



MICRO-CREDENTIAL

CIRCULAR ECONOMY FOR LAND AND WASTE MANAGEMENT

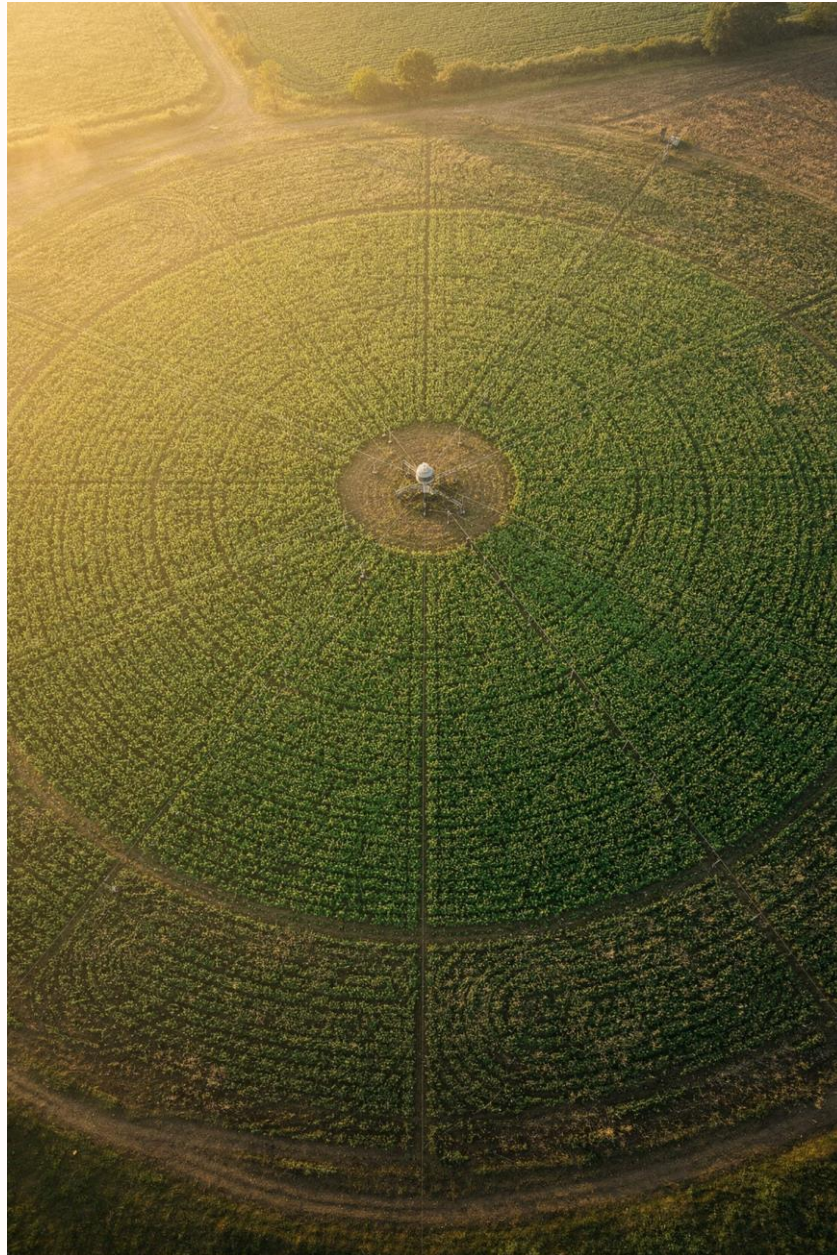
9.- Circular Economy in Agriculture and Rural Areas

Nutrient cycling in agriculture

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Closing the Loop: Nutrient Cycling for a Circular Agriculture

How reimagining farms as biological systems — not linear factories — can reduce costs, restore ecosystems, and build a more resilient food future.



The Open System Problem: Nutrient Nutrient Leakage



Modern agriculture has largely operated as a one-way pipeline — nutrients flow in as purchased inputs and flow out as pollution. Understanding where and why nutrients escape is the first step toward closing the loop.

The Farm as an Open System

Inputs Enter...

