both as input providers and as output harvesters. Compared to the usual metrics used in assessing production performances (mostly the tonnes of produce per hectare farmed), the varied metrics used in material and energy flow accounting allow for a variety of analyses and assessments. In particular, the energy feedback flows between subsystems can be accounted for, such as:

- the unharvested phytomass (UPH) that is left to feed the associated biodiversity and the ecosystem services they provide;
- the part of harvested produce that is reinvested within the system (biomass reused, or BR); and
- the leftover organic material that is recycled in the farmland from the livestock/barnyard subsystem as part of livestock/barnyard services.

The various energy carriers are explained in the **Annex**.

FIGURE 4. A SOCIAL METABOLIC MODEL OF AN AGROECOSYSTEM, WITH A SPECIFIED BOUNDARY



Note: Yellow arrows represent energy flows, and green squares represent energy subsystems.

Source: Tello, E., Galán, E., Cunfer, G., Guzmán, G., González de Molina, M., Krausmann, F., Gingrich, S. *et al.* 2015. *A proposal for a workable analysis of Energy Return on Investment (EROI) in agroecosystems*. Part I: Analytical approach. IFF Social Ecology Working Papers, 156: 1–110.

One of the main indicators that can be measured with material and energy flow accounting is the energy return on input, a ratio that compares the magnitude of the input flows with the amount of produce extracted by the agroecosystem, thus representing an effective energy efficiency indicator. A more detailed explanation of energy return on input indicators is provided in **Box 1**. Monitoring energy return on input indicators through time can provide useful insights on the extraction pressure that the natural resource funds are facing, as well as the rate of energy recycling occurring within the system, as opposed to the dependency on external inputs.

One of the most tested and analysed material and energy flow accounting applications to agroecosystems is the one applied to Vallés County in the Spanish region of Catalonia (Font *et al*., 2020; Marull *et al*., 2019b; Padró *et al*., 2020; Tello *et al*., 2016, 2008, 2012), where the energy return on input ratios were calculated for the historical comparison of 1860 and 1999 scenarios. The comparative analysis highlights a dramatic decrease in energy efficiency, with the overall energy output/input ratio dropping from 1.01 to 0.22, mostly due to a stark increase in energy input values. (For more on these ratios, see Box 1 on p. 17). This decreasing energy efficiency trend was confirmed by other studies applied to the different geographical contexts of North America and Europe (Marull *et al*., 2019a), southern Spain (Guzmán Casado and González De Molina, 2009), the United Kingdom of Great Britain and Northern Ireland (Schandl and Schulz, 2002), Austria (Krausmann *et al*., 2003), Colombia (Delgadillo-Vargas, Garcia-Ruiz and Forero-Álvarez, 2016) and Mallorca Island (Fullana Llinàs *et al*., 2021; Marull *et al*., 2016).

The drop in energy efficiency seems to be associated with decreasing landscape complexity and with polarization in land uses between untouched natural areas (including forests that were historically used for biomass extraction) and intensive agricultural patches. This resulted in growth for the species that prefer a simplified landscape matrix but also a strong loss in biodiversity associated to the traditional mix of low-input cropland, hedges, small wooded areas and seminatural areas.

The link between landscape complexity and biodiversity is solid and well documented (Estrada-Carmona *et al*., 2022; Marull *et al*., 2019b; Mayer, 2020; Tscharntke *et al*., 2012). Higher-complexity landscapes host more biodiversity (richness, abundance and evenness), with potential benefits for both agricultural production and nature conservation that are likely underestimated. It is a common misconception to think of biodiversity conservation and agricultural production as conflicting objectives, resulting in a separation of the two fields that then miss out on each other's potential synergy: "**Our findings provide a strong scientific evidence base for synergistically managing agriculture at the landscape level for biodiversity conservation and sustainable production**" (Estrada-Carmona *et al*., 2022).

Higher-complexity landscapes host more biodiversity, with potential benefits for both agricultural production and nature conservation.


© Nenad Radojcic


© Uneke Ub

While this material and energy flow accounting application to agroecosystems can provide useful information on the key system's features of energy storage and mobilization, it still fails to take into consideration landscape and systemic complexity. In order to fill this gap, the energy-landscape integrated analysis was developed. Here, the analysis of energy flows is complemented by landscape complexity indicators. These are elaborated in the form of a modified Shannon diversity index that measures energy flows coupling and distribution through the subsystems (Font *et al*., 2020; Marull and Font, 2017). Incorporating these indicators can further deepen the range of territorial analysis of nature-positive production agriculture systems, but they also require fairly advanced mathematical and statistical tools that are beyond the scope of this paper.

Performing material and energy flow accounting or energy-landscape integrated analysis requires thorough data collection and processing. Some of the challenges that arise may be the effective accountancy of human labour; how to account for the embedded energy of machineries, fuel and other imported inputs; and the risk of double accounting energy flows. For a comprehensive guide on how to apply material and energy flow accounting, a reference to the aforementioned article by Tello *et al*. (2015) is suggested, while Marull and Font (2017) and Padró *et al*. (2020) detail how to conduct energy-landscape integrated analysis. Because these tools are designed to take into consideration the energy/matter exchanges that connect farmland with other land uses (forestry, pastures, natural areas, etc.), they are best applied at the landscape or territorial scale rather that at the farm scale; hence, considering the application scale and the resources required, the administrative bodies or research centres appear to be the most adequate actors to undertake material and energy flow accounting or energy-landscape integrated analysis.

BOX 1.

Measuring energy return on input

According to the boundaries defined in Figure 3, the total energy turnout can be calculated dividing the final produce (FP) flow by the total input consumed (TIC) flow. This ratio is the **final energy return on input (FEROI)** and gives us a measure of the energy efficiency of a farming system. If the FEROI is higher than 1, the system is a net "energy provider." If it is lower than 1, the system has to be considered an "energy sink" that produces less energy than what is consumed in the farming activities. FEROI can be a useful indicator, but according to the ecological theories previously discussed, the need to also assess internal energy circling arises. In order to do so, we can further divide FEROI into two separated components: external FEROI and internal FEROI, where external FEROI is calculated dividing final produce by biomass reused (BR), and internal FEROI is calculated by dividing final produce by external inputs (EI).

- Final EROI (FEROI): FP / TIC
- External FEROI (EFEROI): FP / EI
- Internal FEROI (IFEROI): FP / BR

EFEROI should be interpreted similarly to the global FEROI: It reflects the capacity of the system to generate rather than consume energy – the higher the value, the more efficient the system. IFEROI has a more complex interpretation, considering that biomass reused is at the denominator. Here, a higher value reflects low effort in replenishing the soil fertility and other natural resources funds, whereas a low value means that a higher percentage of the produced biomass is reinvested within the system. Traditional low-input systems are more likely to have higher EFEROI and lower IFEROI compared to industrialized high-input systems.

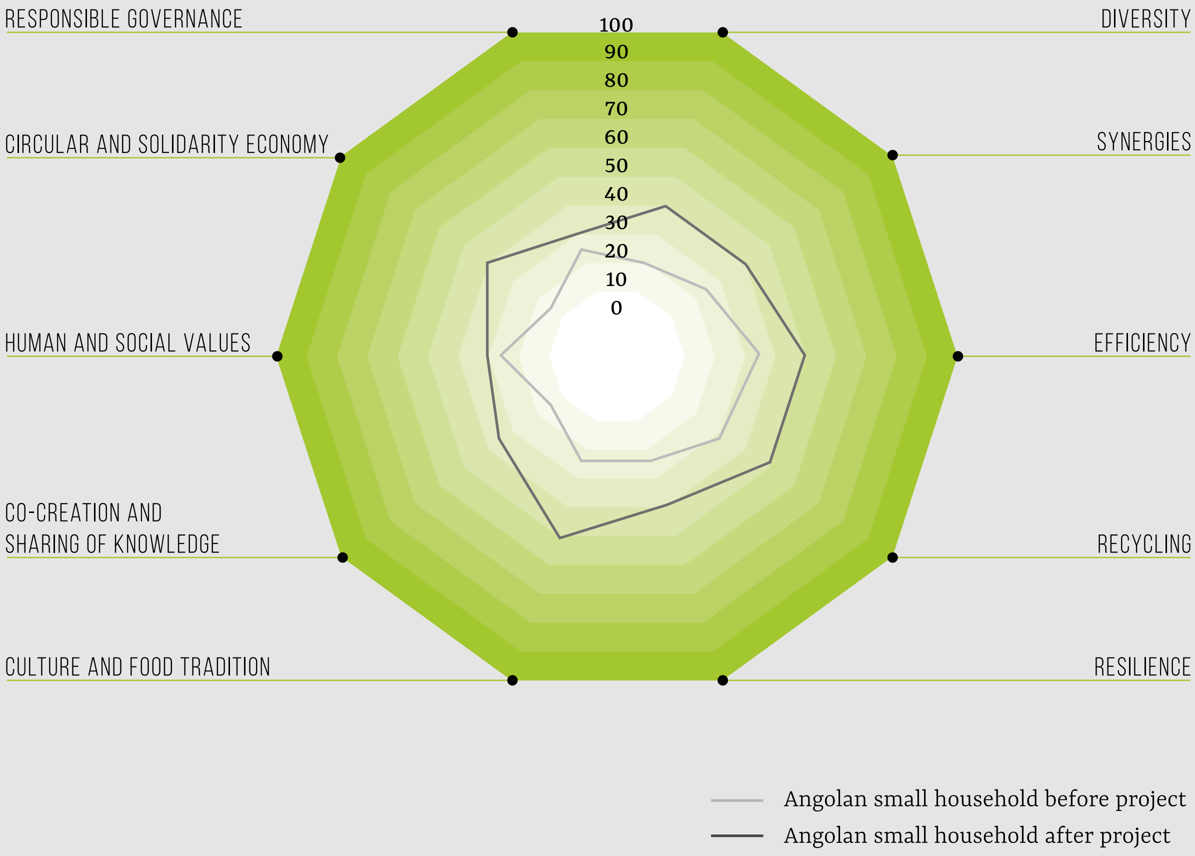
These indicators all provide information on the energy efficiency of the system and can be especially useful in comparative analyses, but there isn't a single way to interpret them; their values and their changes over time need to be assessed together with the overall analysis of the practices and the environmental conditions under which the system is operating. An EFEROI lower than 1 means that more energy is poured into the system than is extracted. This is often the case in industrial, high-input agriculture. This kind of "energy sink" is, by definition, not sustainable in the long run, but a similar low EFEROI would also be expected in the case of soil recovery activities, where a lot of work is done on the system to restore soil fertility/structure while little if no produce is harvested. In the opposite case, if a very rich and fertile soil is "mined" with an intensive crop production, the quantity of input applied might be very low compared to the final produce. The EFEROI might be very high, but this would in fact reflect a process of soil fertility depletion.

It's worth mentioning that these indicators do not account for the solar energy intake from the primary producers. This is because the methodology adopts the standpoint of the farmer, to whom solar radiation is a sort of "gift of nature." It is an energy flow that they cannot control in any way and is considered as a given environmental condition. FEROI, EFEROI and IFEROI are specifically designed to assess the energy efficiency of farming activities solely.

Thus, a further EROI indicator can be developed to understand the energy efficiency of the system from the point of view of phytomass production: the actual net primary production (NPPact) reflects the amount of solar radiation fixed into phytomass by the plants in a given system, as opposed to potential net primary production (NPPpot), which is the hypothetical measure of net primary production if humans hadn't modified a certain area through land cover change and agriculture. NPPact can be measured today quite effectively through remote sensing. If we divide NPPact by total input consumed (external inputs plus biomass reused), we get the NPPact EROI measure, which tells us the amount of energy units fixed into new phytomass per unit of total input from the farmers. This indicator might be one of the most suitable to assess ecosystem recovery activities in farmland contexts.

Sources: Authors' own elaboration. Marull, J., Cattaneo, C., Gingrich, S., De Molina, M.G., Guzmán, G.I., Watson, A., MacFadyen, J., Pons, M. & Tello, E. 2019a. Comparative Energy-Landscape Integrated Analysis (ELIA) of past and present agroecosystems in North America and Europe from the 1830s to the 2010s. Agricultural Systems, 175: 46–57. https://doi.org/10.1016/j.agsy.2019.05.011

FIGURE 5. VISUALIZATION OF THE RESULTS OF A CHARACTERIZATION OF AGROECOLOGICAL TRANSITION



Source: FAO, 2019.

2.2. JUDGING AGROECOLOGICAL PERFORMANCE

The Tool for Agroecology Performance Evaluation is an analytical framework built to produce evidence and a database on the performance of agroecological systems (FAO, 2019). It was developed based on the need of "methodologies and indicators to measure sustainability performance of agricultural and food systems beyond yield at landscape or farm level" (FAO, 2018b), and it integrates the ten elements of agroecology and key attributes from existing methodologies.

This tool is aimed at performing the analysis in a multidimensional and participatory basis. Five dimensions were identified for this purpose:

- environment and climate change
- health and nutrition
- society and culture
- economy
- governance

During the construction of this tool, 20 principles were identified as key elements. For the purpose of this article, we highlight the following:

- Be theoretically robust but operationally flexible to be adaptable to specific contexts.
- Measure key data, minimizing the cost of data collection, especially the burden on producers.
- Collect data that focus on the farm/household and community/territorial levels as a priority but allowing for aggregation at higher level.
- Apply a socioecological systems approach that is able to address integrated production systems (crops-livestock-trees-fish).

