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Position Paper

Circular Bioeconomy as a Driver of Regenerative Multifunctional Landscapes

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CGIAR Multifunctional Landscapes Program

Multifunctional Landscapes is a CGIAR Science Program that aims to enhance the resilience, productivity, and sustainability of agricultural landscapes by integrating diverse land uses, ecosystem services, and livelihood strategies. The initiative supports evidence-based policies and innovations that balance food production with climate adaptation, biodiversity conservation, and social inclusion. By working with local communities, governments, and partners, it promotes landscape-level approaches to managing natural resources for long-term ecological and economic benefits. To learn more about the CGIAR Research Portfolio, please visit www.cgiar.org/cgiar-researchporfolio-2025-2030/

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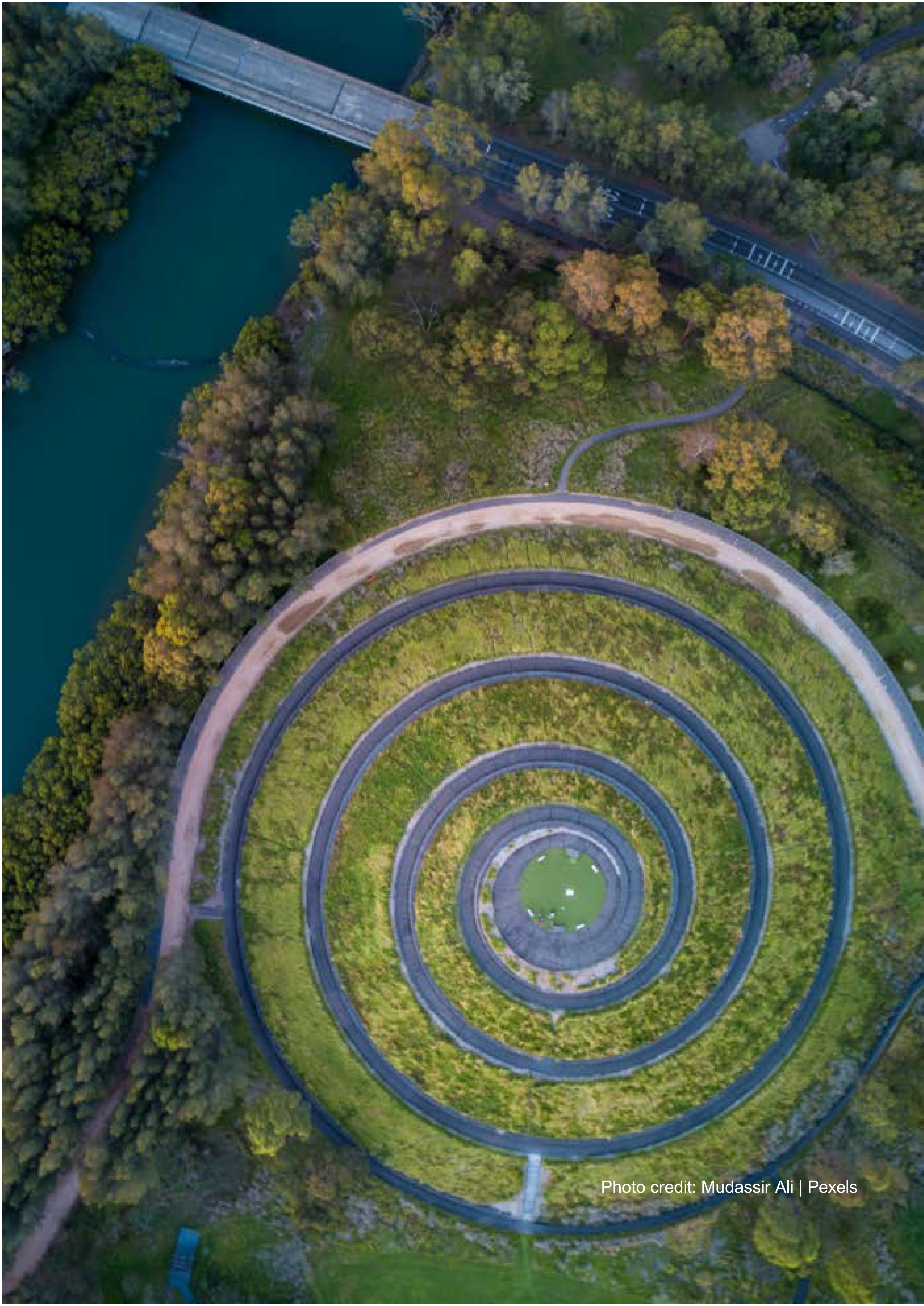
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Executive Summary

This position paper advocates for a systematic integration of Circular Bioeconomy (CBE) principles into the design and implementation of Multifunctional Landscapes (MFLs) as a pathway to achieving low-carbon, resource-efficient, socially inclusive, and ecologically balanced development. Combining these approaches can regenerate degraded agricultural landscapes, strengthen rural–urban linkages, and diversify rural economies, opportunities that remain largely underexploited in current practice.

CBE provides practical strategies for closing nutrient, water, energy, and material loops, transforming organic waste and residues into valuable inputs such as biofertilizers, water, renewable energy, and bio-based materials. These approaches can reduce reliance on synthetic inputs, lower greenhouse-gas emissions, reduce freshwater use and rebuild soil fertility, while generating new rural enterprises and livelihood opportunities that reinforce local value chains. MFLs, by contrast, seek to harmonize land uses to deliver multiple ecosystem services, such as biodiversity conservation, soil regeneration, water regulation, carbon storage, and livelihoods, through participatory planning and adaptive governance. When pursued jointly, both frameworks can transform rural territories into resilient socio-ecological systems that deliver economic value while maintaining ecological integrity.

Yet, current efforts to integrate CBE into landscape initiatives are fragmented. For example, many existing landscape programs focus primarily on biophysical design, with limited consideration of the regenerative business models and economic systems needed to sustain multifunctionality over time. In these landscapes. mechanisms that support circular resource flows, value retention, and inclusive livelihood opportunities are often overlooked or insufficiently embedded in management strategies. Policy incoherence, particularly incentives favoring bioenergy over higher-value material uses, drives maladaptation and feedstock overexploitation. Market-driven biomass production risks degrading soils, water quality, and biodiversity. Governance is often siloed, with limited cross-sectoral coordination and weak participation of women, smallholders, and indigenous groups. More importantly, financial and investment mechanisms to reward circular practices are poorly developed, and data on resource and waste flows are scarce, outdated, or inconsistent, limiting evidence-based planning and investment.

This paper calls for policy coherence, inclusive governance, innovative financing, and integrated knowledge systems to mainstream circularity in landscape management.

Specifically, it urges:

- **Policy and governance alignment across sectors such as agriculture, energy, water and forestry** to overcome institutional silos and harmonize incentives for circular investments.
- **Innovative financing mechanisms**, including payments for ecosystem services, blended finance, and targeted incentives to de-risk and attract investment in circular enterprises.
- **Participatory and inclusive decision-making platforms**, ensuring that women, youth, and smallholders equitably share in benefits and shape landscape governance.
- **Integrated knowledge and data systems**, which combine spatially explicit resource-flow mapping with local and indigenous knowledge to guide evidence-based planning.
- **Robust monitoring and evaluation frameworks with clear performance indicators and targets** to track the outcomes of CBE–MFL integration and enable adaptive landscape management.
- **Nexus-based planning approaches** to ensure CBE solutions and land-use decisions maximize synergies and minimize trade-offs across land, water, energy, and food systems, while promoting multi-purpose, climate-resilient, and nature-positive practices.

1. A Tipping Point for Nature and People

Agricultural landscapes are deteriorating under climate stress and linear production models. Without urgent action, resource depletion and biodiversity loss will lock economies into decline.

For many years, Earth's stable climate and ecological balance have supported the growth of agriculture and human civilization. This period of environmental stability provided favorable conditions, such as moderate temperatures, dependable rainfall, fertile soils, and balanced nutrient cycles, that enabled societies to prosper. However, since the Industrial Revolution, this stability has faced unprecedented pressure. Human activity has become the main driver of global environmental change, marking the beginning of what scientists describe as the Anthropocene, an era when humanity itself has become a planetary force (Rockström et al. 2009).

The planetary boundaries framework (Figure 1) illustrates how human pressures have already exceeded safe limits in three critical domains: climate change, biodiversity loss, and disruption of the nitrogen cycle, while others, such as land-use change and freshwater withdrawal, are rapidly approaching their thresholds (Rockström et al. 2009; 2024). The disruptions are destabilizing hydrological and nutrient cycles, depleting soil nutrients, contaminating freshwater supplies, fragmenting habitats, and accelerating biodiversity loss.

Nowhere is this crisis more visible than in agriculture. The dominance of intensive monocultures, extractive production methods and widespread land-use conversion has led to the replacement of multifunctional landscapes with simplified, single-function systems designed to maximize short-term yields (Nair 2023). Traditional landscapes, once rich mosaics of ecosystems and livelihoods, have been reduced to uniform production zones. Crossing the safe ecological thresholds has profound implications for agricultural landscapes. The IPCC (2019) warns that climate stress is compounding land degradation, reducing yields, and amplifying risks of desertification.

Similarly, FAO (2017) and Pengue et al. (2018) highlight declining soil fertility, biodiversity loss, and nutrient depletion as systemic threats undermining food security and ecosystem resilience. The feedback loops between climate change and land degradation further entrench this downward spiral: degraded soils lose their capacity to store carbon and retain moisture, which, in turn, exacerbates drought stress, reduces vegetation growth, and increases greenhouse gas emissions. As productivity declines, farmers are forced to expand cultivation into marginal areas, accelerating deforestation and biodiversity loss.

Furthermore, in many regions, particularly across the Global South, environmental pressures intersect with socio-political fragility. Ahmadnia et al. (2022) note that competition over land and water, tenure insecurity, and rural displacement are driving cultivation into ecologically sensitive zones. These conditions link environmental degradation with poverty, social exclusion, and conflict, weakening the resilience of water–energy–food–ecosystems. In such contexts, landscape degradation is not merely an ecological outcome but also an issue of equity and livelihood crises. When communities lose secure access to natural resources, adaptive capacity declines, reinforcing cycles of unsustainable resource extraction and vulnerability to climate shocks.

The collapse of ecological functions undermines nature's capacity to function as both a productive base and a climate buffer, threatening the very foundations of sustainable agriculture. A fundamental shift is thus required to transform extractive practices to regenerative and circular models, practices that can restore diversify production systems, create more equitable, sustainable rural economies and strengthen livelihoods.

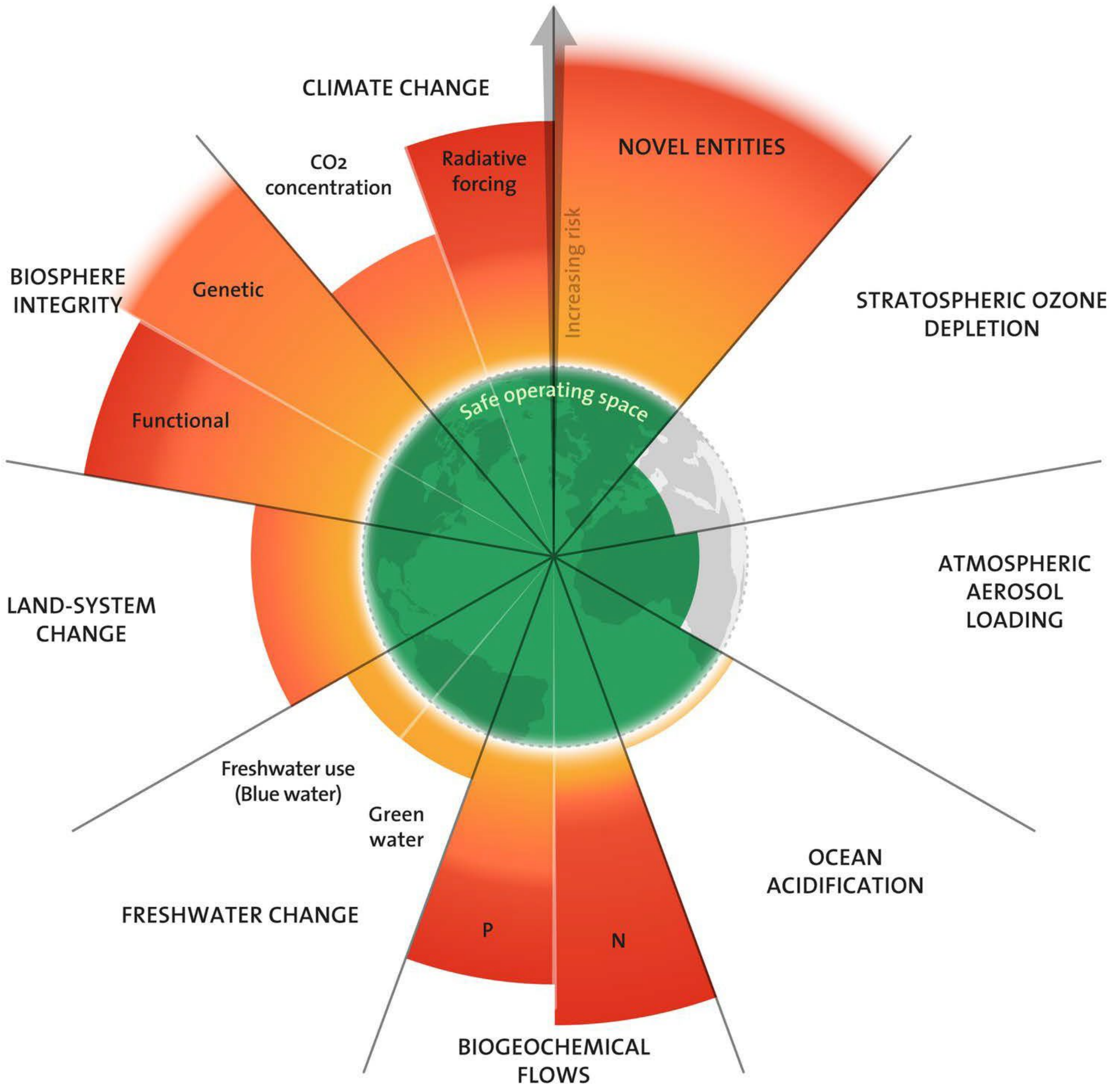

Figure 1. Planetary boundaries and the safe operating space for humanity.
Credit: Azote for Stockholm Resilience Centre, based on analysis Sakschewski and Caesar et al. 2025).