Nutrients arrive on the farm as purchased fertilizers, animal feed, and imported organic matter — representing significant financial investment each season.

...But Much Leaks Out

Most farms operate as open systems where a significant portion of applied nutrients never reaches the intended crop. Instead, they escape through runoff, volatilization, and leaching into air and waterways.

Every leaked nutrient represents money spent **twice**: once to purchase the input, and again to address the environmental damage it causes downstream. Closing this gap is both an economic imperative and an ecological necessity.

Major Leakage Pathways

Nutrients leave farms through four primary pathways, each driven by distinct soil, climate, and management conditions.

Nitrogen Volatilization

Ammonia loss to the atmosphere accounts for **20–40% of applied nitrogen** from fertilizer and manure. Losses accelerate in warm, windy, and alkaline conditions — making timing and application method critical.

Phosphorus Runoff

Phosphorus binds to soil particles and is carried away by eroding soil or dissolved in surface water. The downstream consequence is widespread eutrophication of rivers, lakes, and coastal zones.

Potassium Stripping

Continuous cropping without nutrient return steadily depletes potassium reserves — a particular risk in silage systems where the *entire* above-ground biomass is removed from the field.

Nitrate Leaching

Highly mobile nitrate ions migrate below the root zone, particularly in sandy soils during wet periods. Once leached, this nitrogen is irretrievable and contributes to groundwater contamination.

The Cost of Leakage: Environmental Environmental Damage

Nitrogen in Waterways

Excess nitrogen drives harmful algal blooms that deplete oxygen, create dead zones, and devastate aquatic biodiversity in rivers, lakes, and coastal waters.

Phosphorus in Runoff

Even small concentrations of phosphorus in surface water can trigger explosive algal growth, degrading aquatic ecosystems and making water unsafe for humans and wildlife.

Ammonia Volatilization

Ammonia emissions contribute to poor air quality and acid deposition. Redeposited nitrogen can fertilize sensitive habitats where it causes biodiversity loss and ecosystem disruption.