This tool contains five main steps, which are outlined below:

STEP 0: description of the main socioeconomic, environmental and demographic characteristics and contexts of the systems.

STEP 1: characterization of agroecological transition, consisting of characterizing the level of transition to agroecology of agricultural systems, based on the ten elements of agroecology. The ten elements are used as criteria to define semi-quantitative indices that take the form of descriptive scales with scores from 0 to 4 (a modified Likert-type scale).

STEP 1B: proposed as an optional step that consists of analysing and categorizing the results of the characterization of agroecological transition by means of a typology. This is relevant when working at local, territorial or regional levels and when sampling resources are limited and various systems are homogeneous.

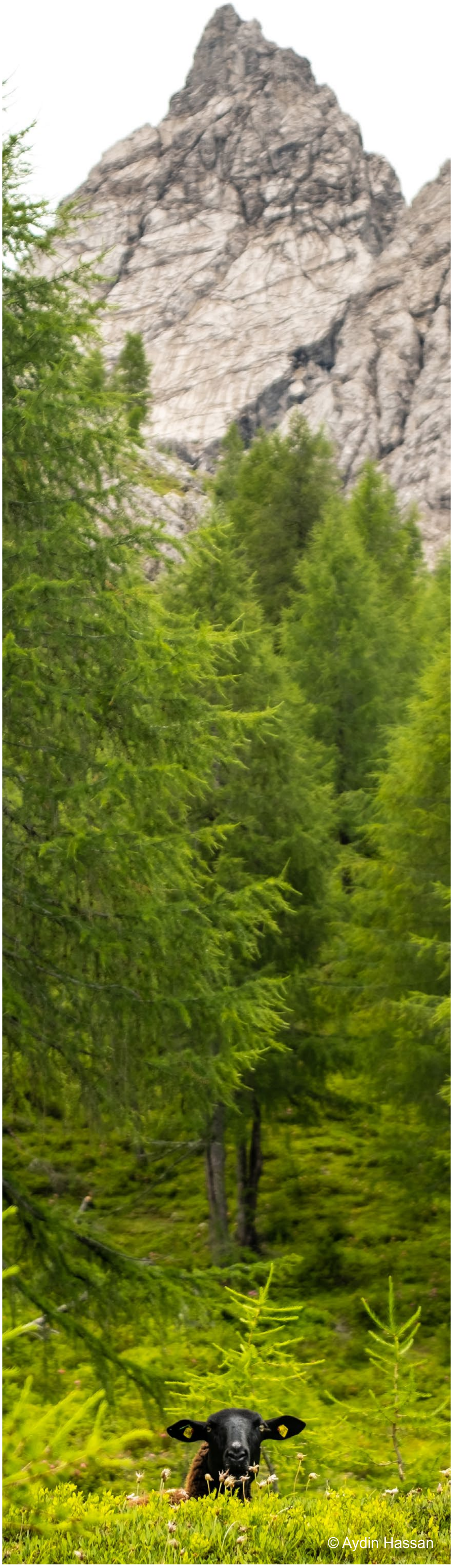
The simplest way to categorize systems in agroecological transition is by the stage in which they are in the transition (e.g. non-agroecological, incipient transition, advanced transition, model agroecological system). The aforementioned average score of ten elements can guide this categorization and define relevant ranges for each category.

STEP 2: consists of assessing the performance of the system (e.g. farms, households, territories) on the five dimensions considered during the construction of the tool. For this purpose, a list of ten core criteria, most of them directly linked with SDG indicators, is the bare minimum that should be assessed systematically in order to generate evidence on the multidimensional performance:

1. secure land tenure (or mobility for pastoralists)
2. productivity (and stability over time)
3. income (and stability over time)
4. added value
5. exposure to pesticides
6. dietary diversity
7. women's empowerment
8. youth employment
9. agricultural biodiversity
10. soil health

STEP 3: This last step should be conducted in a participatory mode with the community. It consists of an analysis of the results of steps 0, 1 and 2 and a participatory interpretation of this analysis. The objective is to identify trade-offs or synergies and design possible paths towards a more advanced stage in the agroecological transition.

The aim of this section was to reflect on this tool in a brief and descriptive way, highlighting the methodical and comprehensive structure of analysis and its participatory territorial application feature. Detailed information on the TAPE, including the description of the indicators for each criterion, their linkage to the SDGs, the protocols and questionnaire for the data and examples on their application can be found in the TAPE guidelines (FAO, 2019).


© Aydin Hassan


© GIAHS

Raising fish, both wild and domesticated species, inside rice paddy fields is a common practice in many traditional agriculture areas of Asia.

CHAPTER 3. IMPLEMENTING NATURE-POSITIVE PRODUCTION AGRICULTURE WITH AGROECOLOGICAL NATURE-BASED SOLUTIONS

This third chapter focuses on the proposal of practical tools to implement nature-positive production agriculture under the following premises:

- The more energy circling within the system, the higher its energy efficiency and production capacity.
- Soil is the most relevant element in the energy efficiency of agroecosystems.
- Nature-based solutions in agriculture are the fundamental approach towards nature-positive food systems.

Nature-based solutions (NbS) were defined by the United Nations Environment Assembly (2022) in a resolution on nature-based solutions for supporting sustainable development as: "actions to protect, conserve, restore, sustainably use and manage natural or modified terrestrial, freshwater, coastal and marine ecosystems which address social, economic and environmental challenges effectively and adaptively, while simultaneously providing human well-being, ecosystem services, resilience and biodiversity benefits."

The European Commission has defined NbS as "solutions that are inspired and supported by nature,"[2] in line with this paper's initial hypotheses. The effective implementation of NbS also requires an inclusive, participative approach aimed at the co-design of NbS management plans (Sonneveld *et al*., 2018); consequently, the involvement and coordination of stakeholders at the landscape or territorial scale is a key element.

NbS in agriculture are those practices that imitate or seek synergy with the natural functioning of ecosystems in order to pursue a solution to societal challenges (food production, fibre production, water availability, etc.). As such, they are the main way forward to implement nature-positive production agriculture. NbS are extremely context specific, as ecosystems work differently in different environmental conditions. The knowledge behind NbS requires thorough and persistent observation and analysis of the natural phenomena, such as the changes in soil properties, the species distribution and climate patterns, and the interaction among all living and non-living elements. The FAO Globally Important Agricultural Heritage Systems (GIAHS)[3] programme represents a unique, worldwide repository of time-tested traditional knowledge systems that have been transmitted from generation to generation through centuries and millennia (Arnés García and Santivañez, 2021) – an invaluable atlas of NbS.

© GIAHS

Nature-based solutions are extremely context specific, as ecosystems work differently in different environmental conditions.

---

[2] The European Commission (2020) defines NbS as: "Solutions that are inspired and supported by nature, which are cost-effective, simultaneously provide environmental, social and economic benefits and help build resilience. Such solutions bring more, and more diverse, nature and natural features and processes into cities, landscapes and seascapes, through locally adapted, resource-efficient and systemic interventions."

[3] FAO, through the Globally Important Agricultural Heritage Systems (GIAHS) Programme, acknowledges traditional agricultural systems worldwide that are examples of resilient systems characterized by remarkable agrobiodiversity, traditional knowledge, invaluable cultures and landscapes, sustainably managed by farmers, herders, fishers and forest people in ways that contribute to their livelihoods and food security. For more information, visit https://www.fao.org/giahs/en/.

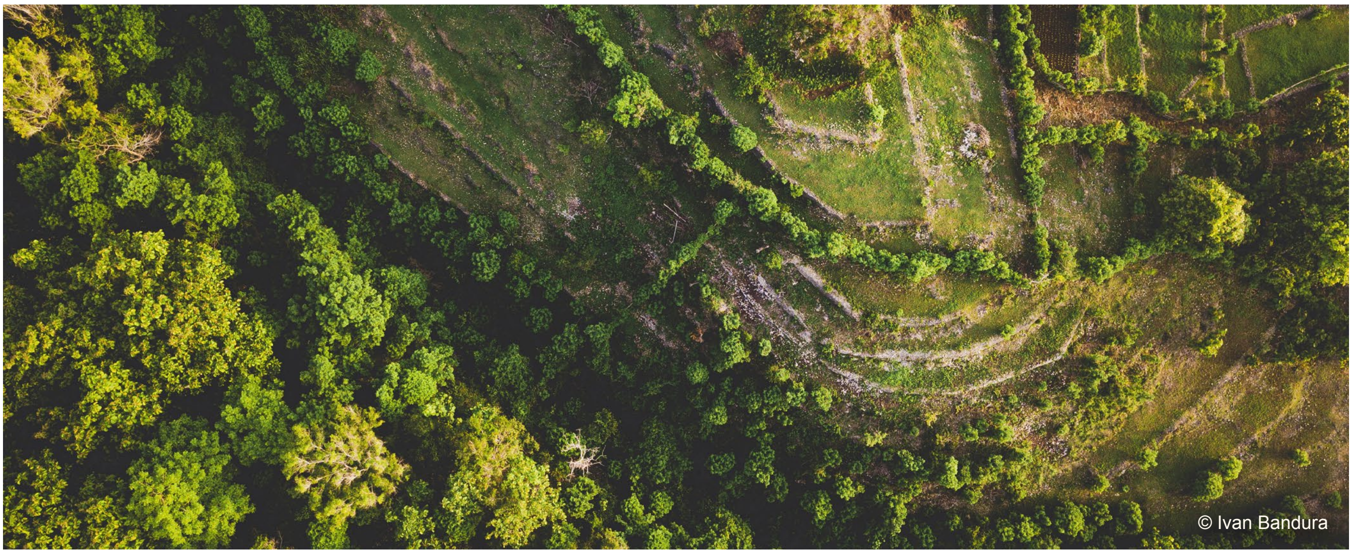

© Annie Spratt

Many NbS can be applied to improve energy storage and circling within agroecosystems; these solutions are generally oriented towards an improvement in complexity, in the diversity of crops and/or animals, in the way that soils are managed or by enriching the landscape with diversified elements (hedges, trees, ponds, etc.). Many of these solutions are generally well known in the practice of agroecology and other sustainable approaches to food production, and while a certain scientific consensus is developing around the benefits of complexity and diversification – the effects of diversification on yield have been found to be positive or neutral more often than negative (Isbell *et al*., 2017; Tamburini *et al*., 2020) – the biggest question remaining is how to implement them effectively in the context of food systems that have historically evolved around simplified, monocultural productive models.

A list of NbS priorities is hereby suggested to guide the transition to nature-positive production agriculture at the farm level, according to the main ecosystem features highlighted in Figure 1: energy storage, energy mobilization and systemic complexity. Although each priority is addressed separately, they are all strictly connected as they converge towards the same objectives: to limit energy dispersal outside of the system; to increase internal energy circling, mainly in relation to the maintenance of natural resources and soil biota; and to reduce the need for external inputs.

Soil (priority 1 and 2) is at the centre of the thermodynamic functioning of agroecosystems, and as such it is given the highest priorities, together with water, which is just as much important as an energy carrier. The absolute relevance of soil and water management also has emerged as one of the top priorities in FAO's national consultations in the Europe and Central Asia region, as an outcome of the UNFSS (FAO, 2023c). The European Commission also recently launched a regional soil strategy in an attempt to revert the phenomena of soil degradation and pollution (European Commission, 2021).

Diversification and complexity are tackled by priorities 3, 4 and 5. Biodiversity can be enhanced by increasing the genetic diversity of crop species and by naturally controlling pest outbreaks, while switching to more integrated agricultural systems (agroforestry, agro-silvo-pastoral systems, livestock and/or aquaculture integrated systems) results in higher energy efficiency and energy residence time. These priorities are inspired by and in line with the ten elements of agroecology developed by FAO, particularly the first one, diversity, but also synergies, recycling and circular economy. The same applies to the most technical principles of permaculture design: "integrate rather than segregate," "use and value diversity," "catch and store energy" and "produce no waste" (Holmgren, 2002). The integration of biomass flows also implies the development of resource management under a bioeconomy perspective, which is growing more and more relevant in political and institutional agendas worldwide (FAO, 2022), particularly in Europe (European Commission, 2018).


© Ivan Bandura

Priority 1: Soil and water conservation: Ensuring the least losses of soil and water will result in richer soils and more resources available for soil biota, plants and animals.