The diagram shows nine critical Earth-system processes that regulate the planet's stability and resilience. These include climate change, biosphere integrity, land-system change, freshwater use, biogeochemical flows (nitrogen and phosphorus), ocean acidification, atmospheric aerosol loading, stratospheric ozone depletion, and novel entities (such as chemical pollution). The green zone represents the safe operating space, while the red areas indicate where planetary boundaries have been exceeded their safe limits, signaling heightened risk to Earth-system stability. While the framework provides a powerful global lens for understanding Earth-system limits, it is not without conceptual and practical challenges. Scientifically, measuring complex interactions and defining precise thresholds remain uncertain, and some boundaries are influenced by normative judgments about acceptable risk. In practice, its application at sub-global scales can be difficult, and interactions between boundaries may be oversimplified. Governance and equity issues also arise, as global limits invite debate over how the "safe operating space" should be shared among nations and communities. Nonetheless, the planetary boundaries framework remains a valuable heuristic, offering a unifying scientific perspective to guide sustainable development and collective stewardship of the Earth system.

2. Defining Multifunctional Landscapes in Practice

Landscapes that feed people, conserve biodiversity and sustain rural livelihoods can replace today's extractive farming, if circular bioeconomy principles turn vision into practice.

Multifunctional landscapes (MFLs) provide an integrated framework for how land can simultaneously support people, nature, and economies. While there is no single definition, MFLs are described as land-use mosaics or spatial arrangements that simultaneously integrate and provide multiple benefits or services, including ecological, economic, and socio-cultural functions (Brandt & Vejre 2004; Peng et al. 2019; Garibaldi et al. 2023).

McGranahan (2014) offers one of the most explicit agricultural-context descriptions of MFLs, portraying them as systems that connect agroecological practices with landscape-level processes across scales, from fields, farms to entire landscapes. In this framing, MFLs are not just an aggregate of different land uses but are spatially and functionally connected systems, deliberately designed to deliver multiple, coexisting outcomes. These outcomes could include a mix of agricultural production, biodiversity conservation, and the maintenance of ecosystem services, all managed in ways that recognize trade-offs and build synergies between functions. Schaan et al. (2025) similarly describe these agricultural landscapes as mosaics of interacting land uses managed to provide multiple benefits, from biodiversity conservation to agricultural productivity to improved livelihoods. While the study does not explicitly use the term, their description of agricultural landscapes along a gradient of compositional and configurational heterogeneity, which can vary from simple, intensively farmed areas to complex mosaics rich in semi-natural features, aligns closely with MFL concepts.

Beyond their ecological and productive roles, MFLs are also described as repositories of cultural heritage, spaces for recreation and carriers of traditional knowledge (Garibaldi et al. 2023). They form arenas where material and non-material benefits are co-produced through the interplay of natural capital, human agency, and governance arrangements (Bruley et al. 2021). Recent studies highlight MFL's contribution to human well-being through cultural identity, health benefits, and livelihood diversification (Fagerholm et al. 2020). These contributions are embedded in place attachment, social cohesion, and opportunities for intergenerational knowledge transfer, reinforcing the importance of relational and social values (Quinn & Allen 2021; Westholm & Ostwald 2019). In this context, social well-being and cultural identity become explicit management outcomes alongside biodiversity and production goals, yielding strengthened community cohesion, enhanced recreational and educational opportunities, and the preservation of local traditions and place-based identities.

Multifunctionality also results from integrating diverse stakeholder values, negotiated trade-offs, and land-use planning frameworks that accommodate both tangible and intangible benefits (Quinn & Allen 2021). Participatory approaches are increasingly used to identify and spatially represent locally-valued cultural services (Fagerholm et al. 2020; Bruley et al. 2021). Such tools capture the experiential and context-specific aspects of landscape values, which are often neglected in standard ecosystem service assessments. Governance structures also play a crucial role in mediating access to these benefits, influencing how trade-offs are resolved between competing land uses and whose values are prioritized (Quinn & Allen 2021; Westholm & Ostwald 2019). When governance is inclusive and responsive to different value systems, MFLs can boost adaptive capacity, equity, and the resilience of social-ecological systems; conversely, exclusionary or market-driven governance may undermine their cultural and social dimensions.

2.1 Features of Multifunctional Landscapes

Brandt and Vejre (2004) identify three interlinked dimensions of multifunctionality: spatial, temporal and social. Spatial multifunctionality captures the co-location of diverse land functions, agriculture, biodiversity conservation and recreation, within the same area. Temporal multifunctionality recognizes sequential uses over time, such as seasonal habitats or landscapes that evolve as ecological conditions and social priorities shift. Social multifunctionality reflects the different perceptions, values and uses of a landscape held by farmers, planners and conservationists. Together, these dimensions underscore that MFLs are both socio-institutional and ecological constructs, shaped by policy frameworks and collective decision-making (Yang et al. 2013; Coles et al. 2018).

Across studies (McGranahan, 2014; Mastrangelo et al. 2014; Coles et al. 2018; Garibaldi et al. 2023), five recurring features characterize MFLs:

- **Co-provision of multiple benefits**: Beyond biodiversity conservation, water regulation and quality, soil fertility enhancement, nitrogen retention, carbon storage, climate regulation, cultural identity and food and fiber production (Mastrangelo et al. 2014; Fagerholm et al. 2020; Garibaldi et al. 2023), MFLs also sustain pollination and biological pest control, buffer climate extremes such as floods, hurricanes and landslides (Garibaldi et al. 2023). They provide recreation, aesthetic values and nature-based climate adaptation options (Lavorel et al. 2022). These regulating, provisioning and cultural services interact to support resilient food systems and long-term human well-being.
- **Structural diversity and spatial. heterogeneity**: MFLs have mosaics of natural and semi-natural habitats, including agroforestry systems, riparian buffers, hedgerows and perennial vegetation that enhance species and functional diversity, pollination, pest control, nutrient retention and hydrological services such as groundwater recharge and flood mitigation (McGranahan 2014). Maintaining a critical share of these habitats increases landscape complexity and ecological connectivity (Garibaldi et al. 2023; Lavorel et al. 2022).
- **Functionality across scales**: From field-level soil conservation and crop diversification to farm-level mixed crop–livestock systems and, at the landscape scale, MFLs embodies coordinated land-sharing/land-sparing strategies and ecological corridors that sustain ecosystem functioning and watershed integrity. This multi-level functionality also encompasses socio-cultural identity (heritage, sense of place, and collective memory), amenities and recreational values, diversified rural livelihoods, and long-term ecological resilience beyond immediate provisioning services (Pitman 2022; Santika et al. 2015).
- **Integrated governance and stakeholder participation**: Policy instruments, economic incentives and sustainability metrics combined with active engagement are used in valuing and planning ecosystem services, with landscapes serving as arenas of negotiation where competing interests are balanced through participatory, adaptive governance and conflict resolution (Brandt & Vejre 2004; Bruley et al. 2021; Fagerholm et al. 2020).
- **Deliberate anticipation and management of trade-offs**: There is a matching of land-use intensity to ecological capacity and accounting for spatial configuration and wider socio-environmental drivers, with a deliberate integration of land uses (agriculture, forestry, settlement, recreation) so that multiple functions can coexist and reinforce one another (Brandt & Vejre 2004; Yang et al. 2013).

Multifunctionality therefore emerges as a *system property*, produced through the interaction of structural diversity, ecological processes and human management rather than as a collection of isolated outputs. Conceptually, it integrates landscape heterogeneity, ecological connectivity and participatory governance to sustain multiple "nature's contributions to people," enabling landscapes to remain resilient to climate change while supporting both people and ecosystems (Liu et al. 2023).


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3. Understanding the Circular Bioeconomy: From Concept to Practice

Circular bioeconomy is not just about recycling materials, it is a regenerative economic model that restores ecosystems, replenishes natural capital and sustains livelihoods through the responsible use of biological resources.

The concept of a circular bioeconomy (CBE) has become a central idea in sustainability discussions, linking the goals of the bioeconomy with the regenerative ambition of the circular economy. It goes beyond merely closing material loops: the CBE seeks to redesign how societies produce and consume, so that biological resources are used, reused, and regenerated while the ecosystems that supply them, and the wider ecological systems that sustain those ecosystems, are actively restored (De Schoenmakere et al. 2018).

Rather than a simple “take–make–reuse” cycle, the CBE promotes regenerative production systems that keep economies within planetary boundaries and strengthen nature’s capacity to renew itself. Some authors present it as an extension of the bioeconomy, improving resource efficiency and environmental performance (Mesa et al. 2024); others describe it as a transformative economic model, where biomass cascades through its highest-value uses before nutrients and energy are returned to ecosystems (De Schoenmakere et al. 2018). Still others view CBE as an integrated systems approach, combining industrial ecology, agroecology and innovation policy to manage biomass flows across food, energy and material sectors while promoting social equity (Nguyen et al. 2025).

Conceptually, CBE is both an economic system and a sustainability strategy: it couples technological innovation with governance and market mechanisms to optimize the use of biological resources while respecting the biosphere’s regenerative capacity. Its aim is not merely to improve productivity and expand the bio-based economy, but to produce, use and recycle biomass in ways that restore ecosystem services, sustain nature’s regenerative functions and create inclusive, low-carbon growth (Schipfer et al., 2024; Jacquet et al. 2025). These principles directly support the objectives of MFLs, which seek to harmonize production, ecosystem integrity, and human well-being.

3.1. Principles of a Circular Bioeconomy

The CBE is based on several interlinked principles (Figure 2) that integrate the cascading use of biomass, nutrient cycling, renewable energy, and inclusive governance (Muscat et al. 2021; Meza et al. 2022; Pink 2023). Market mechanisms, value-chain design and investment frameworks enable these principles to operate in practice, ensuring resource efficiency and equitable benefit sharing (Jordan et al. 2023). Drawing on Muscat et al. (2021), five ecological principles provide a guiding framework for CBE implementation in agriculture include:

1. **Avoids non-essential use and minimize waste:** Biomass demand should be reduced for low-value or non-essential products to prevent the loss of vital resources.
2. **Utilizes and recycles by-products:** Co-products, residues and side streams from primary sectors are maximized through nutrient recycling, composting, anaerobic digestion and biorefining, reducing the need for virgin resource extraction.
3. **Prioritizes biomass for basic needs:** Biological resources are first directed to essential human needs, such as food, medicine, healthcare, and clothing, and to sectors without sustainable substitutes, before allocation is made to low-priority uses.
4. **Use renewable energy and enhance efficiency:** Biomass production and processing are powered by renewable energy and processes are managed for high efficiency throughout the value chain.
5. **Safeguard and regenerate ecosystems:** Production remain within the regenerative and absorptive limits of ecosystems, maintaining biodiversity, soil fertility, carbon stocks and hydrological functions while preventing over-harvesting of finite resources for immediate gains.