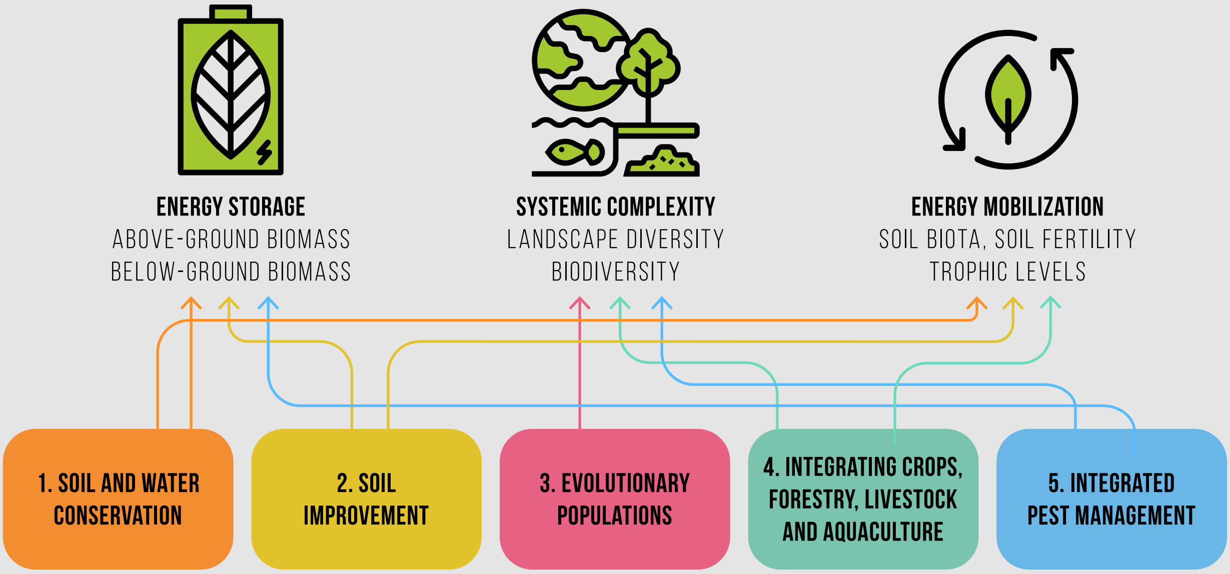
Priority 2: Soil improvement: Optimizing soil management and preventing the depletion of soil organic carbon further strengthens basic ecosystem functions and, consequently, biomass productivity.

Priority 3: Evolutionary populations: Enhancing the genetic pool with populations that are developed locally increases resilience to climate change and pest outbreaks.

Priority 4: Integrating crops, forestry, livestock and aquaculture: Agroecosystems are more simplified than wild ecosystems. Integrating different subsystems is an efficient way to mimic the energy recycling processes that would naturally occur along the trophic chain.

Priority 5: Integrated pest management: Dangerous pest outbreaks can badly affect biomass productivity and biodiversity richness.

FIGURE 6. PROPOSED PRIORITY AREAS AND THEIR INFLUENCE ON KEY FEATURES OF NATURE-POSITIVE PRODUCTION SYSTEMS



Source: Authors' own elaboration.


© Ivan Bandura

Water and topsoil are limited yet irreplaceable resources for agriculture and for many other societal demands, so their efficient management is a major prerequisite for the achievement of the United Nations SDGs.

PRIORITY 1: *Soil and water conservation*

Most relevant associated agroecology principles:

- Efficiency: Carefully preventing the dispersal of soil and water from a system can have a significative impact on the efficiency of their use (water efficiency and land efficiency).
- Resilience: When soil and water losses are minimized, systems are less exposed to such phenomena as dry spells and heavy rains.

Water and topsoil are limited yet irreplaceable resources for agriculture and for many other societal demands, so their efficient management is a major prerequisite for the achievement of the SDGs. Preserving soil is even more important considering that the rates of soil erosion have been estimated to overcome the rates of soil formation under conventional agriculture (FAO and ITPS, 2015). Under these circumstances, the soil should be considered a scarcely renewable resource. Hence, the first priority should be optimizing water and soil use and preventing their premature exit from the farm system (maximizing their "residence time"), even more so in the face of climate change and desertification phenomena. Plantation frames, tillage management, earth and/or stone structures, mulching and water conservation structures are all factors in achieving better soil and water conservation.

The need to actively prevent water and topsoil losses depends largely on the specific climatic and geomorphological conditions. Farmers in arid and semi-arid areas have a long history of fighting soil and water shortages with traditional technologies (e.g. dry-stone or earthen walls, contour bunds, dams, trenches, underground canals, mineral mulching, etc.); the same applies to steep slopes where precipitation runoff becomes too erosive. As some regions are forecasted to suffer from increased incidence of drought, dry spells and concentrated precipitations in future climate scenarios – the Mediterranean region, southern Africa, western Australia and possibly the Caribbean region, according to Fischer *et al*. (2014) – soil and water conservation techniques might become more needed in the future. Once again, traditional and indigenous knowledge collected via the GIAHS programme represents a reservoir of practices and techniques that can inspire future agriculture.

The conservation of soil and the conservation of water are often associated and tackled simultaneously, as their dispersal occurs as the result of the same phenomenon: the formation of surface water runoff during rainfall. This may be amplified by the sloping factor, the soil compaction or structure, a lack of soil coverage (either living plants, organic or inorganic mulching) and the specific character of precipitation. Soil erosion can be reduced by improving the water infiltration speed inside the soil to reduce the runoff flow rate and by slowing down the runoff speed. Runoff and soil erosion affect the availability of water and soil nutrients and plant rooting depth (Wakindiki and Ben-Hur, 2002).

Hereafter, the following categorization of soil and water conservation techniques is suggested (Freie Universität Berlin, 2007):

1. **Physical measures:** physical structures that aim at increasing the water infiltration speed, dividing slopes into shorter strips and/or reducing the sloping factor to reduce runoff formation, flow rate and velocity. This includes:
   - stone or earth terraces
   - stone or earth bunds
   - check dams
   - contour ditches
   - water retention reservoirs
   - dams
   - grassed waterways
   - planting pits

2. **Biological measures:** the use of living plants, shrubs or trees to protect the soil (mostly from the splashing erosion action of droplets), reduce runoff velocity, increase surface roughness, stabilize the soil and increase infiltration thanks to the action of roots and organic matter. This includes:
   - vegetative strips
   - protective bushland
   - natural drainage way protected by a permanent grass cover (live fences)
   - reforestation

3. **Agronomic measures:** managing crop cycles, land uses and plantation frames to prevent the direct impact of rainfall on the bare soil and once again increase infiltration speed. This includes:
   - cover cropping
   - strip cropping
   - mix cropping
   - intercropping
   - fallowing
   - mulching
   - contour ploughing
   - grazing management
   - agroforestry

The effectiveness of these NbS has been analysed and documented by many studies. Positive effects include increased soil organic carbon (Borrelli *et al*., 2016); increased net primary production and crop yields (Kumar *et al*., 2020; Wakindiki and Ben-Hur, 2002); climate change resilience and carbon sequestration (Kumar *et al*., 2020; Wen *et al*., 2021); and biodiversity support, even in abandoned terraced areas (Arévalo *et al*., 2016). The largest benefits were recorded in association with terracing, no-till farming and agroforestry.

Yet, while the benefits of soil and water conservation cannot be denied, the implementation of such measures often entails a trade-off in which land available for crop production is reduced and consequently economic sustainability in the short term can become an issue (Adimassu *et al*., 2017) – yet another proof of the inherent extra land cost of agrarian sustainability (Guzmán Casado and González De Molina, 2009).


© Ivan Bandura


© Jeff Ackley

Soil health is a major goal for ecosystem restoration and a very important prerequisite for sustainable agricultural production.

PRIORITY 2: *Soil improvement*

Most relevant associated agroecology principles:

- Efficiency: Healthy soil is less prone to nutrient depletion. Higher soil organic carbon content also increases water retention.
- Recycling: More active soil biota allows for quicker nutrient recycling.
- Resilience: Soil health is once again connected to resilience to extreme environmental conditions.

Once soil nutrients and water funds are secured within the system as much as possible, the second priority should be the improvement of soil properties (including water retention). This can be accomplished mostly through improving soil organic carbon and promoting soil microbiota in general by reducing or foregoing tillage, avoiding mineral fertilizers, always growing plants or grasses (cover crops) that sustain microbes with their roots, or reincorporating biomass into the farmland.

Soil health is a major goal for ecosystem restoration, on one hand, and a very important prerequisite for sustainable agricultural production, on the other. While soil health is a very complex topic, this section will focus on the components of soil biota and soil organic carbon, which are the most influential to ecosystem productivity and the most affected by intensive agricultural production. These components are also connected with Priority 1, as they are very much linked and affected by the phenomenon of soil erosion.

The Convention on Biological Diversity (1992) defines soil biota as “the variation in soil life, from genes to communities, and the ecological complexes of which they are part, that is from soil micro-habitats to landscapes.” Soil biota plays a major role in a number of key ecological services, as summarized by a report on soil diversity from the European Commission (2010):

- **Soil structure, soil organic matter and fertility:** Soil biota is affected but also influences soil structure through the synthesis of proteins and other chemical compounds. By decomposing soil organic matter, it also contributes to soil aeration, the capacity to absorb water and retain nutrients. As a result, soil biota is directly connected to net primary production. It is worth mentioning that soil organic matter “humus” can only be produced by the complex activity of soil biota.

- **Regulation of carbon flux and climate control:** In one year, soil biota can produce 25 tonnes of organic carbon per hectare (although part of it is released back into the atmosphere by the organisms' respiration). While tree planting is often advocated for as a viable carbon stocking solution, more attention should also be dedicated to soil biota stocking in peatlands and grasslands. Losing soil biodiversity, on the contrary, leads to decreased carbon stocking rates in the soil.

- **Regulation of the water cycle:** As a secondary result of soil structuring action, soil biota affects the infiltration and distribution of water in the soil by creating soil aggregates and pores. The removal or decrease of earthworm populations has been associated to a decrease in soil water infiltration rate by up to 93 percent. Soil biodiversity is also responsible for the biodegradation of contaminants and of pathogenic microbes, thus supporting the water purification process.

- **Pest control:** Ecosystems with higher soil biodiversity are more likely to contain soil-borne pest outbreaks by population control from natural enemies.

- **Decontamination and bioremediation:** Some soil organisms play a key role in bioremediation through the accumulation of pollutants in their bodies and/or through modifying the pollutants into either non-toxic compounds or useful metabolic molecules. Phyto-remediation is also mediated by soil biota.

A review paper by Tahat *et al*. (2020) confirms that soil biota plays a key role in a number of crucial processes for plant growth, from the mineralization of plant residues to the transformation of nitrogen from inorganic to organic forms. Arbuscular mycorrhizal fungi, active bacteria and beneficial nematodes are also highly correlated with crop yield, fruit quality, soil water storage and nutrient cycling.

Soil biota is directly connected to the availability of soil organic carbon in soils, which is one of their main sources of energy and is often addressed as the most relevant indicator for soil health (Neal *et al*., 2020; Ngoune Liliane and Shelton Charles, 2020; Shah and Wu, 2019; Stockmann *et al*., 2015). Neal *et al*. (2020) define soil microbe systems as "self-organizing states with organic carbon acting as a critical determining parameter. This perspective leads us to propose carbon flux, rather than soil organic carbon content as the critical factor in soil systems."

The complexity of the carbon cycle and the local conditions should always be taken into consideration to design proper soil organic carbon management strategies, as too much carbon inputs can interfere with other nutrients' cycles (Kuzyakov, Friedel and Stahr, 2000, particularly highlight the risk of nitrogen immobilization by microorganisms).

Soil organic carbon abundance and soil biota richness have been linked mostly with the use of organic fertilizers and no-till farming (Tahat *et al*., 2020). These two practices should be encouraged for nature-positive production. There is evidence that the use of alternative organic fertilizers may yield less produce in conventional agricultural systems; to access their positive outcomes, their application needs to be included in a holistic management strategy of all the processes in farming.

- **Alternative organic fertilizers** are not just the ones defined in the Principles of Organic Agriculture, but also biofertilizers and biostimulants (which are based on microorganisms that mobilize and provide nutrients directly to plant structures, sometimes bypassing soil completely), including fungal biofertilizers. More comprehensively, restoring soil fertility should be addressed as a holistic strategy that may include fertilizers, composted manure, fertigation (fertilized waters), biochar, green manure (cover crops and phytomass leftovers) and/or other nutrient sources. The use of leguminous plants as key providers of nitrogen, either in rotation or in association with other crops, should be part of fertilizing strategies. Legume nodules also can be harvested to produce locally adapted rhizobia bacteria inoculants as alternative nitrogen fertilizers, which were shown to be most effective in organic and no-till management (Thilakarathna and Raizada, 2017).

- **Reduced-till or no-till farming** is one of the pillars of conservation agriculture. Tillage is an energy intensive activity that can considerably affect the energy return on input of a given agroecosystem. Research on the effects of recurring yearly tillage on soil biodiversity, compared to no-till farming, has shown very heterogeneous results. The most effective soil management strategy is therefore likely to depend on specific conditions such as soil structure, rainfall patterns, sloping factor, crop types and other farming practices. Many studies also have highlighted how the effects of no-till farming on yield can vary considerably. Yet, a general trend of positive effects on soil organic carbon stocks have been recorded in a meta-analysis in China (Zhao *et al*., 2017), the Indo-Gangetic Plain of Pakistan, northern India and Bangladesh (Somasundaram *et al*., 2020) as well as globally (Haddaway *et al*. 2017). The same studies have found out that cover cropping and crop rotation are the most likely to enhance the positive effects and prevent the negative effects of no-till farming. Skaalsveen *et al*. (2019) also stress its functionality in preventing soil erosion. "Tillage exacerbates the vulnerability of cereal crops to drought" (Quinton, Öttl and Fiener, 2022), which raises an alarm bell on the practice of continuous tillage in sloping farmland.

© FAO/Jeremy Cornejo

Genetic diversity is one of the main components of agrobiodiversity and is, consequently, a key element in an agroecosystem's complexity.

PRIORITY 3: *Evolutionary populations*

Most relevant associated agroecology principles:

- Diversity: Evolutionary populations increase considerably the genetic component of crop agrobiodiversity.
- Resilience: Crops with higher inner genetic diversity can adjust more quickly to changing environmental conditions.
- Circular and solidarity economy: Evolutionary populations are independent from the globalized seed industry, allowing for a re-territorialized, circular seed provision.