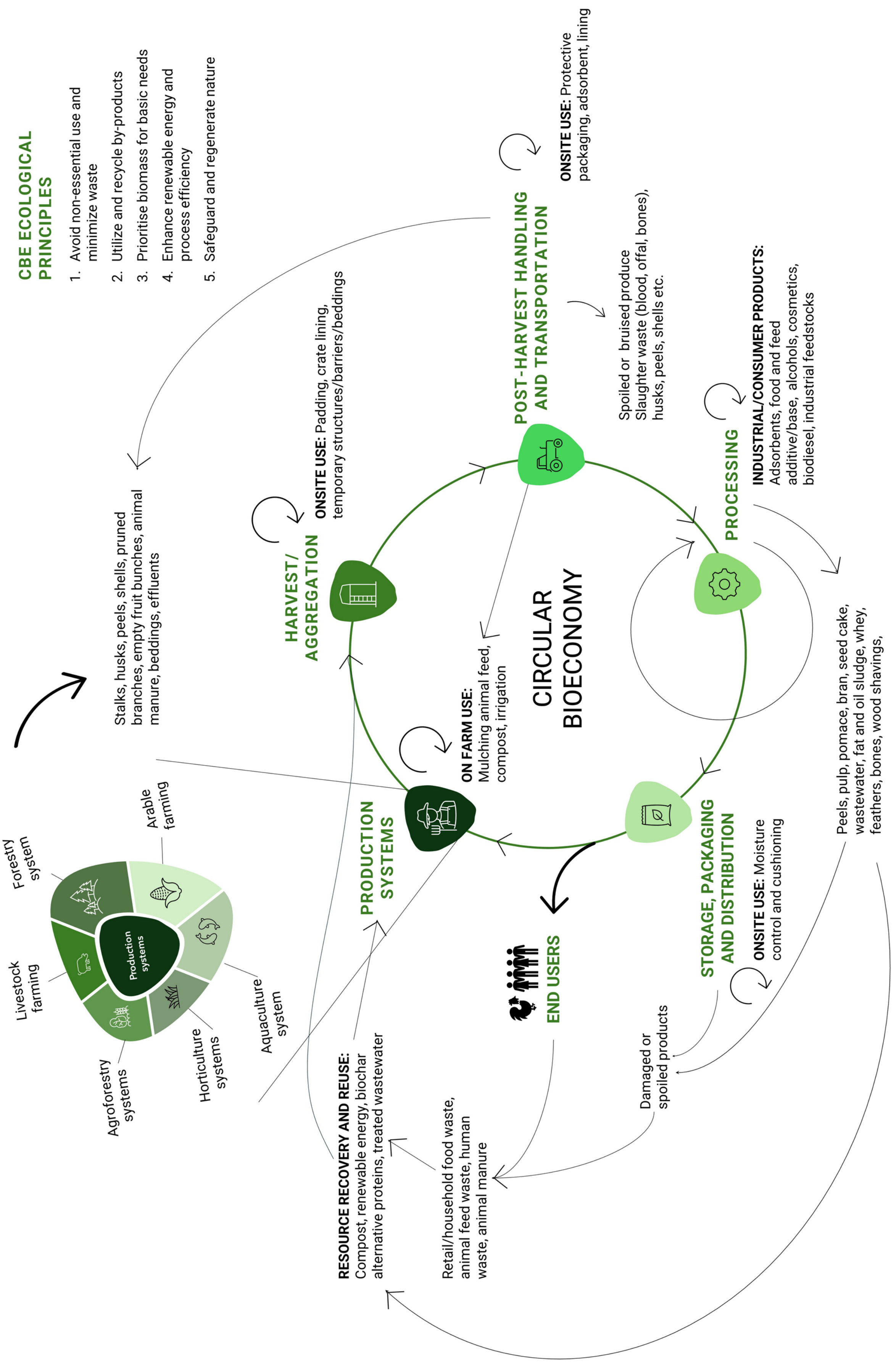

Figure 2 − Circular bioeconomy system and flow of agri-food resources across value-chain stages. Source: Tosin Somorin (IWMI), Icon adapted from PresentationGo.com

4. Driving Regenerative Landscapes through a Circular Bioeconomy

Beyond simple recycling, circular bioeconomy strategies integrate resource flows into productive mosaics and create new market opportunities, transforming multifunctional landscapes into resilient socio-ecological systems that can sustain both people and nature for generations.

Agroecology recognizes that healthy food systems and the creation of regenerative landscapes depend on the continuous recycling of nutrients, water and organic matter, and long before the term “circular bioeconomy” emerged, agroecological practices have promoted closing on-farm loops through composting, manure management, nitrogen-fixing legumes and diversified crop–livestock systems. These measures provide the ecological foundation and field-level practices for nutrient cycling, maintaining soil fertility, and reducing dependence on synthetic fertilizers, as well as enhancing natural nitrogen fixation and nutrient-use efficiency in MFLs (Morais et al. 2021). However, CBE extends far beyond the traditional focus on resource recycling. As outlined by Muscat et al. (2021), the CBE is an integrated systems approach that links industrial ecology, agroecology, and innovation policy to manage biomass flows across the food, energy, and material sectors, while safeguarding ecosystem functions and promoting social equity. It does not simply reuse nutrients within the farm gate; it redesigns production and consumption systems so that biological resources are cascaded through their highest-value uses, nutrients and energy are recovered from urban and agro-industrial wastes, and governance and market mechanisms create inclusive bio-based value chains. It links rural landscapes to urban resource flows, creating markets for bio-based products, and embedding regeneration and social equity into the very architecture of economies. This next sub-sections provide practical and technical insights into how CBE strategies facilitate spatial–ecological integration within MFLs, promoting resource circularity, value chains, and resilient socio-ecological–economic systems within a regenerative framework.

4.1. Resource Circularity as the Engine of Regeneration

CBE strategies enable closed-loop flows of nutrients, energy and biomass, transforming waste streams into valuable inputs and reducing dependence on finite resources. Research shows that nutrient loops, especially nitrogen recycling through composting, manure management, combined with agroecological measures such as the integration of legumes, can offset the demand for synthetic fertilizers and restore soil fertility (Rodríguez-Espinosa et al. 2023; Regassa et al. 2023). Equally critical is the recovery and reuse of phosphorus and other key nutrients from animal manures, food-processing residues and urban organic wastes (Buckwell & Nadeu 2016; Oenema et al. 2012). This could decrease dependency on mined phosphate rock and allow agricultural production to remain within planetary boundaries (Richardson et al. 2023).

Agroecological practices that build soil organic matter, such as incorporating cover crops or integrating legumes, are often overlooked in production systems but central to sustainable farming (Clara et al., 2017; Laban et al. 2018). CBE initiatives can facilitate the adoption of these practices by supplying recycled organic inputs, such as compost, biochar, and digestate. When combined with permanent cover crops, these amendments can improve soil carbon levels, cation-exchange capacity, microbial activity and water-holding capacity (Ighalo et al. 2025; Shyam et al. 2025). Integrated crop–livestock systems also strengthen these loops by coupling manure recycling with carbon and nitrogen-fixing legumes and by feeding crop residues back to animals (Sekaran et al. 2021; Tadesse et al. 2021; Duncan et al. 2023; Shanmugam et al. 2024). Higher soil carbon, in turn, reinforces nutrient and water cycles, rebuilds soil biodiversity and supports ecosystem services such as pollination, water purification and carbon sequestration (Derpsch et al. 2024).

This relationship is mutually reinforcing. The structural diversity of MFLs, mosaics of croplands, agroforestry systems, riparian buffers, semi-natural habitats and restored ecological corridors, provides a continuous, year-round mix of biomass streams (crop residues, agroforestry prunings, livestock manure, aquatic biomass and small-scale processing by-products) that sustains nutrient circularity (Meza et al. 2022). In turn, nutrient-circular practices, composting, biochar application and the return of digestate, feed organic matter back into soils, rebuilding fertility and supporting the vegetative complexity that generates diverse feedstock. Co-locating decentralized resource recovery hubs, such as composting stations, anaerobic digesters, and carbonization equipment, within these landscapes creates near-closed-loop systems where outputs from one land use become inputs for another (Jordan et al. 2023). This reciprocal feedback, (landscape diversity enabling nutrient circularity and nutrient circularity reinforcing landscape diversity), reduces transport costs and emissions, diversifies feedstock supply, and maintains biomass extraction within ecological limits while enhancing both ecological resilience and long-term resource security.

4.2. Enabling Low-Carbon Transition

CBE also creates low-carbon production systems by converting organic residues into renewable energy and reducing carbon emissions. For example, agricultural and food-processing by-products, such as animal manures and spent brewery waste that cannot be absorbed by livestock farming, can be channeled into anaerobic digesters to generate biofuel for heat and electricity (Rowan et al. 2022). The resulting digestate can be used to reinforce the nutrient cycle while cutting reliance on fossil fuels. Biotic energy storage, where soil organic matter and perennial biomass function as both internal energy reservoirs and long-lived carbon pools can further be deployed to support renewable energy generation and long-term carbon sequestration (Hercher-Pasteur et al. 2023).These practices maximize resource efficiency and strengthen long-term carbon sequestration (Hercher-Pasteur et al., 2023).

While the direct use of crop residues for energy is not a first priority when higher-value applications such as soil amendment or animal feed are possible, CBE strategies promote a cascading approach, e.g., using crop residues first for mulching or animal bedding before diverting the remaining material to energy recovery. Integrating such waste-to-energy pathways, where surplus biomass exists, not only reduces greenhouse-gas emissions, it also diversifies on-farm income streams and increases the overall resilience of agri-food systems (Ssegane et al. 2015; Couthouis et al. 2023).

Renewable energy supply can be expanded further through the integration of solar-based systems, such as on-farm photovoltaic arrays, integrated solar dryers, and agrivoltaic installations, which enable the coexistence of irrigable food and fodder production with electricity generation (Dinesh & Pearce 2016; Coşgun et al. 2024). Such integration strengthens energy self-sufficiency and diversifies household income while maintaining productive land use. Together, these measures reduce greenhouse-gas emissions and help safeguard natural capital stocks that underpin resilient, low-carbon MFLs over the long term.

Biogas plant to support low-carbon, circular agriculture.
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4.3. Water Management, Reuse and Ecosystem Restoration

MFLs integrate water provisioning, purification and flood regulation as core ecosystem services, and CBE strategies strengthen these functions by closing water loops and regenerating hydrological systems. Evidence shows that green-gray infrastructure reduces runoff and pollutant loads at the watershed scale while sustaining more stable stream flow (Yang & Li 2013). Riparian zones, floodplains and other biogeochemical “hotspots” act as natural connectors of surface and groundwater flows, filtering nutrients and sediments and maintaining hydrological connectivity across catchments. Protecting and restoring water areas help rebuild soil biodiversity, stabilize nutrient and water cycles, and sustain wider regulatory ecosystem services such as water purification and carbon sequestration (Laudon et al. 2016).

From a hydrological perspective, water acts as a medium and connector, linking uplands and lowlands, and terrestrial and aquatic systems. The “small water cycle” within a catchment is central to maintaining local climate, soil moisture, and vegetation productivity (Rulík & White 2020). Deforestation and drainage alterations disrupt this cycle, reducing water retention and increasing the risk of drought or flooding. Restoring it requires natural drainage, infiltration, and wetland connectivity to re-establish balanced flows between surface and groundwater. Water therefore serves as an entry point for landscape restoration. Managing hydrological flows can regenerate degraded lands and boost productivity, as they underpin soil fertility, vegetation growth, and microclimate regulation (Tengberg et al. 2019). Integrated forest–water–agriculture planning and nature-based solutions, such as tree planting, soil restoration, and wetland rehabilitation, enhance infiltration, groundwater recharge, and climate resilience across MFLs.