Genetic diversity is one of the main components of agrobiodiversity and is, consequently, a key element in an agroecosystem's complexity. Agrobiodiversity has seen a huge decline in recent decades due to the rise of the globalized seed industry, which has resulted in the displacement of many local landraces, with only a few crop varieties that are developed and grown in laboratories. In many cases, the optimal and controlled environmental conditions under which they are developed are reflected by the varieties' dependence on high-input management models, as well as poor performance under biotic or abiotic stress. This genetic erosion is associated with increased vulnerability to the impacts of climate change (Keneni *et al*., 2012) and pest outbreaks (Fisher *et al*., 2018).

The evolutionary populations (also referred to as evolutionary plant breeding) approach, by contrast, is based on the development of crop varieties that evolve naturally, through multiple generations, under the influence of the local environmental and climate conditions. Using evolutionary populations instead of commercial seeds can provide a number of benefits, such as (Ceccarelli *et al*., 2022; Ceccarelli and Grando, 2020):

- phenology adapting to earlier or later maturing, depending on the adaptive advantages of these traits in said local conditions;
- increased yield combined with increased yield stability;
- increased yield in drought seasons, hence an effective and fast solution to mitigate the impacts of climate change;
- higher crop height; and
- more controlled disease spread, as the result of more genetically diversified pest resistance and susceptibility.

Since 2010, participatory wheat and barley evolutionary plant breeding programmes were successfully implemented in Iran and Italy. The populations performed better than the commercial varieties, especially in marginal, low-fertility and rainfed land, under low-input management. Farmers consistently reported enhanced yield stability and resistance to biotic and abiotic stress. The flours obtained from evolutionary populations were also found to have better nutritional qualities and better taste, which resulted in higher economic gains for the farmers (Ceccarelli *et al*., 2022).

Today, the biggest obstacle for a larger implementation of evolutionary populations are the seed laws, which often favour the characteristics of standardization and uniformity, and a certain institutional reluctance to supporting the complex processes that are needed to successfully implement evolutionary populations.

PRIORITY 4: *Integrating crops, forestry, livestock and aquaculture*

Most relevant associated agroecology principles:

- Synergies: The main rationale behind this priority is to exploit the potential synergies among the different subsystems in agriculture, thanks to the exchange of biomass.
- Recycling: Matching a subsystem's output with another subsystem's input needs, once again, enhances the energy recycling rates within the agroecosystem.
- Circular and solidarity economy: Integrating subsystems is an effective way to implement circular economy and bioeconomy.

The more energy recycling within the system, the higher its energy storage capacity. Connecting plants, trees, animals, water bodies and fish can be an effective way to integrate each subsystem's output, which could otherwise become waste or unused matter. Some of the solutions in this area of intervention may not always be available to individual farmers, especially smallholders, so this priority would certainly benefit from the activation of local administrations, cooperatives and professional associations. Each of the practices and solutions presented in this section would require a more extensive analysis; we will present brief descriptions and the benefits suggested by the scientific literature from the perspective of ecosystem and environmental regeneration.

1. **Intercropping:** This is the simultaneous growing of two or more crops in the same land unit over a certain period of time. It benefits from a mutualistic relationship among crop species as well as different time and space patterns of niche occupations. Intercropping has been implemented globally in many different environmental conditions and crop associations; it has been associated with increases in productivity and ecosystem services, greater yields per land unit compared to monocultures, reduced risk of crop failure and resilience to market fluctuations – all of this with a reduced use of off-farm inputs but also a higher request of labour (Glaze-Corcoran *et al*. 2020). Intercropping typologies include:

    - **Mixed intercropping:** Crops are grown without any spatial separation.
    - **Strip intercropping:** Crops are sown in parallel strips wide enough to allow for cultivation and harvest but narrow enough to allow for interspecific interactions between different plants.
    - **Row intercropping:** Similar to strip intercropping, here at least one species is sown in single or double rows among other strips of crops to maximize

© Rod Long

> *Intercropping has been associated with increases in productivity and ecosystem services, greater yields per land unit compared to monocultures, reduced risk of crop failure and resilience to market fluctuations.*

the effects of interactions such as shading, root mingling and water/nutrient competition, which may result in disease suppression.

- **Relay intercropping:** More connected to time differentiation, relay intercropping includes spatial subdivisions that may resemble strip intercropping, but the different crops are sown and harvested at different times, with only partial overlapping along the growing season.

A global meta-analysis of maize and soybean intercropping (Xu *et al*., 2020) discovered that the highest benefits were gained with the association of maize with short-term cycles of cereals and legumes that had substantial temporal niche differentiation from maize, adding more evidence to the diversification theory. The study highlighted the potential of intercropping for the sustainable intensification of both low-input and high-input systems, with an average reduction of land use by 16–29 percent and fertilizer use by 19–36 percent.

② **Agroforestry:** The practice of mimicking natural successions and organizing the agroecosystem in vertical layers (arable crops, shrubs, trees, vines, etc.) is one of the most effective ways to improve complexity at the farm scale and increase net primary production. Trees are also known to improve microclimate, water availability and pest control through biodiversity support, while their pruning can provide effective organic carbon inputs for soil organic carbon stocks.

While intercropping could be considered a "re-engineered" version of the prairie ecosystems, agroforestry mimics the functioning of forest ecosystems, which are even more complex and layered. Forests are the most productive terrestrial ecosystems and are consequently associated with high recycling rates, biomass accumulation and soil development. Agroforestry seeks to channel the dynamics of these abundant ecosystems towards satisfying the human need of food production. Integrating trees with crops can take a very wide variety of forms, including alley cropping (in which tree rows are used to break down large crop fields into smaller fields), silvopasture (in which trees are integrated in pastureland) and various associations of trees that are layered according to their sunlight requirement (such as tall palm trees with shorter fruit trees, or cocoa and coffee shrubs associated with tall shading trees and smaller annual plants such as banana trees). Agroforestry systems also have a high potential for contributing to mitigating climate change, as they reduce carbon emissions and promote carbon sequestration in soil and biomass (Fornara *et al*., 2018; IPCC, 2000).


© GIAHS/Pareto Paysages

Forests are the most productive terrestrial ecosystems and are consequently associated with high recycling rates, biomass accumulation and soil development. Agroforestry seeks to channel the dynamics of these abundant ecosystems towards satisfying the human need of food production.

Despite its management complexity, agroforestry is associated with many positive benefits: Soil quality is improved with higher inputs of organic matter and carbon, soil erosion is contained and water availability improved, and carbon sequestration is increased compared to monocultures. Total productivity can improve by more than 40 percent compared to the productivity of the same crops in monocultural systems; this makes agroforestry another strong candidate for sustainable intensification strategies (Wilson and Lovell, 2016). Finally, the diversification of ecological niches has positive effects on biodiversity in regard to the richness of species, both in temperate and tropical ecosystems. Agroforestry systems have sometimes been found to host even higher biodiversity than adjacent wild forest ecosystems (Udawatta, Rankoth and Jose, 2019).

3. **Integrated crop–livestock systems:** The rationale behind the integration of crops and livestock can be both metabolic and ecosystemic, as animals offer both energy recycling improvements as well as ecosystem services. As defined by Zhang *et al*. (2007), these include provisioning services (i.e. the production of animal and plant products), supporting services (particularly soil fertility enhancement through manuring and nutrient cycling), and regulating services (such as pest control at the farm or landscape scale and increased carbon storage). The importance of efficient integration systems is even more relevant in mountainous temperate areas, where some land is only available during summertime and can only be exploited for grazing or the production of short-cycle hay/forage. Moraine *et al*. (2014) define the following types of integrated crop–livestock systems:

- **Type 1:** exchange of materials (e.g. grain, forage, straw and animal waste) between specialized farms under a “**coexistence**” rationale
- **Type 2:** exchange of materials between different sectors in a rationale of “**complementarity**,” where crop systems are designed to meet livestock needs and receive their manure in exchange
- **Type 3:** increased temporal and spatial interaction among crops, grassland and livestock to achieve “**farm-level synergy**” with the use of stubble grazing (that is, post-harvest crop field grazing), temporary grasslands in rotations and intercropping forages
- **Type 4:** increased temporal and spatial interaction among crops, grassland and livestock in a rationale of “**territory-level synergy**,” with a high level of coordination and organization in resource allocation, knowledge and work sharing among farms

A study comparing specialized and livestock-integrated soybean systems in southern Brazil recorded 23-percent-higher field-level economic productivity (measured as the sum of crop and animal production) between 1961 and 2017, with crop biomass production in integrated systems only 10 percent lower than specialized systems. This yield gap is forecasted to decrease to less than 5 percent in future climate scenarios, while the economic productivity gap is expected to increase to 32 percent (Peterson *et al*., 2020). Similar data were collected in Australia, where the median yield of livestock-integrated grain and pasture farms were, on average, 9 percent higher than same-crop specialized farms (Bell, Moore and Kirkegaard, 2014).

It is worth mentioning that crop–livestock integrated systems require careful design and may have high annual variability if the cycles of crop–forage–pasture don’t line up with the best environmental and climatic conditions. The sustainable management entails ensuring a correct ratio of animals per land unit, using animals most adapted to the local conditions, maximizing grazing time over stable time to minimize manure concentration, ensuring enough resting time for the land (such as in the **adaptive multi-paddock system**) and managing manure in order to minimize waste production.

4. **Integrated agriculture–aquaculture:** The last element that can contribute to the complexity of energy circling and storing within a farming system is aquaculture. As with the integration of livestock, but with very different territorial patterns, aquaculture can provide more fertilization sources and biodiversity niches, but most importantly it can influence water availability and water use efficiency.

According to Prein (2002), integrated agriculture–aquaculture “is defined as concurrent or sequential linkages between two or more human activity systems (one or more of which is aquaculture), directly on-site, or indirectly through off-side needs and opportunities, or both.” It is based on the synergism in which “an output from one sub-system [...] which otherwise may have been wasted becomes an input to another sub-system, resulting in a greater efficiency of output” (Edwards *et al*. 1988 in Prein 2002). The same author emphasizes how the diversity introduced by aquaculture “provides opportunities for more nutrient linkages” at the expense of more labour required.

According to Ahmed, Ward and Saint (2014), the two main typologies of integrated agriculture–aquaculture are:

- **Pond-based integrated agriculture–aquaculture:** In order to be productive, ponds need a nutrient input flow, usually rich in nitrogen; this can be aquatic macrophytes that live inside or near the pond, grasses, spontaneous plants or crop residues. Alternatively, ponds can be fed by animal manure (preferably but not exclusively poultry manure, which is richer in nitrogen) and even slaughterhouse waste for carnivorous fish. In return, nutrient-rich pond mud is used to fertilize vegetables and fruit trees, whereas spontaneous aquatic plants can be fed to either fish or cattle. Ponds can also interact directly with livestock if they are reared in their vicinity.
- **Rice–fish farming:** Raising fish, both wild and domesticated species, inside rice paddy fields is a common practice in many traditional agriculture areas of Asia. In these systems, fish are also often used for their pest control services, sometimes together with ducks; even in this case, productivity can be enhanced by an association with cattle, which can be fed rice straws that would otherwise become waste material.

Integrated agriculture–aquaculture systems have been found to increase water productivity by at least 10 percent, with increasing gains the more integrated and diversified the system is. Water productivity is defined by Molden as “the ratio of the net benefits from the whole system including crop, fishery and livestock to the amount of water used to produce those benefits” (cited in Ahmed, Ward and Saint, 2014).

Furthermore, the management of water bodies has the potential to be integrated into other bioeconomy processes, such as water treatment and phytodepuration, or the supply of nutrients-rich waters for irrigation (fertigation).

Integrated agriculture–aquaculture systems have been found to increase water productivity by at least 10 percent, with increasing gains the more integrated and diversified the system is.

© Russell Watkins/Department for International Development

PRIORITY 5: *Integrated pest management*

Most relevant associated agroecology principles:

- Diversity: Preventing pest outbreaks through the combination of biological and cultural controls, with limited pesticide use, is a way to maintain higher biodiversity in a system. Biodiversity, in return, can itself become a natural pest control agent.
- Efficiency: Pests can severely affect the net productivity of an ecological niche, and consequently its energy efficiency.

FAO defines integrated pest management as "the careful consideration of all available pest control techniques and subsequent integration of appropriate measures that discourage the development of pest populations and keep pesticides and other interventions to levels that are economically justified and reduce or minimize risks to human health and the environment. IPM emphasizes the growth of a healthy crop with the least possible disruption to agroecosystems and encourages natural pest control mechanisms" (FAO, 2023b).

Integrated Pest Management (IPM) is:

- an ecosystem-based strategy that focuses on the long-term prevention of pest damages by keeping their population under the economic threshold (defined as the population density at which the yield loss value exceeds the cost of active intervention);
- an interdisciplinary approach that combines techniques such as biological control, habitat manipulation, modification of cultural practices and the use of pest-resistant varieties.

IPM aims at:

- controlling pests in an integrated way by incorporating biological, physical and chemical strategies, without aiming at the total pest elimination;
- limiting the possible negative effects of plant protection interventions to beneficial insects and other living organisms;
- using information on the life cycles of pests and their interaction with the environment to develop the best management strategy and select the best protection tools;
- minimizing the potential harm of pest control measures to human health and the environment;
- minimizing the application of chemicals;

An effective IPM strategy should be designed accordingly to the eight principles defined by Barzman *et al.*, 2015[4] and used by FAO (FAO, 2020):

1. **Prevention and/or suppression of harmful organisms** should be targeted and achieved by combining various options such as:
   - Crop rotation and intercropping;
   - Use of adequate cultivation techniques (e.g. seedbed sanitation, sowing/planting time and plant densities, under-sowing, conservation tillage, pruning, and direct sowing);
   - Use of resistant/tolerant cultivars and standard/certified seed and planting material, where deemed appropriate;
   - Balanced nutrient supply and optimal water management;
   - Field sanitation and hygiene measures (e.g. removal of infected plants, plant parts and plant debris, and regular cleaning of machinery and equipment);
   - Protection and promotion of beneficial organisms (e.g. utilization of "ecological services" inside and outside production sites).

2. **Monitoring**

   Harmful organisms must be monitored by adequate and cost-effective methods and tools, where available. Such adequate tools should include observations in the field as well as scientifically sound warning, forecasting and early diagnosis systems, where feasible, and the use of advice from professionally qualified advisors.

3. **Decision making**

   Based on the monitoring results, the user has to decide whether and when to apply plant protection measures. Robust and scientifically sound threshold values communicated in an easily applicable framework are essential components for decision making. For harmful organisms, threshold levels defined for the region, specific areas, crops and particular climatic conditions must be taken into account before treatments.

4. **Non-chemical plant protection measures**

   Sustainable biological, physical, mechanical and other non-chemical methods must be preferred to chemical methods if they provide satisfactory pest control levels.

5. **Specific pesticides**

   The pesticides applied shall be as specific as possible for the target and the situation and shall have the least side effects on human health, non-target organisms and the environment.

6. **Reduced pesticide use**

   The user should keep the use of pesticides and other forms of intervention to the lowest levels that are necessary, e.g. by reduced doses, reduced application frequency or partial applications.

7. **Anti-resistance strategies**

   Where the risk of resistance against a plant protection measure is known and where the level of harmful organisms requires repeated application of pesticides to the crops,

---

[4] Barzman, M., Bàrberi, P., Birch, A.N.E. *et al.* Eight principles of integrated pest management. *Agron. Sustain.* Dev. **35**, 1199–1215 (2015). https://doi.org/10.1007/s13593-015-0327-9

available anti-resistance strategies should be applied to maintain the effectiveness of the products. This may include the use of different pesticides with different modes of action.

8. **Evaluation**
Based on the records on pesticides use and on the monitoring of harmful organisms, the user should check the success of the applied plant protection measures.

The IPM approach is in line with the other "nature-positive" principles described in this report, such as addressing the landscape scale rather than focusing on the farm scale, adopting an integrated approach, and maximizing and prioritizing the contribution of biodiversity to the provision of ecological services. As is clear from the list of principles and guidelines, integrated pest management is more than a practice; it is a philosophical approach that can translate into a wide variety of solutions depending on local environmental and socioeconomic conditions.

While the main concepts were already conceived and designed in the 1960s, integrated pest management struggled to find actual and systemic application in farming practices. Deguine *et al.* (2021) provided an overview of this shortcoming, highlighting how integrated pest management in practice got lost in an ocean of different and sometimes opposite interpretations, which led to inconsistent levels of implementation in the field. Scientific reviews have stressed positive outcomes from integrated pest management implementation programmes, with an average cut of pesticide use around 60–75 percent in different continents and cultural contexts. However, these positive outcomes were often offset in the long run by a lack of project financial sustainability, insufficient training among farmers, and pesticide lobby interference. The scientific research itself seems to have heavily overlooked ecological functioning when addressing integrated pest management, focusing instead on control methods and economical evaluations, in stark contrast with its own founding principles (Deguine *et al.*, 2021).

Another factor that has hindered the spread of integrated pest management practical implementations is its relative complexity compared to the simplicity of pesticide use, as well as a widespread focus on the short-term in farming, which doesn't consider the development of population immunity and soil degradation phenomena. Conventional pesticides keep being positively valued because of their low cost, simplicity of use and short-term efficiency (Bueno *et al.*, 2021). Among its various shortcomings, integrated pest management has been criticized for not being explicitly pollinator friendly. This, together with rising concern on the status of pollination species all over the world, led to the stablishment in 2015 of the concept of integrated pest and pollinator management (Biddinger and Rajotte, 2015), which attempts to raise awareness on further regulating pesticides to minimize their impact on a range of pollinator species (not only honey bees) and to include considerations about their life cycles in the development of strategies for integrated pest management and the management of farmland.

Despite its troubled history, integrated pest management and integrated pest and pollinator management principles are still at the basis of new concepts and theoretical frameworks for the natural prevention of pest outbreaks, such as agroecological crop protection, which draws from groecology principles and is based on the main pillars of biodiversity (Priority 3) and soil health (Priority 1 and Priority 2). Traditional and indigenous agriculture should once again be considered a repository of useful and efficient practices to inspire integrated pest management applications (Morales, 2002; Mushtaq *et al.*, 2020; Rathore *et al.*, 2021).

The concept of integrated pest and pollinator management attempts to raise awareness on further regulating pesticides to minimize their impact on a range of pollinator species.

© Nadiia Ploshchenko

CONCLUSIONS

© Sies Kranen

Nature-positive production agriculture requires that agricultural systems be approached as "agroecosystems," stressing their inner working as ecosystems. As such, the analysis from the thermodynamic perspective suggests that their productivity is mostly dependent on their capacity to store and quickly recycle energy. In a natural setting, these capacities are correlated to the amount of biomass available, soil biota activity and the length of the food chain (trophic levels); all these properties, along with productivity, naturally improve with the "ecological successions," which bring an ecosystem to maturity and entail a gradual increase in systemic complexity.

Because of the continuous and intensive biomass removal, monocultural systems are kept at a very early successional stage, which is characterized by low complexity, low biodiversity and consequently low natural productivity. Ancient organic systems, on the contrary, had higher complexity and higher natural productivity, which generated a higher energy efficiency per input unit.

© Badal Sarker for the Department of Agricultural Extension, Bangladesh

Hence, a nature-positive agroecosystem needs to improve productivity by operating at a higher successional stage than monocultural systems by supporting these three main features: energy storage, energy recycling capacity and systemic complexity. Some of the ways to do so are:

- having high crop diversity, both at the genetic, spatial and timescale;
- having high landscape complexity to support more biodiversity;
- ensuring the cyclic renewal of all the underlying ecological funds;
- managing nutrient cycles at the territorial scale, integrating biomass flows from different subsystems (cropland, livestock, forestry, aquaculture, etc.) to maintain soil fertility in farmland;
- minimizing the need for external inputs by changing farming methods where possible;
- substituting the external inputs still required with locally available, organic inputs; and
- analysing and adjusting the agroecosystem's energy profile at the territorial scale (applying the material and energy flow accounting, energy-landscape integrated analysis methodology or the Tool for Agroecology Performance Evaluation) to better understand the natural resources funds' dynamics over time.

The main obstacles in the way of agriculture becoming more nature-positive and working hand in hand with ecosystem services are the large-scale use of external, fossil-fuel-based inputs and intensive farming methods. These have driven the energy efficiency of farm systems down and heavily degraded soil health, despite increases in crop productivity. Intensive farming and simplified landscapes are incompatible with the basic functionalities of ecosystems, which are based on complexity, nutrient recycling feedbacks and mutual population control among different species and trophic levels. Biodiversity and complex land cover mosaics play a key role in supporting these ecosystem functionalities. Hence, the management of a nature-positive production system should prioritize reducing the need for external inputs with nature-based solutions and management practices, in the first place, and only secondly substituting the inputs that are still needed with locally available resources – which have lower embedded energy compared to globalized, fossil-fuel-based inputs.

Considering the vital role that complexity plays in the sustainability of living systems, individual farms might not always have enough resources to implement nature-positive production by themselves. Furthermore, complex agroecosystems such as agroforestry and silvopastoral systems are indeed less prone to nutrient depletion but would most likely still depend on external inputs in order to reach net zero on depletion, if not becoming nature positive. These inputs should be produced locally, as much as possible, and in a coordinated way. Coordination among actors and effective policymaking emerge as being of capital importance for our productive systems to turn nature positive. This need is also stressed in a 2021 United Nations Food Systems Summit paper on boosting nature-positive production (Hodson *et al*. 2021), in which scientists advocated for a more effective framing of the issue at the landscape scale.

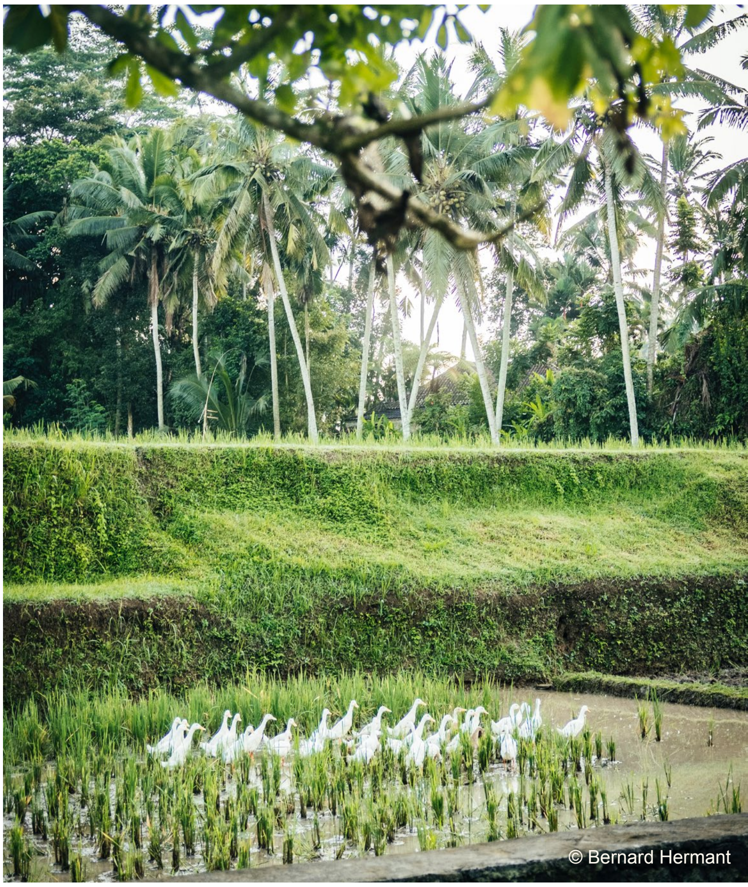
"Nature-positive" requires a cultural change as much as it does a technical change. Historical, pre-green-revolution agricultural systems have many lessons to teach about working hand in hand with nature. Evidence shows that the sustainability of these systems depended mostly on the closed energy flows that connected the farmland with animal husbandry, forestry and surrounding natural areas through the exchange of biomass and ecosystem services. Farmers had to solve complex trade-offs with limited technological resources, although little research effort has been produced to investigate how they did it. Studying ancient organic systems could inspire future agriculture as practices and principles find new, better application with today's technological and societal advances. The FAO GIAHS Programme offers a useful compendium of traditional practices.

THINKING AHEAD

As suggested by the 2021 United Nations Food Systems Summit's conclusions (Hodson *et al*. 2021), policies should be designed to address the broader context and the larger system, rather than simply farm enterprises and the productive sector.[5] Some of the measures suggested by the analyses made in the previous chapters include:

1 **Establishing monitoring facilities that analyse and track the energy efficiency of farming systems.** According to the models and methodologies shown in this work, key indicators should include the complexity of land uses, the amount of external inputs used (along with their embedded energy profile), agricultural production, net primary production (including unharvested phytomass) and possibly the amount of biomass reused within the system. Other relevant indicators could measure waste materials produced, soil erosion rates, soil properties and water retention capacity.

2 **Favouring exchanges of biomass and organic material among different land uses and sectors.** The recycling of any organic matter that mimics the natural nutrient cycles in ecosystems should be promoted. Such measures should take into consideration the management of the whole biomass production in a territory rather than just the waste flows, so monitoring and data gathering are important prerequisites. Effective governance structures and cooperation among actors are key aspects in this policy line.


© Bernard Hermant

3 **Favour the transition towards more complex and diversified farming systems**, in opposition to today's predominance of simplified, monocultural systems. Improving complexity at the spatial level includes using intercropping, alley cropping and/or other agroforestry systems that alternate species, as well as integrating natural patches, hedges and forest areas inside farmland. Complexity in the time dimension can be favoured again by agroforestry (if plants with different life cycles are associated, such as trees and annual crops), cover cropping, temporary grazing and fallowing.

4 Promote innovative initiatives that **integrate and connect research and practices on biodiversity conservation with agriculture** at the landscape scale, including the traditional knowledge of farmers and rural communities, in order to understand and monitor their mutual effects over time.

At the supranational level, favouring nature-positive production agriculture means favouring smallholders and diversified productive systems. If this is to be successful, not only the supply chains on which agriculture depends (i.e. seeds, fertilizers, machineries, etc.) need to be redesigned to exploit local resources and fit local conditions, but also all the other food system sectors have to adapt. Consumers' habits and the distribution sector have to shift from the current paradigm based on the large-scale retail of few farmed species to **a new paradigm that valorizes local and traditional varieties and diversified, seasonal diets**. Communication and education are the main operative lines for governments and regional actors to foster this cultural or behavioural change.