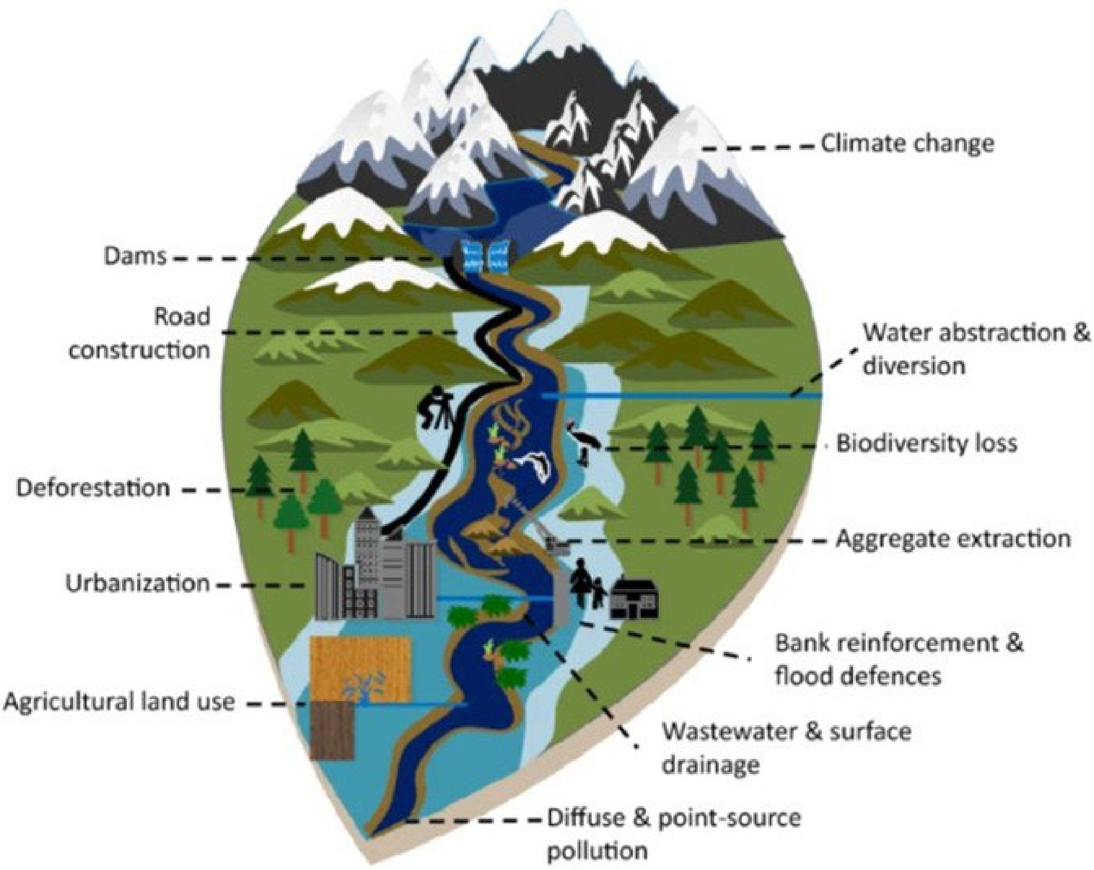
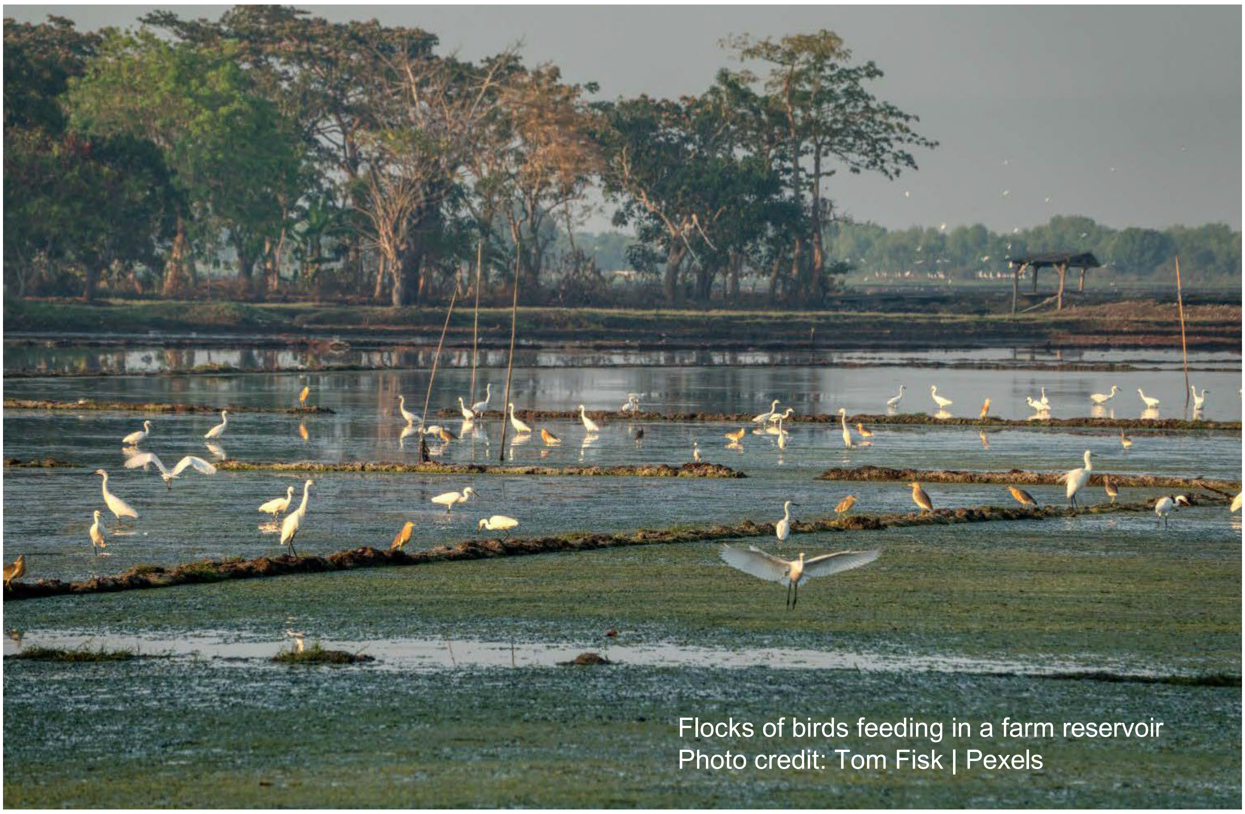


Figure 3 − Human pressures affecting river basins and water ecosystem services (Grabowski et al. 2022). A range of human activities, such as dam construction, urbanization, and agricultural expansion, alter land and water processes across the landscape restoration interface, with impacts that can occur far from their source or emerge long after disturbance.

As illustrated in Figure 3, numerous human activities, such as dam construction, road building, deforestation, urbanization, and intensive agriculture, alter natural hydrological pathways and disturb the interactions between land, water, and people. These impacts can occur far from the source or manifest long after the initial disturbance, illustrating the spatial and temporal connections between hydrological and ecological processes.

Recognizing this connectivity is vital for designing CBE and nature-based interventions that restore water balance, ecosystem function, and social benefits within the landscape restoration interface. CBE practices enable and enhance these water services by integrating water reuse and recovery into landscape management. Treated municipal or agro-industrial wastewater can be reused to supply both water and nutrients to agricultural systems, reducing pressure on freshwater withdrawals while supporting soil fertility. Resource recovery technologies, such as aerobic and anaerobic treatment units, nutrient-stripping bioreactors, and decentralized reuse schemes integrated within agricultural or urban landscapes, transform wastewater into a dependable source of irrigation and fertilizer.

Combining nature-based solutions with CBE interventions strengthens these functions further. For instance, bioswales, rain gardens, permeable pavements and restored riparian corridors paired with resource recovery and reuse technologies can reduce storm water peaks, improve infiltration, sustain baseflows and water quality (Yang & Li 2013). Constructed wetlands, CBE-aligned treatment systems that mimic natural wetland processes, can enhance hydrological connectivity by slowing runoff, polishing effluent, capturing nutrients and providing carbon sequestration and habitat benefits (Kominami et al. 2012). Taken together, these approaches ensure that water and nutrients are safely recirculated across the landscape, linking upstream and downstream ecosystems and safeguarding ecosystens. They reinforce the ecological foundations and long-term water resilience of MFLs while contributing to climate adaptation, landscape connectivity and ecosystem restoration.


Flocks of birds feeding in a farm reservoir
Photo credit: Tom Fisk | Pexels

4.4. Strengthening Circular Value Chains and Bio-based Markets

CBE strategies create economic value while regenerating natural capital by reshaping supply chains and expanding markets for bio-based products. By turning organic waste and renewable biological resources into marketable goods, CBE strengthens rural–urban linkages and fosters resilient local economies. Global experience shows that bioeconomy development can generate millions of jobs and significant value-added production, particularly in rural areas (Lima et al. 2022). Across Africa, the circular bioeconomy offers pathways to diversify rural livelihoods, reduce poverty, and improve food security by connecting producers to new biobased industries and regional trade opportunities (Tabler et al. 2024).

A core strategy involves the strategic siting of nutrient-recovery hubs, bioenergy facilities, and other resource-recovery plants near urban and peri-urban centers. This reduces transport costs and emissions, while returning nutrients and renewable energy to farms. Integrating these hubs within MFLs enhances the recirculation of water, energy, and nutrients, creating synergies between agricultural production, ecosystem restoration, and enterprise development. Resources such as compost, biofertilizer, biochar, biogas and renewable electricity can substitute imported synthetic inputs and open premium markets for low-carbon products (Stupak et al. 2021). Such circular value chains create income opportunities for smallholders, women and youth entrepreneurs, while integrating informal waste collectors into formal business models, turning a potential social liability into a driver of inclusive growth.

UNDP's experience with climate-resilient value chains shows that integrating smallholders and micro-enterprises through skills training, finance access, and market linkages can significantly raise incomes and resilience (UNDP 2020). CBE-driven markets can thus serve as platforms for inclusive enterprise, supported by cooperative governance and digital traceability systems that improve transparency and trust. Embedding gender equality and youth entrepreneurship in these value chains further strengthens social equity and innovation capacity (ECE/FAO 2023; Tabler et al. 2024). Developing multi-product cascading biorefineries, where waste from one process becomes feedstock for another, creates economies of scope and multiple revenue streams while reducing biomass degradation and transport costs. Using unavoidable food-processing residues as a stable, homogeneous feedstock can further strengthen these value chains (Muscat et al. 2021). In African and Asian contexts, modular biorefineries co-located with agro-industrial clusters (e.g., palm oil, cassava, sugarcane, or fish processing) enhance efficiency and circular industrial symbiosis (ECE/FAO 2023).

Applying a biorefinery model in agriculture, utilizing all parts of biomass such as maize, sugarcane or oil-palm residues, enables the production of biofuels, biochemicals and other high-value bio-products, thereby supporting sustainable agricultural value chains and reducing waste. When embedded in MFLs, these systems also improve soil fertility, reduce pollution, and restore biodiversity, linking economic performance with ecosystem health. Cost-reduction strategies include improving logistics for biomass collection, lowering water and energy consumption and optimizing resource recycling (Jaroenkietkajorn et al. 2024).

Scaling these circular models requires supportive policies, blended finance, and public–private partnerships to de-risk investment and foster innovation ecosystems (UNDP 2020; ECE/FAO 2023). Regional trade initiatives can expand markets for bio-based, low-carbon products while promoting sustainable production and consumption (Tabler et al. 2024). Figure 4 illustrates multiple CBE innovations and the recovery and reuse of diverse bioproducts including water, nutrients, energy, and biomass. All of these can be continuously cycled across sectors and scales. More importantly, these interconnected flows form the backbone of circular value chains that sustain livelihoods.

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4.5. Spatial and Socio-Ecological Integration

CBE strategies go beyond closing resource loops or expanding value chains; they also knit together social and ecological processes across space, ensuring that MFL function as connected socio-ecological systems. This means aligning land uses, agriculture, forestry, settlements and natural habitats, so that flows of water, nutrients, energy, biodiversity and human interactions remain continuous across the landscape.

Well-designed, connected landscape mosaics, including agroforestry systems, riparian buffers and habitat corridors, can link otherwise fragmented habitats, allowing wildlife movement, pollination and natural pest regulation while sustaining soil and water functions (Blattert et al. 2023). These mosaics exemplify the “nature’s contributions to people” perspective, where ecological and social processes jointly produce benefits for human well-being and environmental resilience (Bruley et al. 2021). Integrating CBE interventions into this spatial design, for example, by strategically locating resource recovery sites within rural–urban linkages can improve spatial planning, reduce habitat fragmentation and strengthen the resilience of both production systems and natural ecosystems. Notable examples include Stockholm’s Hammarby Sjöstad eco-district, where wastewater is treated and converted to biogas and fertilizer for surrounding farms (Pandis Iveroth et al. 2013); and Costa Rica’s National Biological Corridor Program, which connects agroforestry landscapes with protected areas to maintain biodiversity while supporting coffee and cacao production (Daugherty 2005; Moran et al. 2019).

Water also serves as a powerful socio-ecological connector, linking people and landscapes, by supporting livelihoods, cultural values and shared stewardship of natural resources. Evidence from European MFLs show that ecosystem services such as clean water contribute directly to human well-being and social cohesion (Bruley et al. 2021. Innovative approaches such as “smart irrigation as a service” platforms and precision irrigation technologies with digital advisory services and pay-per-use models (Lampridi et al. 2022; Ceccarelli et al. 2022), demonstrate how sustainable water management can increase on-farm water-use efficiency, enhance crop productivity and strengthen value chains (Kumar et al. 2024 by reducing pressure on freshwater resources while enabling farmers to access premium markets.

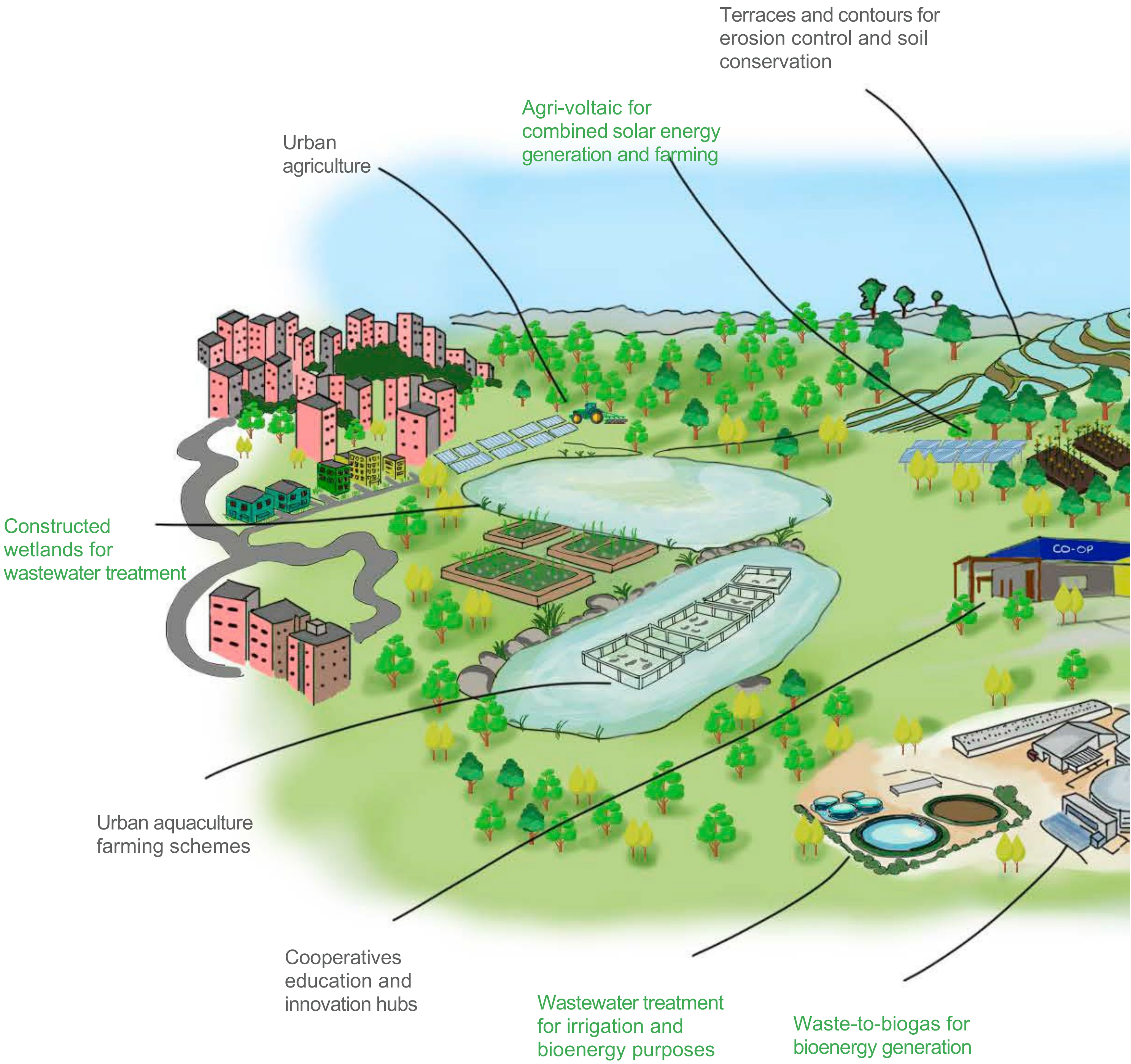

Photo credit: EcoAgriculture partners

4.6. Enabling Inclusive Governance

The capacity of MFLs to deliver diverse benefits depends on how stakeholder values and governance arrangements are integrated. Participatory mapping and other co-production methods can reveal locally valued cultural ecosystem services that conventional ecosystem service assessments overlook (Fagerholm et al. 2020; Bruley et al. 2021). Governance, both formal and informal, determines how competing land-use objectives are negotiated and whose values prevail. Inclusive, responsive governance can enhance equity, adaptive capacity and the resilience of social–ecological systems, whereas exclusionary or purely market-driven approaches risk undermining cultural and social dimensions (Quinn & Allen 2021). CBE strategies strengthen socio-ecological linkages and landscape governance by creating platforms for inclusive decision-making, shared stewardship and adaptive management across MFLs. Rather than relying on top-down regulation, successful initiatives emphasize participatory planning and co-creation, bringing together farmers, local communities, private enterprises, researchers and policymakers.

Research on MFLs indicates that long-term success hinges on collaborative planning and the acknowledgment of diverse knowledge systems (Fagerholm et al. 2020; Cerreta et al. 2021). Living labs, landscape stewardship councils, and multi-stakeholder platforms enable local actors to shape the design of CBE interventions, such as composting hubs or bioenergy cooperatives, so that technology choices reflect local ecological conditions and cultural values. Circular value chains can create fair economic opportunities for smallholders, women and youth entrepreneurs, while integrating informal waste collectors into formal business models (Stanek & Lovell 2020). However, cooperative ownership and benefit-sharing arrangements are most effective when supported by clear governance rules and transparent revenue-sharing mechanisms, which strengthen community trust and make resource-recovery businesses more resilient to market shocks. CBE-enabled governance frameworks can link ecological restoration with human well-being (Blattert et al. 2023; Ohman & Karlsson 2025) and ensure that women, youth, smallholders and other marginalized groups are represented in decision-making and benefit-sharing (Quinn & Allen 2021). Such approaches create the institutional, policy and social foundations for fair, locally rooted bio-based value chains (Jordan et al., 2023; Pink, 2023). By co-creating activities with farmers, processors, and local authorities, governance systems ensure equitable benefit-sharing through job creation, market access, and revenue from high-value bio-products (Meza et al. 2022), promoting legitimacy and local ownership. Robust governance frameworks also help manage trade-offs between competing land uses, for example, balancing residue harvesting for bioenergy with soil organic matter conservation, or commercial biomass extraction with habitat preservation.

Building knowledge and adaptive capacity is equally critical. MFLs depend on continuous social learning, knowledge co-production and capacity building (Reyers et al. 2009; Fagerholm et al. 2020). Participatory mapping, scenario building, and living-lab approaches enable farmers, community groups, and researchers to integrate scientific evidence with local ecological knowledge, ensuring that CBE interventions remain relevant as conditions change. Training programmes, digital advisory services, and peer-to-peer farmer networks strengthen the skills needed to operate composting hubs, innovative irrigation services, or bioenergy facilities, while empowering women and youth to participate in emerging bio-based markets. Together, these inclusive governance arrangements provide the institutional foundations for scaling CBE strategies across MFLs. However, the ability to turn this potential into lasting impact is constrained by broader weaknesses, ranging from policy incoherence and market distortions to gaps in technical integration, data, and local capacity.


Terraces and contours for erosion control and soil conservation
Agri-voltaic for combined solar energy generation and farming
Urban agriculture
CO-OP
Constructed wetlands for wastewater treatment
Urban aquaculture farming schemes
Cooperatives education and innovation hubs
Wastewater treatment for irrigation and bioenergy purposes
Waste-to-biogas for bioenergy generation

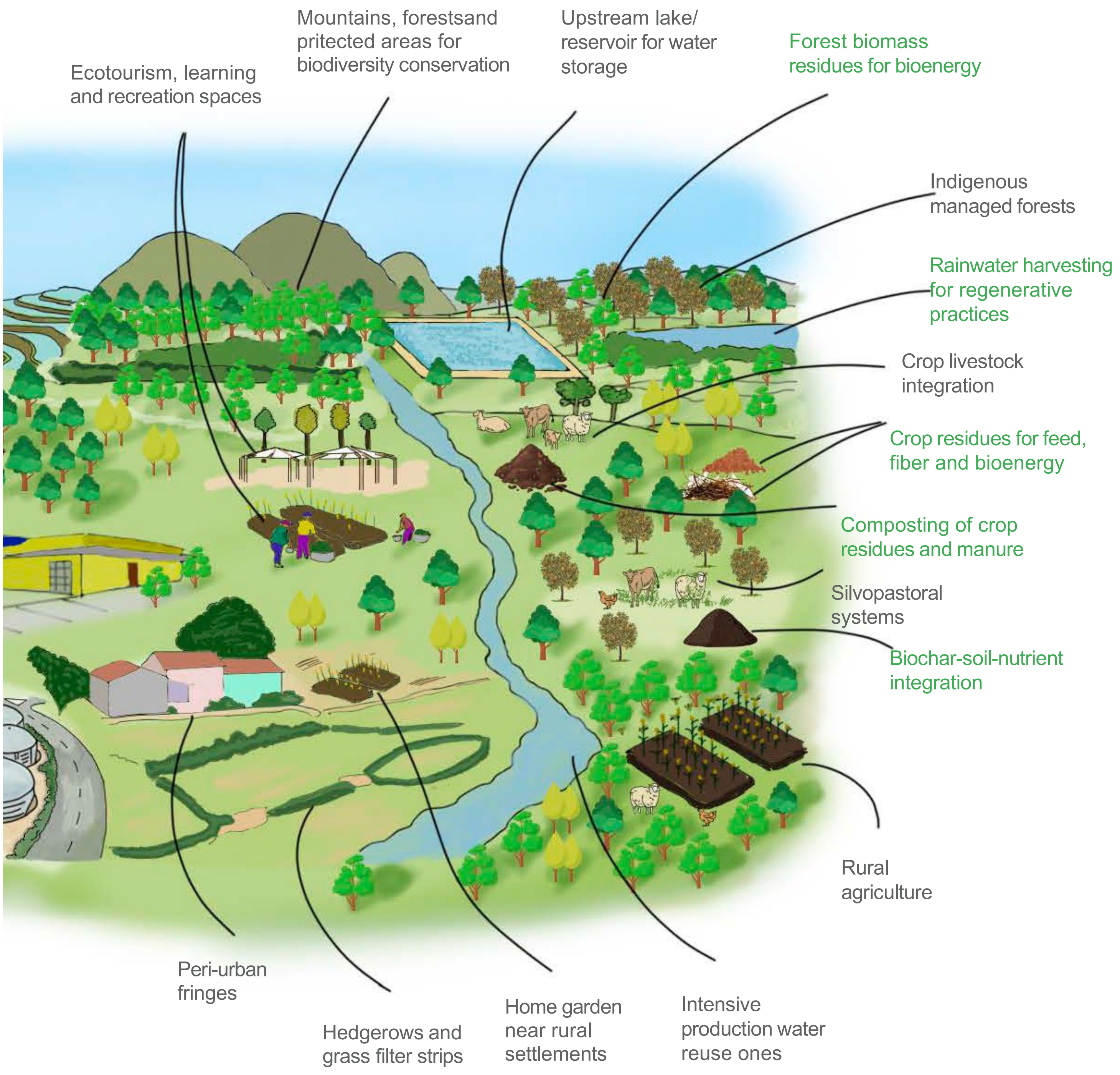


Figure 4. Integration of CBE principles in MFLs (Source: Tosin Somorin, IWMI; illustrated by Jonathan Dickson).

The illustration depicts interconnected rural–urban systems where water, nutrients, energy, and biomass are continuously cycled across sectors and scales. Through technologies such as composting, biochar production, waste-to-biogas conversion, agroforestry, and constructed wetlands, resources are recovered and reinvested into productive systems. These feedback loops foster ecological integrity, climate resilience, and inclusive livelihoods, linking agriculture, forestry, and urban ecosystems into a regenerative, multifunctional landscape.

Photo credit: Ron Lach | Pexels

Case Study 1: A Blueprint for CBE–MFL in Lake Victoria's Catchment

A notable example of CBE in MFLs is provided by the Nature-Positive Aggregated Farms in Western Kenya, situated within the Lake Victoria Basin, one of East Africa's most critical watersheds. This basin drains the Nzoia, Yala and other rivers into Lake Victoria, supporting rich fisheries, extensive smallholder agriculture and dense rural settlements. It is also a hotspot of nutrient losses and land degradation, making it an ideal setting to pilot and test how circular resource flows and landscape restoration can be combined. Within the basin, three pilot sites demonstrate how CBE practices can be integrated into MFLs to regenerate soils, close nutrient and water loops, and diversify rural livelihoods. Agoro East demonstrates complete spatial aggregation (Figure 5a), Jimo East shows a quasi-spatial model (Figure 5b), and Lyanaginga in Vihiga County represents a cluster-based network, together capturing a spectrum of approaches to cooperative land management and circular resource use in the watershed.