---

[5] In addition, the cost-effectiveness and reliability of NbS depend on good planning and implementation management, which requires productive stakeholder engagement (Sonneveld *et al.*, 2018). If they aren't managed in the appropriate way, there is a risk of increased management costs and reduced labour productivity. This complex trade-off between economic and environmental sustainability is an intrinsic characteristic of nature-positive production agriculture systems, which has to be addressed by the institutions and the communities from a systemic perspective (Seddon *et al.*, 2020).

ANNEX. SPECIFIC ENERGY DIMENSIONS FOR DIFFERENT ENERGY CARRIERS

ENERGY CARRIERS	ENERGY FORM ACCOUNTED	EQUIVALENCES
Actual Net Primary Production (NPPact)	Enthalpy	NPPact = UPH+LP
Unharvested Phytomass (UPH)	Enthalpy	UPH = NPPact – LP ≈ NPPeco
Total Produce (TP) Land Produce (LP) Lovestock-Barnyard Produce (LBP)	Enthalpy	TP = LP + LBP TP = BR + FP + FW LP = BR + FP – LBP + FW
Final Produce (FP) Farming Community Subsistence (FCS) Surplus Produce (SP)	Enthalpy	FP FCS + SP
Total Inputs Consumed (TIC)		TIC = EI + BR TIC = ASI + L + FCI + BR
Biomass Reused (BR) Farmland Biomass Reused (FBR) Livestock/Barnyard Biomass Reused (LBBR)	Enthalpy	BR = FBR + LBBR
External Inputs (EI) Societal Inputs (SI) Farming Community Societal Inputs (FCSI) Agroecosystem Societal Inputs (ASI) Farmland Societal Inputs (FSI) Livestock/Barnyard Societal Inputs (LBSI)	Embodied Energy & Enthalpy (only Embodied Energy in food & feed bought outside)	EI = SI + FCI + L SI = FSCI + ASI ASI = FSI + LBSI
Farming Community Inputs (FCI)		
Labour (L) Farm Labour (FL) Livestock/Barnyard Labour (LBL)	Enthalpy of food intake by labouring people multiplied by the ratio ***working time ÷ total time*** (plus the energy embodied in transport when food comes from outside the system).	L = FL + LBL
Livestock/Barnyard Services (LBS) Draught Power (DP) Manure (M)	Enthalpy Work Enthalpy	LBS = DP + M
Waste (W) Farmland Waste (FW) Livestock/Barnyard Waste (LBW)	Enthalpy	W = FW + LBW

Source: Tello, E., Galán, E., Cunfer, G., Guzmán, G., González de Molina, M., Krausmann, F., Gingrich, S. *et al.* 2015. A proposal for a workable analysis of Energy Return on Investment

REFERENCES

Adimassu, Z., Langan, S., Johnston, R., Mekuria, W. & Amede, T. 2017. Impacts of soil and water conservation practices on crop yield, run-off, soil loss and nutrient loss in Ethiopia: Review and synthesis. *Environmental Management*, 59(1): 87–101. https://doi.org/10.1007/s00267-016-0776-1

Ahmed, N., Ward, J.D. & Saint, C.P. 2014. Can integrated aquaculture-agriculture (IAA) produce "more crop per drop"? *Food Security*, 6(6): 767–779. https://doi.org/10.1007/s12571-014-0394-9

Altieri, M.A. 1999. The ecological role of biodiversity in agroecosystems. *Agriculture, Ecosystems & Environment*, 74(1–3): 19–31. https://doi.org/10.1016/S0167-8809(99)00028-6

Arévalo, J.R., Tejedor, M., Jiménez, C., Reyes-Betancort, J.A. & Díaz, F.J. 2016. Plant species composition and richness in abandoned agricultural terraces vs. natural soils on Lanzarote (Canary Islands). *Journal of Arid Environments*, 124: 165–171. https://doi.org/10.1016/j.jaridenv.2015.08.012

Arnés García, M. & Santivañez, T. 2021. *Hand in hand with nature – Nature-based Solutions for transformative agriculture*. FAO. https://doi.org/10.4060/cb4934en

Attiwill, P.M. 1994. The disturbance of forest ecosystems: the ecological basis for conservative management. *Forest Ecology and Management*, 63(2–3): 247–300. https://doi.org/10.1016/0378-1127(94)90114-7

Bell, L.W., Moore, A.D. & Kirkegaard, J.A. 2014. Evolution in crop–livestock integration systems that improve farm productivity and environmental performance in Australia. *European Journal of Agronomy*, 57: 10–20. https://doi.org/10.1016/j.eja.2013.04.007

Bergeron, Y. & Fenton, N.J. 2012. Boreal forests of eastern Canada revisited: old growth, nonfire disturbances, forest succession, and biodiversity. *Botany*, 90(6): 509–523. https://doi.org/10.1139/b2012-034

Biddinger, D.J. & Rajotte, E.G. 2015. Integrated pest and pollinator management — adding a new dimension to an accepted paradigm. *Current Opinion in Insect Science*, 10: 204–209. https://doi.org/10.1016/j.cois.2015.05.012

Borrelli, P., Paustian, K., Panagos, P., Jones, A., Schütt, B. & Lugato, E. 2016. Effect of good agricultural and environmental conditions on erosion and soil organic carbon balance: A national case study. *Land Use Policy*, 50: 408–421. https://doi.org/10.1016/j.landusepol.2015.09.033

Bottrell, D.G. 1979. *Integrated pest management*. Washington, DC, Council on Environmental Quality.

Bueno, A.F., Panizzi, A.R., Hunt, T.E., Dourado, P.M., Pitta, R.M. & Gonçalves, J. 2021. Challenges for adoption of Integrated Pest Management (IPM): the soybean example. *Neotropical Entomology*, 50(1): 5–20. https://doi.org/10.1007/s13744-020-00792-9

Capra, F. 2005. Complexity and Life. *Theory, Culture & Society*, 22(5): 33–44. https://doi.org/10.1177/0263276405057046

Ceccarelli, S. & Grando, S. 2020. Evolutionary plant breeding as a response to the complexity of climate change. *iScience*, 23(12): 101815. https://doi.org/10.1016/j.isci.2020.101815

Ceccarelli, S., Grando, S., Salimi, M. & Razavi, K. 2022. Evolutionary populations for sustainable food security and food sovereignty. In: Y. Nishikawa & M. Pimbert, eds. *Seeds for Diversity and Inclusion*. pp. 121–136. Cham, Springer International Publishing. https://doi.org/10.1007/978-3-030-89405-4_8

Cohen-Shacham, E., Walters, G., Janzen, C. & Maginnis, S., eds. 2016. *Nature-based solutions to address global societal challenges*. IUCN International Union for Conservation of Nature. https://doi.org/10.2305/IUCN.CH.2016.13.en

Dasgupta, P. 2021. *The economics of biodiversity: the Dasgupta review: full report*. Updated: 18 February 2021 edition. London, HM Treasury.

Deguine, J.-P., Aubertot, J.-N., Flor, R.J., Lescourret, F., Wyckhuys, K.A.G. & Ratnadass, A. 2021. Integrated pest management: good intentions, hard realities. A review. *Agronomy for Sustainable Development*, 41(3): 38. https://doi.org/10.1007/s13593-021-00689-w

Delgadillo-Vargas, O., Garcia-Ruiz, R. & Forero-Álvarez, J. 2016. Fertilising techniques and nutrient balances in the agriculture industrialization transition: The case of sugarcane in the Cauca river valley (Colombia), 1943–2010. *Agriculture, Ecosystems & Environment*, 218: 150–162. https://doi.org/10.1016/j.agee.2015.11.003

Edwards, P.R., Maule, C.H., Leatherbarrow, R.J. & Winzor, D.J. 1998. Second-Order Kinetic Analysis of IAsys Biosensor Data: Its Use and Applicability. *Analytical Biochemistry*, 263(1): 1–12. https://doi.org/10.1006/abio.1998.2814

Eggermont, H., Balian, E., Azevedo, J.M.N., Beumer, V., Brodin, T., Claudet, J., Fady, B. *et al.* 2015. Nature-based Solutions: New influence for environmental management and research in Europe. *GAIA - Ecological Perspectives for Science and Society*, 24(4): 243–248. https://doi.org/10.14512/gaia.24.4.9

Estrada-Carmona, N., Sánchez, A.C., Remans, R. & Jones, S.K. 2022. Complex agricultural landscapes host more biodiversity than simple ones: A global meta-analysis. *Proceedings of the National Academy of Sciences*, 119(38): e2203385119. https://doi.org/10.1073/pnas.2203385119

European Commission. 2006. *Rural development 2007–2013 handbook on common monitoring and evaluation framework*. Directorate General for Agriculture and Rural Development.

European Commission. 2010. *Soil biodiversity: functions, threats and tools for policy makers. Final report.* LU, Publications Office. https://data.europa.eu/doi/10.2779/14571

European Commission. 2018. *Bioeconomy: the European way to use our natural resources. Action plan 2018.* LU, Publications Office. https://data.europa.eu/doi/10.2777/57931

European Commission. 2020. Nature-based solutions. In: *European Commission*. https://research-and-innovation.ec.europa.eu/research-area/environment/nature-based-solutions_en

European Commission. 2021. *COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS EU Soil Strategy for 2030 Reaping the benefits of healthy soils for people, food, nature and climate*. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52021DC0699

FAO. 2009. *Report of the FAO expert meeting on how to feed the world in 2050*. Rome. https://www.fao.org/fileadmin/templates/wsfs/docs/EM_report/EM_report.pdf

FAO. 2018a. *Globally Important Agricultural Heritage Systems: Combining agricultural biodiversity, resilient ecosystems, traditional farming practices and cultural identity*. https://www.fao.org/family-farming/detail/en/c/1147754/

FAO. 2018b. *2nd International Symposium on Agroecology: Scaling up agroecology to achieve the Sustainable Development Goals (SDGs)*. Rome. https://www.fao.org/family-farming/detail/en/c/1106818/

FAO. 2019. *Tool for Agroecology Performance Evaluation (TAPE) - Test version: Process of development and guidelines for application*. Rome, Italy, FAO. https://www.fao.org/documents/card/en/c/ca7407en/

FAO. 2022. Sustainable and circular bioeconomy for food systems transformation. In: *Food and Agriculture Organization of the United Nations*. Cited 11 July 2023. https://www.fao.org/in-action/sustainable-and-circular-bioeconomy

FAO. 2023a. The 10 Elements of Agroecology. In: *Agroecology Knowledge Hub*. https://www.fao.org/agroecology/overview/overview10elements/en/

FAO. 2023b. Integrated Pest Management (IPM). In: *Pest and Pesticide Management*. https://www.fao.org/pest-and-pesticide-management/ipm/integrated-pest-management/en/

FAO. 2023c. *Outcomes of the United Nations Food Systems Summit in Europe and Central Asia*. FAO. https://doi.org/10.4060/cc5319en

FAO & Intergovernmental Technical Panel on Soils (ITPS). 2015. *Status of the World's Soil Resources (SWSR) – Main Report*. https://www.fao.org/3/i5199e/i5199e.pdf

Fischer, E.M., Sedláček, J., Hawkins, E. & Knutti, R. 2014. Models agree on forced response pattern of precipitation and temperature extremes. *Geophysical Research Letters*, 41(23): 8554–8562. https://doi.org/10.1002/2014GL062018

Fisher, M.C., Hawkins, N.J., Sanglard, D. & Gurr, S.J. 2018. Worldwide emergence of resistance to antifungal drugs challenges human health and food security. *Science*, 360(6390): 739–742. https://doi.org/10.1126/science.aap7999

Flombaum, P. & Sala, O.E. 2008. Higher effect of plant species diversity on productivity in natural than artificial ecosystems. *Proceedings of the National Academy of Sciences*, 105(16): 6087–6090. https://doi.org/10.1073/pnas.0704801105

Font, C., Padró, R., Cattaneo, C., Marull, J., Tello, E., Alabert, A. & Farré, M. 2020. How farmers shape cultural landscapes. Dealing with information in farm systems (Vallès County, Catalonia, 1860). *Ecological Indicators*, 112: 106104. https://doi.org/10.1016/j.ecolind.2020.106104

Fornara, D.A., Olave, R., Burgess, P., Delmer, A., Upson, M. & McAdam, J. 2018. Land use change and soil carbon pools: evidence from a long-term silvopastoral experiment. *Agroforestry Systems*, 92(4): 1035–1046. https://doi.org/10.1007/s10457-017-0124-3

Freie Universität Berlin. 2007. Soil and Water Conservation. In: *Geolearning*. Cited 1 July 2022. https://www.geo.fu-berlin.de/en/v/geolearning/watershed_management/soil_and_water_conservation/index.html

Fullana Llinàs, O., Tello Aragay, E., Murray Mas, I., Jover-Avellà, G. & Marull López, J. 2021. Socio-ecological transition in a Mediterranean agroecosystem: What energy flows tell us about agricultural landscapes ruled by landlords, peasants and tourism (Mallorca, 1860-1956-2012). *Ecological Economics*, 190: 107206. https://doi.org/10.1016/j.ecolecon.2021.107206

Georgescu-Roegen, N. 1971. *The entropy law and the economic process / [by] Nicholas Georgescu-Roegen*. Cambridge, Mass., Harvard University Press.