Spatial Aggregation at Agoro East

In the lower Yala catchment, 83 farmers voluntarily agreed to merge about 26 ha of adjoining plots into a single management unit. This spatial aggregation supports mechanized land preparation, rotational cropping and shared irrigation, while enabling large-scale composting and black soldier fly larvae production that recycle crop residues and livestock manure into fertilizer and protein-rich feed. While the complete set of collective enterprises and management arrangements is still being established, the initiative aims to create a fully integrated production system that incorporates closed nutrient loops, thereby restoring soil fertility and reducing downstream nutrient runoff into Lake Victoria.

Quasi-spatial Aggregation at Agoro East

Near the Winam Gulf, 45 farmers coordinate activities across roughly 9 ha of neighboring plots without merging land titles. This quasi-spatial model allows farmers to synchronize crop calendars, share machinery and irrigation infrastructure, and jointly market produce through their cooperative. Composting of crop residues and livestock manure is being scaled up to supply organic fertilizer, while black soldier fly larvae units are planned to convert food scraps into high-protein animal feed. Although the cooperative is still formalizing its business operations, the approach is designed to strengthen nutrient cycling, cut fertilizer costs and reduce nutrient runoff toward Lake Victoria while creating a stable base for diversified bio-based enterprises.

Cluster-based arrangement in Lyanaginga

In the Maragoli Hills catchment, 51 farmers manage a dispersed network of small farms amounting to about 10 ha through a cluster-based arrangement. Farmers remain on their individual plots but coordinate planting schedules, pool compost and manure resources and collectively market vegetables and seed. Plans include community-run BSF larvae units and small-scale biogas production to recycle organic waste and generate cooking fuel. While collective enterprises are still in their early stages, the cluster model relies on substantial social capital to achieve economies of scale, close nutrient and energy loops, and reduce sediment and nutrient losses to the Basin.

Across these three archetypes, the aggregated farms integrate core CBE practices. Central to the model is nutrient recycling, which is achieved with the establishment of composting hubs and black soldier fly larvae production that convert market organic waste, crop residues, community food waste and livestock manure into organic fertilizer and protein-rich animal feed. These closed-loop flows of nutrients and biomass turn waste streams into valuable inputs, restore soil fertility and reduce dependence on synthetic fertilizers while enhancing soil carbon and water-holding capacity. Solar-powered irrigation systems complement farming by supplying year-round irrigation, recharging.

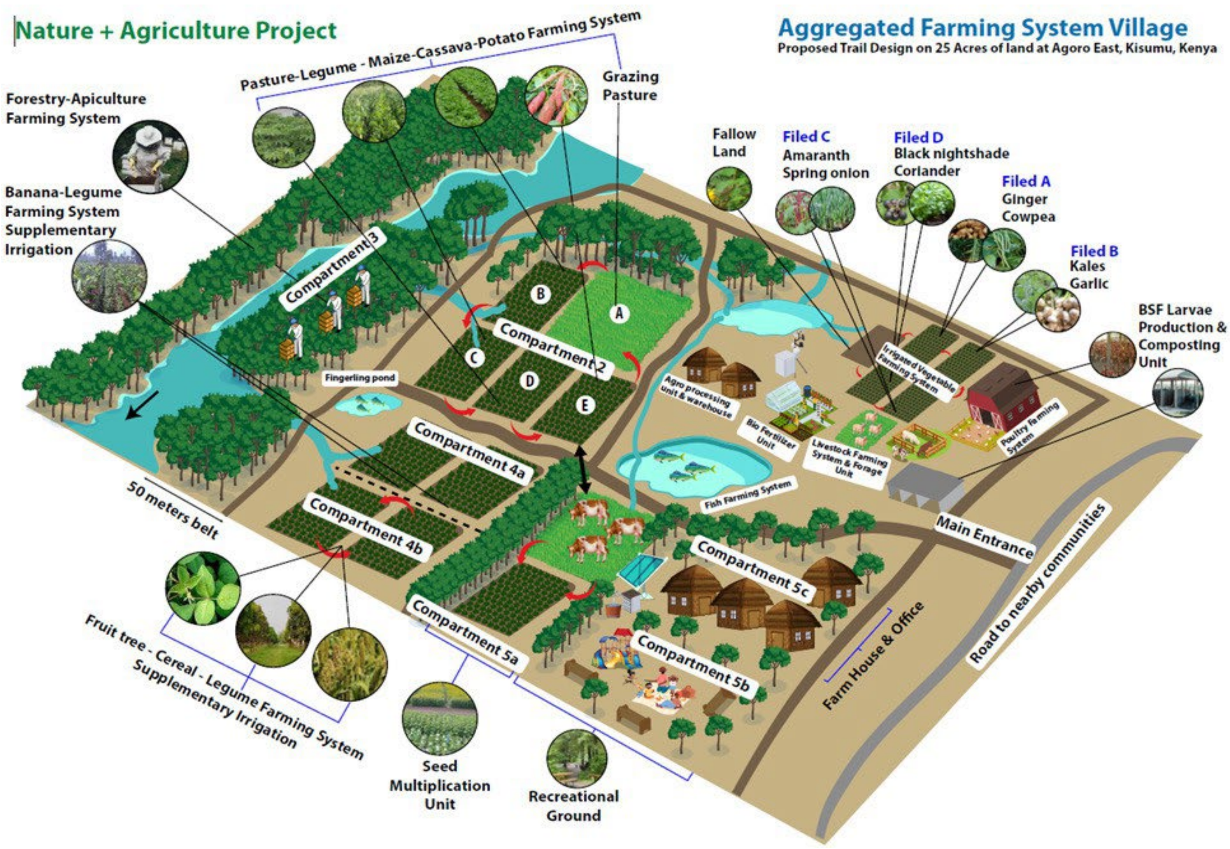


Figure 5a − Proposed farming system design of the aggregated farm at Jemo East under Nature Positive Agricultural practices (Source: Adamtey Noah, *forthcoming*)

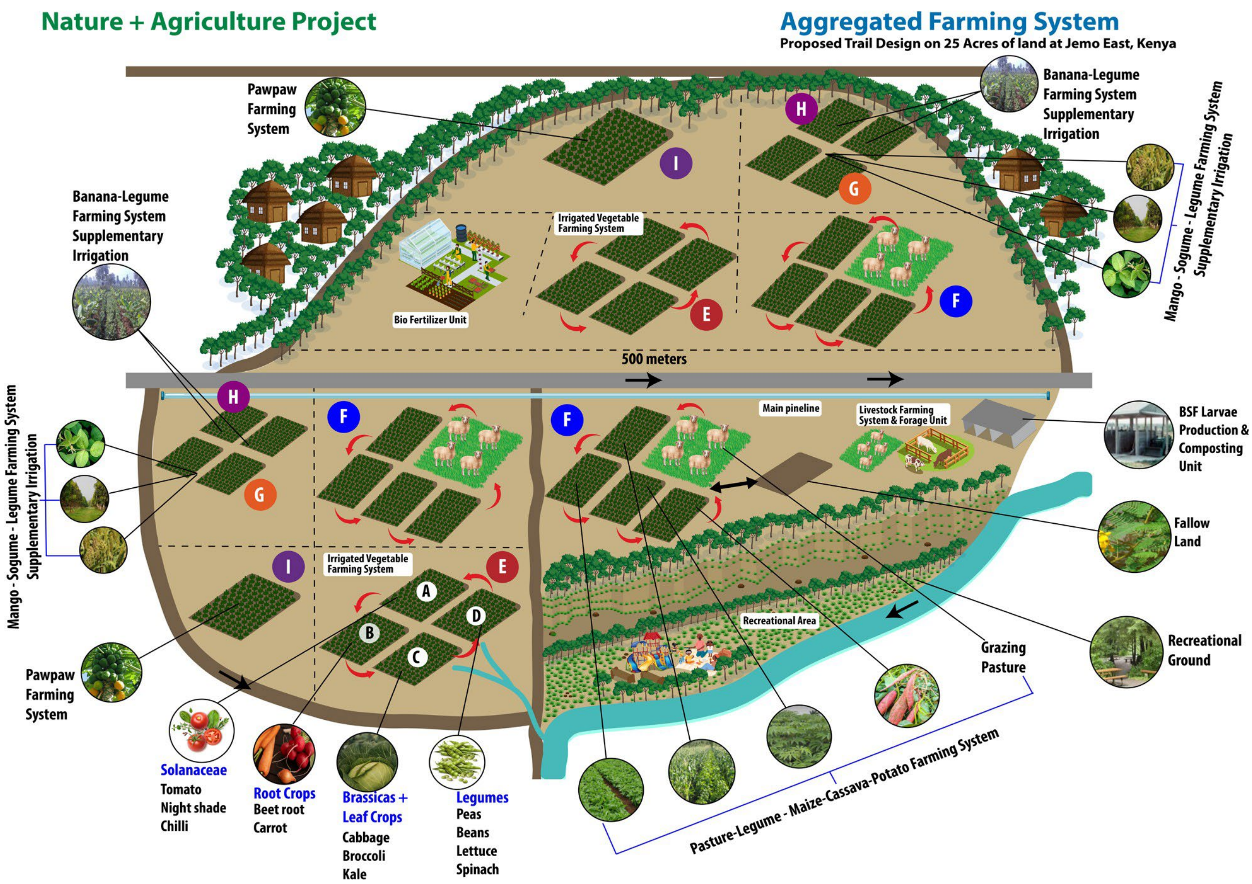


Figure 5b − Proposed farming system design of the aggregated farm at Agoro East under Nature Positive Agricultural practices (Source: Adamtey Noah, *forthcoming*).

groundwater and stabilizing local water cycles while supporting both agricultural productivity and ecosystem services. This reduces fossil-fuel use, creating low-carbon production systems and diversifying farm income, while also bringing back into productive use parcels of degraded land that would typically remain fallow or underutilized.

In addition, the farms employ agroforestry and mixed crop–livestock systems, integrating nitrogen-fixing trees, fodder banks, and perennial cover to enhance biodiversity, provide shade, and stabilize soils. Clustered rainwater-harvesting ponds and constructed wetlands slow runoff, improve water quality and reinforce watershed resilience. Community seed production and on-farm biogas units strengthen local value chains by supplying high-quality seed and renewable energy while recycling nutrients through digestate. Plans are also underway to establish recreation and learning spaces, including demonstration plots, farmer field schools, and visitor trails, that will showcase nature-positive, agroecological, and circular practices, acting as living laboratories for neighboring communities, schools, and policymakers. Strong cooperative governance underpins these initiatives. Each pilot operates through democratically elected committees and jointly managed bank accounts, enabling farmers to co-design land-use plans, set bylaws and define transparent rules for revenue allocation.

This ensures that economic returns from compost, BSF larvae meal, vegetables, seed production and renewable energy are equitably shared among members, including women and youth. By giving all stakeholders a voice in planning and decision-making, the model builds trust and reduces conflicts over resource use. It also creates platforms where trade-offs can be negotiated openly, strengthening the resilience and long-term viability of these CBE initiatives.

To achieve a lasting impact, research is underway to strengthen governance, focusing on understanding what works, for whom, and under which local conditions, and to develop practical frameworks for assessing the outcomes of the CBE. This includes designing and validating indicators that capture ecological regeneration, economic benefits, and social equity, and testing participatory monitoring approaches that allow farmers, community groups, and policymakers to co-evaluate progress and adapt management across the Lake Victoria Basin. In parallel, new enterprises and value chains are being added to the aggregated farms to diversify rural livelihoods and reinforce circular resource flows. Continued investment and sustained community cooperation, however, remain significant challenges. Mobilizing long-term finance for decentralized infrastructure and maintaining the high level of farmer participation required for cooperative management demands consistent technical support, transparent benefit-sharing mechanisms and enabling policy frameworks. Addressing these constraints will be critical to scaling the aggregated farm model and ensuring that the gains are maintained over time.

Case Study 2: Women-led Agroecological Homestead Models in Mandla and Andhra Pradesh, India

In the tribal districts of Mandla, Madhya Pradesh, and in complementary agroecological pilots in Andhra Pradesh, India, the CGIAR Initiative on Agroecology has uncovered a remarkable pathway to sustainable farming through women-led Agroecological Homestead Models (AHMs). These innovative models are not merely theoretical; they are rooted in participatory co-design and co-learning with women, ensuring that their priorities, knowledge, and lived experiences shape both the design and outcomes. A defining feature of this participatory approach was the "4A framework", assessing farmers' attitudes, abilities, access to resources, and assurances of support, to foster inclusive engagement, particularly among women's Self-Help Groups.

Each AHM occupies part of a 1,000 to 4,000 square meters (m^2) homestead, with approximately 400 m^2 dedicated to agroecological production practices (Figure 6a-b). Rooted in agroecological principles that emphasize resource recycling and efficiency, the models integrate multi-layer cropping (where different plant species grow in tiers), crop rotation to maintain and enhance soil fertility, and practices like composting and water harvesting through structures known as Jal Kunds. Additionally, it integrates backyard poultry and beekeeping, further enhancing pollination, productivity, nutrient cycling, food diversity, and land-use efficiency. These features demonstrate CBE links with soil health, waste valorization, and sustainable livelihoods (Malaiappan et al. 2024).

Women farmers were trained to prepare and apply bio-inputs such as Jeevamrit, Neemastra, Agniastra, and Brahmastra to manage nutrients and control pests, replacing synthetic fertilizers and pesticides with locally prepared organic formulations. They implemented multi-layered crop systems combining tubers (ginger, colocasia), leafy vegetables (spinach, amaranth, fenugreek), shrubs (tomato, brinjal, chili), and climbers (gourds, cowpea, cucumber) on bamboo trellises. Boundary crops such as papaya and moringa contributed to diversifying nutrition and income, while residue recycling improved soil organic matter and reduced waste.

A major strength of the initiative lies in its multi-actor governance model, implemented jointly by IWMI and PRADAN with active support from local agencies, including the Zila Panchayat, SRLM, KVKs, and the Forest Department. Capacity-building and collective learning were strengthened through Farmer Field Schools, exposure visits, and peer-to-peer exchanges, fostering community and shared ownership of agroecological transitions (Malaiappan et al. 2024).

Implemented across four villages in Mandla (Kunda, Kondra, Dargarh, and Jujhari), the AHMs achieved striking early outcomes: production diversity increased by 350%, dietary diversity doubled, and leafy vegetable consumption rose by 70%. Gross returns rose between 8 and 22 times relative to baseline levels. Input costs declined as women substituted locally available organic resources for purchased agrochemicals. These changes contributed to enhanced nutrition, household income, and qualitative improvements in soil health, pollination, and water retention, though these ecological indicators are still under participatory monitoring rather than fully quantified. Beyond immediate productivity gains, the initiative catalyzed social and ecological co-benefits. Women gained greater say in income and resource allocation, while SHGs began aggregating bio-inputs and produce, creating localized value chains and improving market access for agroecological products.

The success of the Mandla AHMs has informed district-level policy dialogue and scaling strategies. Integration into agricultural extension systems and MGNREGA schemes is under discussion to support water structures and composting units, while the development of AHM typologies based on resource endowments aims to guide replication across India's diverse landscapes. These AHMs exemplify how agroecological innovation, grounded in CBE principles, can regenerate landscapes while improving the livelihoods of smallholder systems. They offer a scalable blueprint for regenerative and equitable food systems across India and comparable agroecological regions.

Figure 6a: Women-led multilayer agroecological homestead system in Mandla, Madhya Pradesh
Photo credit: Gopal Kumar

Figure 6b: A portable above-ground Jal Kund water-storage system (10–12 m³ capacity) installed beside multilayer vegetable plots in Mandla. Adjacent composting pits recycle crop residues into organic manure.
Photo credit: Gopal Kumar


Photo credit: Quang Nguyen Viah | Pexels

5. Critical Gaps in Linking Circular Bioeconomy Integration

Turning circular bioeconomy ambition into landscape action demands more than intent, it requires coherence, capacity, and commitment across scales.

When CBE is poorly aligned with MFLs, the risk of maladaptation is high, leading to policy, market, institutional, and ecological consequences that can weaken both concepts. This section highlights critical and often overlapping gaps, policy and market incoherence, fragmented governance, weak data and technical capacity, that hinder effective integration of CBE principles into MFLs and risk maladaptation.

5.1. Poor ecological and technical integration is a systemic weakness in MFL design, implementation and assessment

A review of recent literature (e.g., Hoff 2011; Liersch et al. 2023; Muscat et al. 2021; Jordan et al. 2023) shows that, despite advances in MFL planning, CBE principles remain only partially embedded. Water, energy, food, and ecosystem (WEFE) interactions are rarely planned holistically, leaving wastewater reuse, multipurpose water infrastructure, and energy-water trade-offs underdeveloped (Hoff 2011; Liersch et al. 2023). While a number of sectoral projects, including hydropower and irrigation schemes worldwide, are addressing resource needs, they are typically designed in isolation

and seldom account for cross-sectoral synergies or trade-offs. As a result, opportunities to co-invest in multipurpose infrastructure, combine nature-based and engineered solutions, or optimize resource

flows across the nexus are frequently missed. This siloed approach constrains the potential of CBE to embed circular water, nutrient and energy management within MFLs, ultimately limiting gains in overall resource efficiency.

At the same time, nutrient recycling, despite being a core principle of agro-ecological systems, is often poorly implemented: safeguards to prevent the over-harvesting of crop residues or long-term nutrient mining are frequently absent, risking declines in soil fertility

Likewise, renewable energy options such as anaerobic digestion, biochar production and agrovoltaics remain marginal in landscape planning. Within landscape designs, energy is still treated largely as a by-product rather than an intentional service. Discussions often stop at recognizing fuelwood potential or estimating carbon offsets, instead of embedding renewable energy as a design goal. Few frameworks explicitly co-design renewable energy systems together with ecological functions, missing key opportunities for low-carbon transitions, diversified rural incomes, and reduced pressure on natural forests (Stanek & Lovell, 2020; Garibaldi et al. 2023). When considering energy, monitoring and evaluation tools are typically carbon- or biodiversity-centric and rarely track energy yield, reliability, avoided fossil-fuel use, or local energy access benefits (Lavorel et al., 2020). In addition, governance and financing mechanisms for decentralized renewables, such as community ownership models, feed-in tariffs, or payments for avoided deforestation, are seldom incorporated, limiting the role of renewable energy as both an ecological service and a driver of CBE strategies.

5.2. Weak value-chain development and limited local markets for recovered resources restrict the economic incentives needed to scale CBEs

and ecosystem functioning (Muscat et al. 2021).

Although research on MFLs increasingly highlights ecosystem services and participatory planning, it seldom embeds circular resource flows within rural value-chain development.

Case studies illustrate the gap: Asante-Yeboah et al. (2024) show that geodesign can enhance multifunctionality in Ghana’s mosaic landscapes but stop short of integrating CBE strategies to market opportunities; Do et al. (2021) demonstrate that participatory planning in Vietnam improves ecosystem services and supports NDCs, yet focuses mainly on carbon indicators rather than on creating circular resource flows that underpin rural enterprise; and Garibaldi et al. (2023) provide practical guidelines for shifting monocultures toward MFLs but omit explicit CBE components that would translate ecological gains from resource recycling into diversified rural markets. At a broader scale, CBE literature remains sectoral, concentrating on agrifood systems (Salvia et al. 2018) and failing to capture rural–urban interconnections critical for territorial sustainability transitions (Gu & Subramanian 2012). Innovations such as urban metabolism and living labs (Ternell et al. 2024) are beginning to combine multifunctional land use, circular resource flows, and ecosystem services. Nevertheless, they remain predominantly city-centered and have not been adapted to rural settings or scaled to strengthen rural–urban value chains.

Overall, despite growing evidence of ecological gains and the benefits of participatory design, institutional coordination, financing mechanisms, and markets for recovered resources remain weak. In particular, the absence of dedicated financing instruments, such as payments for ecosystem services, blended finance for circular infrastructure, or targeted subsidies for resource recycling initiatives undermines the ability of local actors to invest in circular practices. This financing gap limits incentives for circular practices and leaves the transformative potential of integrated CBE–MFL approaches largely untapped. Bridging this gap calls for a territorial approach that couples ecological sustainability with circular resource use and establishes robust investment frameworks to foster inclusive rural value chains, diversify rural enterprises and strengthen rural–urban linkages (Salvia et al. 2018; Gu & Subramanian 2012; Asante-Yeboah et al. 2024; Do et al. 2021; Garibaldi et al. 2023; Ternell et al. 2024).

5.3. Fragmented governance and weak institutional gaps stall efforts to align CBEs with MFLs

Although MFLs are increasingly acknowledged as a means to integrate ecological, economic and social goals, the governance architecture needed to embed circular bioeconomy principles remains fragmented. Policies for agriculture, forestry, energy and conservation are still largely crafted and implemented in isolation, creating overlapping mandates and policy contradictions that weaken coordination across the landscape and limit adaptive management (Quinn & Allen 2021). In practice, governance structures remain sectoral and fragmented, with policies for agriculture, forestry, energy, and conservation operating in silos. Land-use strategies, therefore, often emphasize either agricultural intensification or forest conservation without fully considering how these choices interact with ecosystem services, rural livelihoods or climate-adaptation needs, leaving key cross-sector linkages insufficiently addressed (van Noordwijk et al. 2015).

Mechanisms for cross-sectoral coordination and participatory governance remain weak. While the MFL approach relies on inclusive decision-making, participatory mechanisms that include women, smallholders and indigenous groups remain limited, even though these actors hold critical knowledge and agency for co-producing nature's contributions to people (Bruley et al. 2021; Westholm & Ostwald 2020). Persistent power asymmetries and institutional silos reduce the legitimacy and long-term sustainability of landscape interventions. Without robust platforms for collaborative management, trade-offs between competing land uses, such as harvesting residues for bioenergy versus maintaining soil organic matter, cannot be effectively negotiated. In addition, enabling frameworks, such as flexible land tenure arrangements, incentives for circular resource flows, and supportive regulatory environments, are poorly developed (Westholm & Ostwald 2020; van Noordwijk et al. 2015).

Existing instruments, including payments for ecosystem services, agri-environmental schemes and REDD+ programmes, demonstrate potential but often fail to scale, lack long-term financial sustainability and rarely integrate circular resource flows or local relational values (Quinn & Allen 2021; Reyers et al. 2009). Rigid land tenure regimes, fragmented subsidy structures and restrictive forest codes can discourage adaptive management and stifle innovation (van Noordwijk et al. 2015; Bruley et al. 2021). These barriers undermine the very conditions needed for CBE to reinforce multifunctionality.

Finally, financing and incentive mechanisms to support CBE-aligned governance remain weakly articulated. While restoration funds and emerging carbon markets have gained attention, few mechanisms reward circular practices, such as nutrient recovery, decentralized renewable energy generation or residue-based bioenergy, that underpin low-carbon, resource-efficient landscapes (Lavorel et al. 2020; Reyers et al. 2009). The absence of targeted investment frameworks limits the ability of local actors to capture value from circular resource flows and to sustain long-term multifunctional outcomes.

Addressing these gaps requires landscape-scale governance platforms, institutional reforms and coherent policy incentives that explicitly promote circular resource flows. Strengthening participatory processes and ensuring equitable representation will be crucial to aligning CBE strategies with the social and ecological realities of MFLs and to build the adaptive capacity necessary for long-term sustainability (Quinn & Allen 2021; Westholm & Ostwald 2020).

5.4. Limited data on resource flows and weak local capacity undermine evidence-based planning

Effective integration of CBE principles into MFLs depends on robust evidence systems, accessible knowledge platforms, and strong technical capacity; however, significant weaknesses persist across all three domains. Spatially explicit and interoperable data on land use, ecosystem services, resource flows and socio-economic outcomes are still scarce and often fragmented across sectors and institutions. Monitoring frameworks tend to focus narrowly on commodity outputs or single ecosystem indicators, such as carbon stocks or biodiversity counts, while neglecting holistic metrics (Bruley et al. 2021; Pitman 2022).

Crucially, data on resource flows, particularly the generation, movement and fate of organic waste, are inadequate. Quantitative information on waste volumes, composition, and spatial "hotspots" of biomass residues is patchy, often collected using inconsistent methods and rarely shared across sectors. This makes it challenging to identify priority areas for nutrient recovery, to size and locate resource recovery innovations such as composting or anaerobic digestion plants, or to design efficient circular value chains. In many regions, waste statistics are either outdated or limited to national aggregates, obscuring sub-regional variations and seasonal dynamics that are critical for CBE planning. The absence of detailed flow data also hampers the ability to track leakages, such as nutrient runoff or uncollected organic waste, across rural–urban gradients, limiting opportunities to close material loops and reduce pollution. Without these datasets, planners cannot accurately model trade-offs or quantify the potential economic value of recovered resources, weakening the case for investment and policy support.

Mechanisms for knowledge exchange and co-production remain underdeveloped. Expertise and information relevant to both MFLs and CBE are distributed across scientific disciplines, local communities and policy arenas, but platforms to connect these knowledge holders are limited (Bruley et al. 2021; Quinn & Allen 2021). Local and indigenous knowledge, critical for context-specific innovation and resilience, is often undervalued or excluded from formal decision-making processes, thereby reducing the relevance and legitimacy of landscape interventions (Westholm & Ostwald 2020; van Noordwijk et al. 2015).