Glaze-Corcoran, S., Hashemi, M., Sadeghpour, A., Jahanzad, E., Keshavarz Afshar, R., Liu, X. & Herbert, S.J. 2020. Understanding intercropping to improve agricultural resiliency and environmental sustainability. In: *Advances in Agronomy*. pp. 199–256. Vol. 162. Elsevier. https://doi.org/10.1016/bs.agron.2020.02.004

Guzmán Casado, G.I. & González de Molina, M. 2009. Preindustrial agriculture versus organic agriculture. *Land Use Policy*, 26(2): 502–510. https://doi.org/10.1016/j.landusepol.2008.07.004

Guzmán, G.I., González De Molina, M. & Alonso, A.M. 2011. The land cost of agrarian sustainability. An assessment. *Land Use Policy*, 28(4): 825–835. https://doi.org/10.1016/j.landusepol.2011.01.010

Habel, J.C., Dengler, J., Janišová, M., Török, P., Wellstein, C. & Wiezik, M. 2013. European grassland ecosystems: threatened hotspots of biodiversity. *Biodiversity and Conservation*, 22(10): 2131–2138. https://doi.org/10.1007/s10531-013-0537-x

Haberl, H., Fischer-Kowalski, M., Krausmann, F., Weisz, H. & Winiwarter, V. 2004. Progress towards sustainability? What the conceptual framework of material and energy flow accounting (MEFA) can offer. *Land Use Policy*, 21(3): 199–213. https://doi.org/10.1016/j.landusepol.2003.10.013

Haddaway, N.R., Hedlund, K., Jackson, L.E., Kätterer, T., Lugato, E., Thomsen, I.K., Jørgensen, H.B. & Isberg, P.-E. 2017. How does tillage intensity affect soil organic carbon? A systematic review. *Environmental Evidence*, 6(1): 30. https://doi.org/10.1186/s13750-017-0108-9

Hall, A.R., Miller, A.D., Leggett, H.C., Roxburgh, S.H., Buckling, A. & Shea, K. 2012. Diversity–disturbance relationships: frequency and intensity interact. *Biology Letters*, 8(5): 768–771. https://doi.org/10.1098/rsbl.2012.0282

Hall, C., Lindenberger, D., Kümmel, R., Kroeger, T. & Eichhorn, W. 2001. The need to reintegrate the natural sciences with economics. *BioScience*, 51(8): 663. https://doi.org/10.1641/0006-3568(2001)051[0663:TNTRTN]2.0.CO;2

Ho, M.-W. & Ulanowicz, R. 2005. Sustainable systems as organisms? *Biosystems*, 82(1): 39–51. https://doi.org/10.1016/j.biosystems.2005.05.009

Hodson De Jaramillo, E., Niggli, U., Kitajima, K., Lal, R. & Sadoff, C. 2023. Boost Nature-Positive Production. In: J. Von Braun, K. Afsana, L.O. Fresco & M.H.A. Hassan, eds. *Science and Innovations for Food Systems Transformation*. pp. 319–340. Cham, Springer International Publishing. https://doi.org/10.1007/978-3-031-15703-5_17

Hodson, E., Niggli, U., Kitajima, K., Lal, R. & Sadoff, C. 2020. *Boost Nature Positive Production: A paper on Action Track 3 - draft for discussion*. United Nations Food Systems Summit 2021 Scientific Group, 2020. https://www.un.org/sites/un2.un.org/files/2020/12/3-action_track_3_scientific_group_draft_dec-12-2020.pdf

Holmgren, D. 2002. *Permaculture: principles and pathways beyond sustainability*. Holmgren Design Services.

Intergovernmental Panel on Climate Change (IPCC). 2000. *Land Use, Land-Use Change, and Forestry*. https://www.ipcc.ch/report/land-use-land-use-change-and-forestry/

Isbell, F., Adler, P.R., Eisenhauer, N., Fornara, D., Kimmel, K., Kremen, C., Letourneau, D.K. *et al.* 2017. Benefits of increasing plant diversity in sustainable agroecosystems. *Journal of Ecology*, 105(4): 871–879. https://doi.org/10.1111/1365-2745.12789

Kazakova, Y. & Stefanova, V. 2010. *High nature value farming in the Western Balkans: Current status and key challenges – a scoping document*. Bulgaria, European Forum on Nature Conservation and Pastoralism. https://www.efncp.org/download/HNVF_SEE_v1.pdf

Keneni, G., Bekele, E., Imtiaz, M. & Dagne, K. 2012. Genetic vulnerability of modern crop cultivars: Causes, mechanism and remedies. *International Journal of Plant Research*, 2(3): 69–79. https://doi.org/10.5923/j.plant.20120203.05

Krausmann, F., Haberl, H., Schulz, N.B., Erb, K.-H., Darge, E. & Gaube, V. 2003. Land-use change and socio-economic metabolism in Austria—Part I: driving forces of land-use change: 1950–1995. *Land Use Policy*, 20(1): 1–20. https://doi.org/10.1016/S0264-8377(02)00048-0

Kumar, R., Bhatnagar, P.R., Kakade, V. & Dobhal, S. 2020. Tree plantation and soil water conservation enhances climate resilience and carbon sequestration of agro ecosystem in semi-arid degraded ravine lands. *Agricultural and Forest Meteorology*, 282–283: 107857. https://doi.org/10.1016/j.agrformet.2019.107857

Kuuluvainen, T., Angelstam, P., Frelich, L., Jõgiste, K., Koivula, M., Kubota, Y., Lafleur, B. & Macdonald, E. 2021. Natural disturbance-based forest management: Moving beyond retention and continuous-cover forestry. *Frontiers in Forests and Global Change*, 4: 629020. https://doi.org/10.3389/ffgc.2021.629020

Kuzyakov, Y., Friedel, J.K. & Stahr, K. 2000. Review of mechanisms and quantification of priming effects. *Soil Biology and Biochemistry*, 32(11–12): 1485–1498. https://doi.org/10.1016/S0038-0717(00)00084-5

Liang, J., Crowther, T.W., Picard, N., Wiser, S., Zhou, M., Alberti, G., Schulze, E.-D. *et al.* 2016. Positive biodiversity-productivity relationship predominant in global forests. *Science*, 354(6309): aaf8957. https://doi.org/10.1126/science.aaf8957

Lomba, A., Alves, P., Jongman, R.H.G. & McCracken, D.I. 2015. Reconciling nature conservation and traditional farming practices: a spatially explicit framework to assess the extent of High Nature Value farmlands in the European countryside. *Ecology and Evolution*, 5(5): 1031–1044. https://doi.org/10.1002/ece3.1415

Marull, J., Cattaneo, C., Gingrich, S., De Molina, M.G., Guzmán, G.I., Watson, A., MacFadyen, J., Pons, M. & Tello, E. 2019a. Comparative Energy-Landscape Integrated Analysis (ELIA) of past and present agroecosystems in North America and Europe from the 1830s to the 2010s. *Agricultural Systems*, 175: 46–57. https://doi.org/10.1016/j.agsy.2019.05.011

Marull, J. & Font, C. 2017. The Energy–Landscape Integrated Analysis (ELIA) of Agroecosystems. In: E. Fraňková, W. Haas & S.J. Singh, eds. *Socio-Metabolic Perspectives on the Sustainability of Local Food Systems*. pp. 103–129. Vol. 7. Human-Environment Interactions. Cham, Springer International Publishing. https://doi.org/10.1007/978-3-319-69236-4_4

Marull, J., Font, C., Padró, R., Tello, E. & Panazzolo, A. 2016a. Energy–Landscape Integrated Analysis: A proposal for measuring complexity in internal agroecosystem processes (Barcelona Metropolitan Region, 1860–2000). *Ecological Indicators*, 66: 30–46. https://doi.org/10.1016/j.ecolind.2016.01.015

Marull, J., Font, C., Tello, E., Fullana, N., Domene, E., Pons, M. & Galán, E. 2016b. Towards an energy–landscape integrated analysis? Exploring the links between socio-metabolic disturbance and landscape ecology performance (Mallorca, Spain, 1956–2011). *Landscape Ecology*, 31(2): 317–336. https://doi.org/10.1007/s10980-015-0245-x

Marull, J., Herrando, S., Brotons, L., Melero, Y., Pino, J., Cattaneo, C., Pons, M., Llobet, J. & Tello, E. 2019b. Building on Margalef: Testing the links between landscape structure, energy and information flows driven by farming and biodiversity. *Science of The Total Environment*, 674: 603–614. https://doi.org/10.1016/j.scitotenv.2019.04.129

Marull, J., Tello, E., Bagaria, G., Font, X., Cattaneo, C. & Pino, J. 2018. Exploring the links between social metabolism and biodiversity distribution across landscape gradients: A regional-scale contribution to the land-sharing versus land-sparing debate. *Science of The Total Environment*, 619–620: 1272–1285. https://doi.org/10.1016/j.scitotenv.2017.11.196

Mayer, C. 2020. Life in the context of order and complexity. *Life*, 10(1): 5. https://doi.org/10.3390/life10010005

Moraine, M., Duru, M., Nicholas, P., Leterme, P. & Therond, O. 2014. Farming system design for innovative crop-livestock integration in Europe. *Animal*, 8(8): 1204–1217. https://doi.org/10.1017/S1751731114001189

Morales, H. 2002. Pest management in traditional tropical agroecosystems: Lessons for pest prevention research and extension. *Integrated Pest Management Reviews*, 7(3): 145–163. https://doi.org/10.1023/B:IPMR.0000027502.91079.01

Mori, A.S., Dee, L.E., Gonzalez, A., Ohashi, H., Cowles, J., Wright, A.J., Loreau, M. *et al.* 2021. Biodiversity–productivity relationships are key to nature-based climate solutions. *Nature Climate Change*, 11(6): 543–550. https://doi.org/10.1038/s41558-021-01062-1

Mushtaq, A., Pathania, S.S., Khan, Z.H. & Ahmad, M.O. 2020. Indigenous technical knowledge in pest management. *Journal of Entomology and Zoology Studies*, 8(5): 296–302.

Neal, A.L., Bacq-Labreuil, A., Zhang, X., Clark, I.M., Coleman, K., Mooney, S.J., Ritz, K. & Crawford, J.W. 2020. Soil as an extended composite phenotype of the microbial metagenome. *Scientific Reports*, 10(1): 10649. https://doi.org/10.1038/s41598-020-67631-0

Newman, E.A. 2019. Disturbance ecology in the anthropocene. *Frontiers in Ecology and Evolution*, 7: 147. https://doi.org/10.3389/fevo.2019.00147

Padró, R., Marco, I., Font, C. & Tello, E. 2019. Beyond Chayanov: A sustainable agroecological farm reproductive analysis of peasant domestic units and rural communities (Sentmenat; Catalonia, 1860). *Ecological Economics*, 160: 227–239. https://doi.org/10.1016/j.ecolecon.2019.02.009

Padró, R., Tello, E., Marco, I., Olarieta, J.R., Grasa, M.M. & Font, C. 2020. Modelling the scaling up of sustainable farming into agroecology territories: Potentials and bottlenecks at the landscape level in a Mediterranean case study. *Journal of Cleaner Production*, 275: 124043. https://doi.org/10.1016/j.jclepro.2020.124043

Peterson, C.A., Bell, L.W., Carvalho, P.C.D.F. & Gaudin, A.C.M. 2020. Resilience of an integrated crop–livestock system to climate change: A simulation analysis of cover crop grazing in southern Brazil. *Frontiers in Sustainable Food Systems*, 4: 604099. https://doi.org/10.3389/fsufs.2020.604099

Prein, M. 2002. Integration of aquaculture into crop–animal systems in Asia. *Agricultural Systems*, 71(1–2): 127–146. https://doi.org/10.1016/S0308-521X(01)00040-3

Prigogine, I. 1986. Life and physics: New perspectives. *Cell Biophysics*, 9(1–2): 217–224. https://doi.org/10.1007/BF02797383

Quinton, J.N., Öttl, L.K. & Fiener, P. 2022. Tillage exacerbates the vulnerability of cereal crops to drought. *Nature Food*, 3(6): 472–479. https://doi.org/10.1038/s43016-022-00533-8

Ranaboldo, C. & Leiva, F. 2013. *La valorización de los activos culturales: estrategias innovadoras para el empoderamiento de las mujeres rurales jóvenes*. Instituto de Estudios Peruanos. https://www.rimisp.org/documentos/la-valorizacion-de-los-activos-culturales-estrategias-innovadoras-para-el-empoderamiento-de-las-mujeres-rurales-jovenes-2/

Rathore, S., Chandola, M., Raghuvanshi, R., Kaur, M. & Singh, K.V. 2021. Indigenous pest management practices of Indian Hill farmers: Introspecting their rationale and communication pattern for secure ecosystems. *Sustainability*, 13(21): 11608. https://doi.org/10.3390/su132111608

Schandl, H. & Schulz, N. 2002. Changes in the United Kingdom's natural relations in terms of society's metabolism and land-use from 1850 to the present day. *Ecological Economics*, 41(2): 203–221. https://doi.org/10.1016/S0921-8009(02)00031-9

Schneider, E.D. & Kay, J.J. 1994. Life as a manifestation of the second law of thermodynamics. *Mathematical and Computer Modelling*, 19(6–8): 25–48. https://doi.org/10.1016/0895-7177(94)90188-0

Schneider, S. 2010. Reflexões sobre diversidade e diversificação. Agricultura, formas familiares e desenvolvimento rural. *RURIS*, 4(1).

Schneider, S. & Niederle, P.A. 2010. Resistance strategies and diversification of rural livelihoods: the construction of autonomy among Brazilian family farmers. *The Journal of Peasant Studies*, 37(2): 379–405. https://doi.org/10.1080/03066151003595168

Schrödinger, E. 1944. *What is Life? The Physical Aspect of the Living Cell*. Cambridge University Press.