Furthermore, weak transdisciplinary collaboration hinders the dissemination of best practices, policy innovations, and adaptive strategies that could accelerate CBE adoption. Significant capacity gaps compound these challenges: Local actors often lack the training, extension services, and financial resources necessary to implement regenerative and circular practices (Westholm & Ostwald 2020). Institutions and agencies often lack the technical and managerial expertise necessary for integrated landscape planning, resource recycling, and adaptive policy design. Persistent gender and social inequities further restrict participation in knowledge creation and decision-making, with women and other marginalized groups facing barriers to leadership roles and access to capacity-building.

Addressing these deficiencies will require integrated data and monitoring systems that capture multifunctional outcomes, detailed resource flows and circularity indicators.

6. Pathways and Priorities for Action

Turning circular bioeconomy ideas into regenerative landscapes will require more than vision, coherent policies, inclusive governance, robust data, and innovative finance must work together to deliver lasting benefits for people, nature, and local economies.

The analysis above shows that aligning CBE strategies with the objectives of MFLs is not simply about closing nutrient, water, and energy loops; it is also a transformative agenda that calls for coordinated action across science, policy, and practice. Building on the opportunities and critical gaps identified above, we outline five priority pathways for action:

Priority 1: Understanding Resource Flows to Target Investments and Local Actions

Understanding how nutrients, biomass, water and energy move through agricultural landscapes is the first step toward locating and prioritising CBE actions. This includes quantity and spatial distribution of key resource flows: what and where organic residues and by-products are generated; how and where nutrients are lost from soils and watersheds; the seasonal availability, quality and volume of wastewater suitable for reuse; and the proximity of these resources to markets and end-users. Such information provides the baseline needed to identify hotspots of surplus or loss and to design targeted interventions such as siting composting hubs or anaerobic digesters where residue supply and fertiliser demand coincide, or prioritising wastewater-reuse schemes in irrigation-intensive catchments. To produce comparable evidence across scales, common metrics and indicators are essential: nutrient budgets and nutrient-use efficiency reveal surpluses and deficits; material-flow and substance-flow analyses quantify the volumes and spatial distribution of biomass; WEFE indicators highlight cross-sector trade-offs; and circularity indicators, such as the proportion of biomass recovered or avoided greenhouse-gas emissions track progress over time. When these metrics are combined with spatial decision-support and GIS tools, the data move beyond description to action guiding investment toward locations and technologies that close resource loops and aligning CBE interventions with both local development plans and national sustainability priorities.

Equally important is building the knowledge systems and local capacity needed to generate, share and use these data. Interoperable, open-access platforms, participatory mapping and the inclusion of indigenous and local knowledge can strengthen legitimacy and ensure that evidence is both technically sound and context-specific. Training for local authorities, extension services and community organizations is critical so that resource-flow information informs policy choices and day-to-day management. Without these knowledge and capacity investments, even the best metrics risk remaining underutilized and opportunities to scale CBE practices across MFLs will be missed.

Priority 2: Inclusive Markets, Value Chains and Business Models

Scaling CBE practices depends on vibrant markets, inclusive value chains and innovative business models that can turn recovered materials into reliable sources of income and investment. Building circular value chains starts with creating a stable and diversified demand for bio-based products. This goal can be accelerated through quality standards, product certification, and green procurement policies that give buyers confidence in the safety and performance of CBE products. Local governments can further stimulate markets by integrating CBE products into public procurement, e.g., using compost in municipal landscaping or contracting renewable electricity from biogas plants, thereby signalling long-term demand and encouraging private investment. Linking resource recycling to enterprise development is critical. Resource-recovery operations, such as nutrient recovery facilities, should be designed not only as environmental interventions but as platforms for local enterprise creation. Early identification of market niches (e.g., organic fertilisers, renewable energy services, bio-based construction materials) and tailored business support, training, finance and incubation services, can help community cooperatives, women- and youth-led businesses, and smallholder farmer groups transform waste into marketable products and services (Somorin et al. 2025). Such strategies need to be embedded at the onset of MFL planning to deliberately drive rural entrepreneurship and local economic diversification.

Another powerful complement to product markets is the PES framework, which rewards land stewards for maintaining or restoring ecosystem functions. Integrating CBE within PES schemes can monetize the multiple ecological services generated by circular practices, from improved water quality through nutrient recycling, to carbon sequestration and biodiversity gains. Well-designed PES contracts can provide steady revenue streams that reinforce both CBE interventions and multifunctionality. To capture these opportunities at scale, innovative business models are critical. These models must connect resource-recovery enterprises with end markets, lower transaction costs and ensure that economic benefits and ecosystem-service rewards flow equitably to local communities. Embedding such models within national development strategies and climate or agricultural policies links market incentives to broader sustainability goals. It provides the financial and institutional foundation for CBE strategies to become a mainstream driver of regenerative MFLs. This requires robust evidence on both supply and demand: the types and volumes of recoverable resources, the costs of collection and processing, the willingness of farmers and industries to pay for bio-based products, and the infrastructure and logistics required to move recovered materials to market.

Priority 3: Build Policy Coherence and Strengthen Institutions

The success of CBE strategies in MFLs ultimately hinges on how well policies and institutions coordinate across sectors and the readiness to do so, that is, shift from fragmented, sector-specific approaches toward integrated, cross-sectoral planning that acknowledges the interdependence of water, energy, food, and ecosystems. Policy gaps and technical implementation contradictions in agriculture, energy, water and environmental can dilute incentives for circular practices and slow the uptake of resource-recovery innovations. Renewable-energy subsidies, for instance, may unintentionally draw biomass away from higher-value cascading uses (Muscat et al. 2021; Jordan et al. 2023).

Moving from isolated pilot projects to integrated and landscape-scale adoption, therefore, requires cross-sector policy alignment and institutional willingness and capacity. National development and climate strategies need to embed CBE objectives, such as nutrient recycling, renewable energy generation, ecosystem restoration, and livelihood diversification, within a single, coherent framework. This includes mechanisms for inter-ministerial coordination, flexible land-tenure arrangements, and regulatory tools that reward circular resource flows while protecting ecological thresholds, a paradigm shift to integrated, cross-sectoral planning and governance that acknowledges the interdependencies between water, energy, food, and ecosystems (Bizikova et al. 2013). Key priorities for action include embedding nexus thinking into national and regional strategies, promoting CBE strategies through multi-purpose infrastructure that combines engineered and nature-based systems, and deploying decision-support tools to manage resource allocations and assess trade-offs effectively (Somorin et al., 2023).

Equally critical is fostering inclusive stakeholder coordination, where governments, communities, and the private sector jointly design and implement CBE solutions that deliver broad social, ecological, and economic benefits. Empowering local governance through natural resource user association groups and availing resources enable watershed authorities, municipal councils and farmer organizations to plan, regulate and monitor resource-recovery interventions, manage trade-offs (such as residue harvesting versus soil-carbon conservation), and ensure that benefits reach smallholders and marginalized groups. Policy instruments such as payments for ecosystem services, agri-environmental schemes and results-based carbon credits can link public and private finances directly to nutrient recovery, decentralized renewable energy and other circular practices, providing long-term incentives for multifunctional regenerative landscape management.

Priority 4: Financing Innovations and Investment Mechanisms

To move from promising pilots with high transaction costs to landscape-scale adoption, CBE strategies require dedicated and diversified sources of finance (Bodach et al. 2024). Conventional agricultural and environmental soil-carbon gains, reduced nutrient losses or renewable energy generation. PES can also be scaled to monetize benefits, creating a steady income for land stewards and resource recovery enterprises involved in recycling and landscape restoration. These financial mechanisms must be anchored in coherent policy and institutional frameworks so that incentives reinforce one another rather than compete. Mobilizing finance also depends on credible evidence of resource flows and ecological benefits. For example, transparent monitoring and clear performance indicators can give investors confidence and provide the evidence that investors and policymakers require to assess risk and priorities projects. Overall, coupling innovative finance with strong institutions and reliable evidence, CBE strategies can attract sustained investment and move beyond pilots into bankable ventures.

Priority 5: Adaptive Landscape Management and Inclusive Governance

CBE strategies will only deliver lasting impact if MFLs are managed as living systems that learn and adjust over time. In a world of climate shocks, volatile markets and evolving local priorities, a static blueprint is a recipe for failure. The design and implementation of CBEs in agricultural landscapes must be iterative and evidence-driven, with feedback loops that allow communities and institutions to adapt policies and practices as ecological and social conditions shift. For example, periodic assessments of nutrient budgets, ecosystem service provision, and market performance can help managers recalibrate resource recovery targets and avoid unintended trade-offs. These learning cycles should be integrated into landscape-level planning platforms, where stakeholders jointly review data and refine actions.

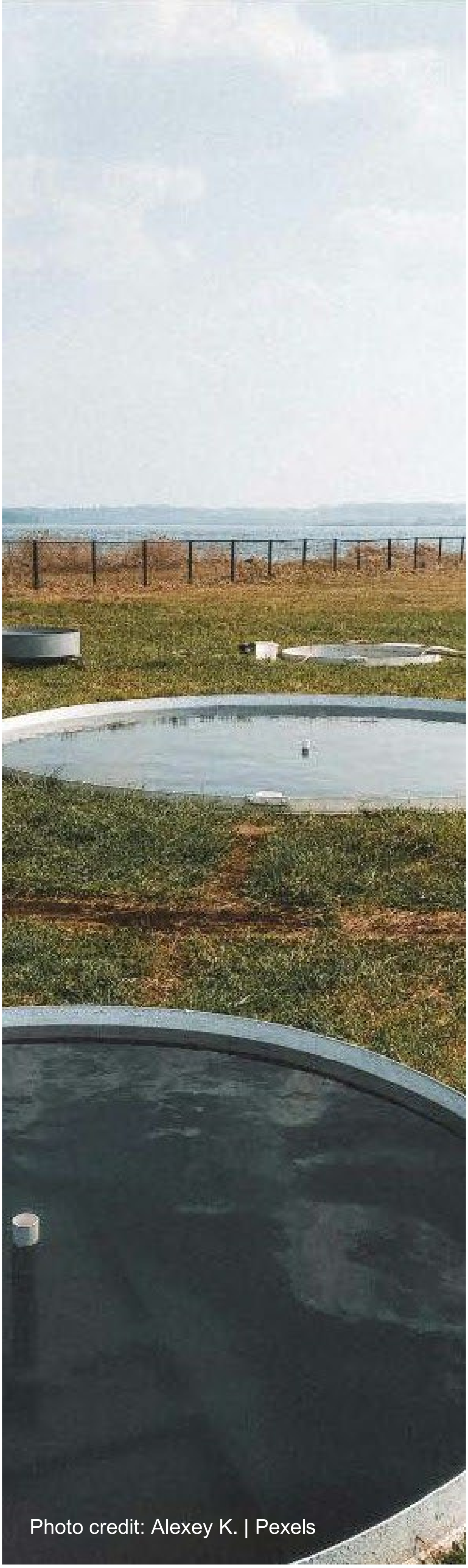
Equally critical is a strong commitment to gender equality and social inclusion. Women, youth, indigenous peoples and other marginalized groups often play key roles in managing organic resources and sustaining ecosystem services, yet face systemic barriers to land rights, finance and decision-making. CBE initiatives should therefore incorporate inclusive governance arrangements, ensure equitable access to training and technology, and establish benefit-sharing mechanisms that recognize their contributions and secure fair, lasting gains for all stakeholders.

7. Conclusion

This position paper set out to explore how circular bioeconomy principles can drive the transition toward regenerative MFLs, those that balance productivity, ecological integrity, and social well-being. The evidence presented demonstrates that circular bioeconomy provides a powerful framework for redesigning agricultural systems through circular nutrient, water, energy, and carbon flows that restore ecosystems while creating inclusive green economies. When embedded in MFLs, these strategies transform waste into value, diversify livelihoods, and strengthen resilience to climate and market shocks.

However, the analysis also highlights critical constraints: fragmented governance, policy incoherence, limited financing, weak local capacity, and data gaps that hinder the scaling of circular innovations. Without coherent institutional frameworks and community participation, well-intentioned interventions risk remaining fragmented or maladaptive. Strengthening integration therefore calls for coordinated planning and investment that link regenerative production systems with territorial value chains and equitable market access.

The paper argues that integrating CBE into MFLs is not a single intervention but a systems transformation. Its success depends on aligning science, policy, and practice. Realizing this potential requires inclusive governance, cross-sectoral policy coherence, innovative financing for circular enterprises, and participatory knowledge systems that empower women, youth, and smallholders. When these enabling conditions are in place, circular bioeconomy pathways can regenerate landscapes, strengthen rural economies, and keep development safely within planetary boundaries. It can turn today's linear challenges into regenerative opportunities for people and nature.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