Seddon, N., Chausson, A., Berry, P., Girardin, C.A.J., Smith, A. & Turner, B. 2020. Understanding the value and limits of nature-based solutions to climate change and other global challenges. *Philosophical Transactions of the Royal Society B: Biological Sciences*, 375(1794): 20190120. https://doi.org/10.1098/rstb.2019.0120

Shah, F. & Wu, W. 2019. Soil and crop management strategies to ensure higher crop productivity within sustainable environments. *Sustainability*, 11(5): 1485. https://doi.org/10.3390/su11051485

Skaalsveen, K., Ingram, J. & Clarke, L.E. 2019. The effect of no-till farming on the soil functions of water purification and retention in north-western Europe: A literature review. *Soil and Tillage Research*, 189: 98–109. https://doi.org/10.1016/j.still.2019.01.004

Somasundaram, J., Sinha, N.K., Dalal, R.C., Lal, R., Mohanty, M., Naorem, A.K., Hati, K.M. *et al.* 2020. No-till farming and conservation agriculture in South Asia: Issues, challenges, prospects and benefits. *Critical Reviews in Plant Sciences*, 39(3): 236–279. https://doi.org/10.1080/07352689.2020.1782069

Sonneveld, B.G.J.S., Merbis, M.D., Alfarra, A., Ünver, O. & Arnal, M.F. 2018. *Nature-Based Solutions for agricultural water management and food security*. Land and water discussion paper 12. Rome, FAO. https://www.fao.org/3/CA2525EN/ca2525en.pdf

Stockmann, U., Padarian, J., McBratney, A., Minasny, B., De Brogniez, D., Montanarella, L., Hong, S.Y., Rawlins, B.G. & Field, D.J. 2015. Global soil organic carbon assessment. *Global Food Security*, 6: 9–16. https://doi.org/10.1016/j.gfs.2015.07.001

Tahat, M.M., Alananbeh, K.M., Othman, Y.A. & Leskovar, D.I. 2020. Soil health and sustainable agriculture. *Sustainability*, 12(12): 1–26.

Tamburini, G., Bommarco, R., Wanger, T.C., Kremen, C., Van Der Heijden, M.G.A., Liebman, M. & Hallin, S. 2020. Agricultural diversification promotes multiple ecosystem services without compromising yield. *Science Advances*, 6(45): eaba1715. https://doi.org/10.1126/sciadv.aba1715

Tandzi, N.L. & Mutengwa, S.C. 2020. Factors Affecting Yield of Crops. In: Amanullah, ed. *Agronomy - Climate Change and Food Security*. IntechOpen. https://doi.org/10.5772/intechopen.90672

Tello, E., Galán, E., Cunfer, G., Guzmán, G., González de Molina, M., Krausmann, F., Gingrich, S. *et al.* 2015. A proposal for a workable analysis of Energy Return on Investment (EROI) in agroecosystems. Part I: Analytical approach. *IFF Social Ecology Working Papers*, 156: 1–110.

Tello, E., Galán, E., Sacristán, V., Cunfer, G., Guzmán, G.I., González De Molina, M., Krausmann, F. *et al.* 2016. Opening the black box of energy throughputs in farm systems: A decomposition analysis between the energy returns to external inputs, internal biomass reuses and total inputs consumed (the Vallès County, Catalonia, c.1860 and 1999). *Ecological Economics*, 121: 160–174. https://doi.org/10.1016/j.ecolecon.2015.11.012

Tello, E., Garrabou, R., Cussó, X. & Olarieta, J.R. 2008. Una interpretación de los cambios de uso del suelo desde el punto de vista del metabolismo social agrario. La comarca catalana del Vallès, 1853-2004. In: *Revista Iberoamericana de Economía Ecológica*. pp. 97–115. Vol. 7. https://econpapers.repec.org/article/ribrevibe/rev7_5f06.htm

Tello, E., Garrabou, R., Cussó, X., Olarieta, J.R. & Galán, E. 2012. Fertilizing methods and nutrient balance at the end of traditional organic agriculture in the Mediterranean bioregion: Catalonia (Spain) in the 1860s. *Human Ecology*, 40(3): 369–383. https://doi.org/10.1007/s10745-012-9485-4

Thilakarathna, M.S. & Raizada, M.N. 2017. A meta-analysis of the effectiveness of diverse rhizobia inoculants on soybean traits under field conditions. *Soil Biology and Biochemistry*, 105: 177–196. https://doi.org/10.1016/j.soilbio.2016.11.022

Tscharntke, T., Tylianakis, J.M., Rand, T.A., Didham, R.K., Fahrig, L., Batáry, P., Bengtsson, J. *et al.* 2012. Landscape moderation of biodiversity patterns and processes - eight hypotheses. *Biological Reviews*, 87(3): 661–685. https://doi.org/10.1111/j.1469-185X.2011.00216.x

Udawatta, R.P., Rankoth, L. & Jose, S. 2019. Agroforestry and biodiversity. *Sustainability*, 11(10): 2879. https://doi.org/10.3390/su11102879

Ulanowicz, R.E. 2001. Information theory in ecology. *Computers & Chemistry*, 25(4): 393–399. https://doi.org/10.1016/S0097-8485(01)00073-0

United Nations. 2022. World Population Prospects 2022: Summary of Results. In: *Population Division*. Cited 11 July 2023. https://www.un.org/development/desa/pd/content/World-Population-Prospects-2022

United Nations Environment Assembly. 2022. Outcomes of the resumed session of UNEA-5 (UNEA-5.2). In: *United Nations Environment Assembly*. Cited 11 July 2023. http://www.unep.org/environmentassembly/unea-5.2/outcomes-resumed-session-unea-5-unea-5.2-0

Wakindiki, I.I.C. & Ben-Hur, M. 2002. Indigenous soil and water conservation techniques: effects on runoff, erosion, and crop yields under semi-arid conditions. *Soil Research*, 40(3): 367. https://doi.org/10.1071/SR01037

Wen, Z., Zheng, H., Smith, J.R. & Ouyang, Z. 2021. Plant functional diversity mediates indirect effects of land-use intensity on soil water conservation in the dry season of tropical areas. *Forest Ecology and Management*, 480: 118646. https://doi.org/10.1016/j.foreco.2020.118646

Wiesmeier, M., Urbanski, L., Hobley, E., Lang, B., Von Lützow, M., Marin-Spiotta, E., Van Wesemael, B. *et al.* 2019. Soil organic carbon storage as a key function of soils - A review of drivers and indicators at various scales. *Geoderma*, 333: 149–162. https://doi.org/10.1016/j.geoderma.2018.07.026

Willig, M.R. & Presley, S.J. 2018. Biodiversity and Disturbance. In: *The Encyclopedia of the Anthropocene*. pp. 45–51. Vol. 3. Oxford, Elsevier.

Wilson, M. & Lovell, S. 2016. Agroforestry: The next step in sustainable and resilient agriculture. *Sustainability*, 8(6): 574. https://doi.org/10.3390/su8060574

Xu, Z., Li, C., Zhang, C., Yu, Y., Van Der Werf, W. & Zhang, F. 2020. Intercropping maize and soybean increases efficiency of land and fertilizer nitrogen use; A meta-analysis. *Field Crops Research*, 246: 107661. https://doi.org/10.1016/j.fcr.2019.107661

Zhang, W., Ricketts, T.H., Kremen, C., Carney, K. & Swinton, S.M. 2007. Ecosystem services and dis-services to agriculture. *Ecological Economics*, 64(2): 253–260. https://doi.org/10.1016/j.ecolecon.2007.02.024

Zhao, X., Liu, S.-L., Pu, C., Zhang, X.-Q., Xue, J.-F., Ren, Y.-X., Zhao, X.-L. *et al.* 2017. Crop yields under no-till farming in China: A meta-analysis. *European Journal of Agronomy*, 84: 67–75. https://doi.org/10.1016/j.eja.2016.11.009

FURTHER READING

Bignal, E.M. & McCracken, D.I. 2000. The nature conservation value of European traditional farming systems. *Environmental Reviews*, 8(3): 149–171. https://doi.org/10.1139/a00-009

Del Monte-Luna, P., Brook, B.W., Zetina-Rejón, M.J. & Cruz-Escalona, V.H. 2004. The carrying capacity of ecosystems. *Global Ecology and Biogeography*, 13(6): 485–495. https://doi.org/10.1111/j.1466-822X.2004.00131.x

Dewar, J.A. 2007. *Perennial polyculture farming: Seeds of another agricultural revolution?* RAND Corporation. https://www.rand.org/pubs/occasional_papers/OP179.html

Georgescu-Roegen, N. 1975. Energy and Economic Myths. *Southern Economic Journal*, 41(3): 347. https://doi.org/10.2307/1056148

González De Molina, M. & Guzmán Casado, G. 2017. Agroecology and ecological intensification. A discussion from a metabolic point of view. *Sustainability*, 9(1): 86. https://doi.org/10.3390/su9010086

Haberl, H. 2001. The energetic metabolism of societies Part I: Accounting concepts. *Journal of Industrial Ecology*, 5(1): 11–33. https://doi.org/10.1162/108819801753358481

Hercher-Pasteur, J., Loiseau, E., Sinfort, C. & Hélias, A. 2020. Energetic assessment of the agricultural production system. A review. *Agronomy for Sustainable Development*, 40(4): 29. https://doi.org/10.1007/s13593-020-00627-2

HLPE. 2019. *Agroecological and other innovative approaches for sustainable agriculture and food systems that enhance food security and nutrition*. Committee on World Food Security (CFS). https://www.fao.org/family-farming/detail/en/c/1200043/

Ho, M.-W. 2013. Circular thermodynamics of organisms and sustainable systems. *Systems*, 1(3): 30–49. https://doi.org/10.3390/systems1030030

Keesstra, S.D., Bouma, J., Wallinga, J., Tittonell, P., Smith, P., Cerdà, A., Montanarella, L. *et al.* 2016. The significance of soils and soil science towards realization of the United Nations Sustainable Development Goals. *SOIL*, 2(2): 111–128. https://doi.org/10.5194/soil-2-111-2016

Lehmann, J., Hansel, C.M., Kaiser, C., Kleber, M., Maher, K., Manzoni, S., Nunan, N. *et al.* 2020. Persistence of soil organic carbon caused by functional complexity. *Nature Geoscience*, 13(8): 529–534. https://doi.org/10.1038/s41561-020-0612-3

Pauliuk, S. & Hertwich, E.G. 2015. Socioeconomic metabolism as paradigm for studying the biophysical basis of human societies. *Ecological Economics*, 119: 83–93. https://doi.org/10.1016/j.ecolecon.2015.08.012

Power, A.G. 2010. Ecosystem services and agriculture: tradeoffs and synergies. Philosophical Transactions of the Royal Society B: *Biological Sciences*, 365(1554): 2959–2971. https://doi.org/10.1098/rstb.2010.0143

Tilman, D., Reich, P.B., Knops, J., Wedin, D., Mielke, T. & Lehman, C. 2001. Diversity and productivity in a long-term grassland experiment. *Science*, 294(5543): 843–845. https://doi.org/10.1126/science.1060391

Tscharntke, T., Clough, Y., Wanger, T.C., Jackson, L., Motzke, I., Perfecto, I., Vandermeer, J. & Whitbread, A. 2012. Global food security, biodiversity conservation and the future of agricultural intensification. *Biological Conservation*, 151(1): 53–59. https://doi.org/10.1016/j.biocon.2012.01.068

FROM NATURE-NEGATIVE TO NATURE-POSITIVE PRODUCTION:

A CONCEPTUAL AND PRACTICAL FRAMEWORK FOR AGRICULTURE BASED ON THERMODYNAMICS

How can agriculture be nature-postive? And what does "nature-postive" even mean? The answer lies in understanding and mimicking the way in which ecosystems naturally develop productivity and achieve sustainability.

A theoretical and practical framework is proposed to understand, measure and implement nature-positive production agriculture (NPPA). Nature positivity can be achieved only by designing and managing agroecosystems in a way that replicates natural successions and by increasing systemic complexity and the system's capacity to capture and circulate increasingly larger energy flows. The most critical ecosystem features that mediate these functions are biomass, biodiversity, soil health and landscape diversity. Complexity and the abundance of above- and below-ground biomass thus emerge as key indicators of energy efficiency, in contrast with the simplified, monocultural systems that dominate modern agriculture.

The concept of NPPA was initially conceived during the 2021 United Nations Food Systems Summit. The idea is that agriculture is expected not only to be sustainable, but also to aid in ecological restoration. For that to be the case, agroecosystems must recover the energy efficiency that was lost with the transition towards a production model based on off-farm inputs. In light of the strong correlation that connects biodiversity with ecosystem productivity, agriculture's relationship with biodiversity also must be recovered.

In this paper, methodologies are provided for assessing the energy efficiency of an agroecosystem and its agroecological performance. Drawing from agroecology, permaculture and nature-based solutions, five priority areas are proposed to lead the implementation of NPPA: soil and water conservation; soil improvement; evolutionary populations; integrating crops, forestry, livestock and aquaculture; and integrated pest management. For each priority, some of the most common practices – often linked with traditional knowledge systems and agricultural heritage – are described.

FAO Regional Office for Europe and Central Asia
https://www.fao.org/europe/en/

Food and Agriculture Organization of the United Nations
Budapest, Hungary

ISBN 978-92-5-138089-5

9 789251 380895
CC7414EN/1/10.23