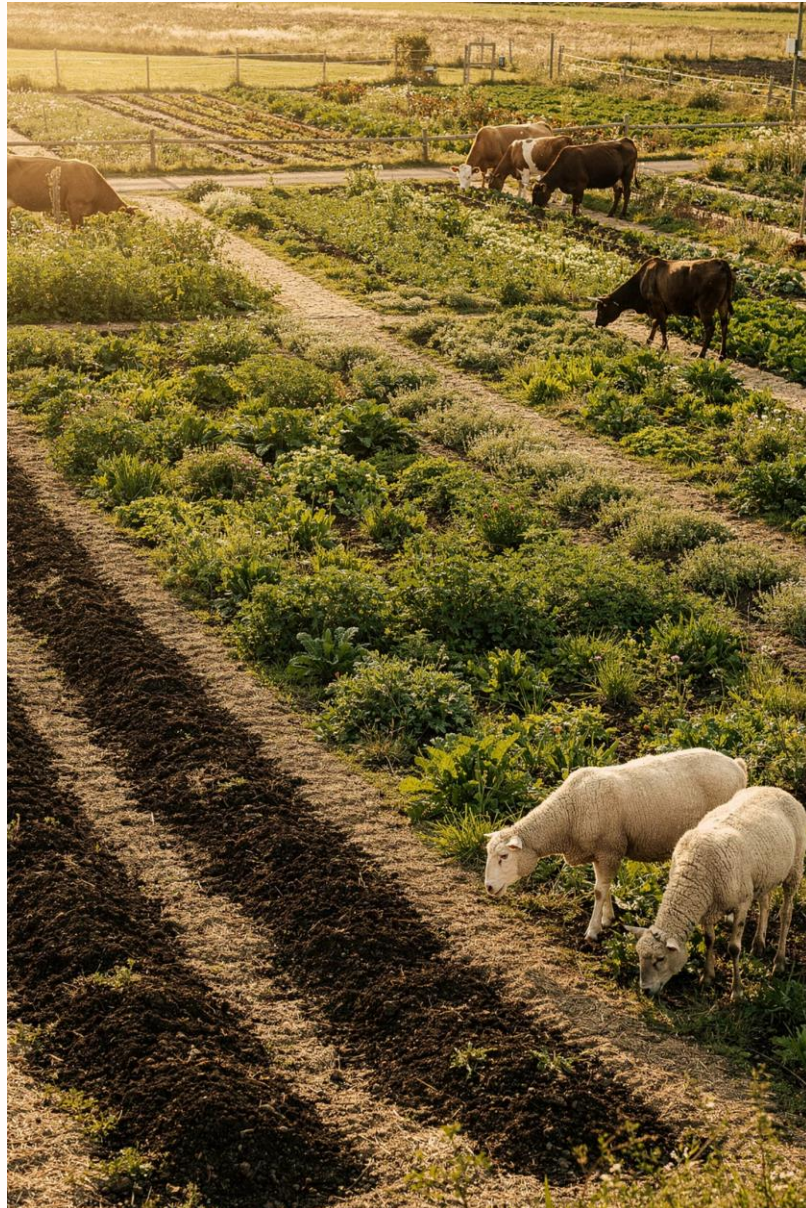
Wasted Nutrients, Damaged Planet



The cumulative effect of nutrient leakage is a double crisis: depleted soils that demand ever more inputs, and degraded ecosystems that bear the cost of those losses. The planet pays the price of an inefficient system built on a linear model that was never designed to last.

The Circular Solution: Maximizing Maximizing Nutrient Cycling

The alternative to open, leaky systems is a fundamentally different design philosophy — one that treats the farm as a living biological system where nutrients circulate, not disappear.



The Core Principle

A closed-loop system treats the farm as a **biological organism** with internal nutrient cycles rather than a factory with inputs at one end and waste at the other. Nutrients that leave one part of the system are captured and returned to another.

This approach draws on the wisdom of traditional mixed farming — integrating crops, livestock, and soil biology — but empowers it with modern precision tools, sensors, and data-driven management.

Three Guiding Principles

- Keep nutrients **cycling within** the farm system rather than flowing through it as waste
- Restore traditional integrated farming practices with **modern precision tools**
- Design every management decision around **nutrient retention** and reuse



From Linear to Circular: The Ideal Farm System

In a circular farm system, crops feed livestock, livestock produce manure that feeds the soil, the soil grows crops — and recycled organic materials from off-farm sources re-enter at every point. The loop is never broken.

Enabling the Circular Nitrogen Economy

Nitrogen is the most expensive, most mobile, and most environmentally impactful nutrient on the farm. Closing the nitrogen loop demands a combination of biological innovation, smart timing, and organic material reuse.



Nitrogen: The Most Expensive and Most Mobile Nutrient

The Challenge

Nitrogen exists in multiple chemical forms that move rapidly between soil, water, and atmosphere. Its mobility makes it uniquely difficult to retain — and uniquely costly when lost. Managing nitrogen in a circular system requires understanding its transformations at every stage.

Legumes: Nature's Nitrogen Factories

Incorporating legumes into crop rotations harnesses biological nitrogen fixation — the conversion of atmospheric N_2 into plant-available forms by root-associated bacteria.

- **Clover and lucerne** can fix **150–300 kg N/ha/year**
- Reduces synthetic fertilizer bills significantly
- Diversifies the farming system and improves soil health
- Provides high-quality feed for livestock in mixed systems

Recycling organic materials back to farmland is a cornerstone of the circular nitrogen economy — turning what was once "waste" into a valuable, crop-available nutrient resource.

Compost & Recyclates

Food and garden organic waste (FOGO), dried bacterial biomass (PPB), and chicken litter manure can all be processed and optimized as targeted soil amendments for specific crops and conditions.

Optimized Mixtures

Carefully formulated blends of organic recyclates — with or without supplemental mineral N — can match the yields achieved by conventional mineral-nitrogen-only programs, reducing reliance on synthetic inputs.

Beyond Nutrients

Compost delivers more than NPK. Bioactive crop-growth modulating substances in mature compost can influence crop development, growth timing, and phenology — benefits no synthetic fertilizer can replicate.

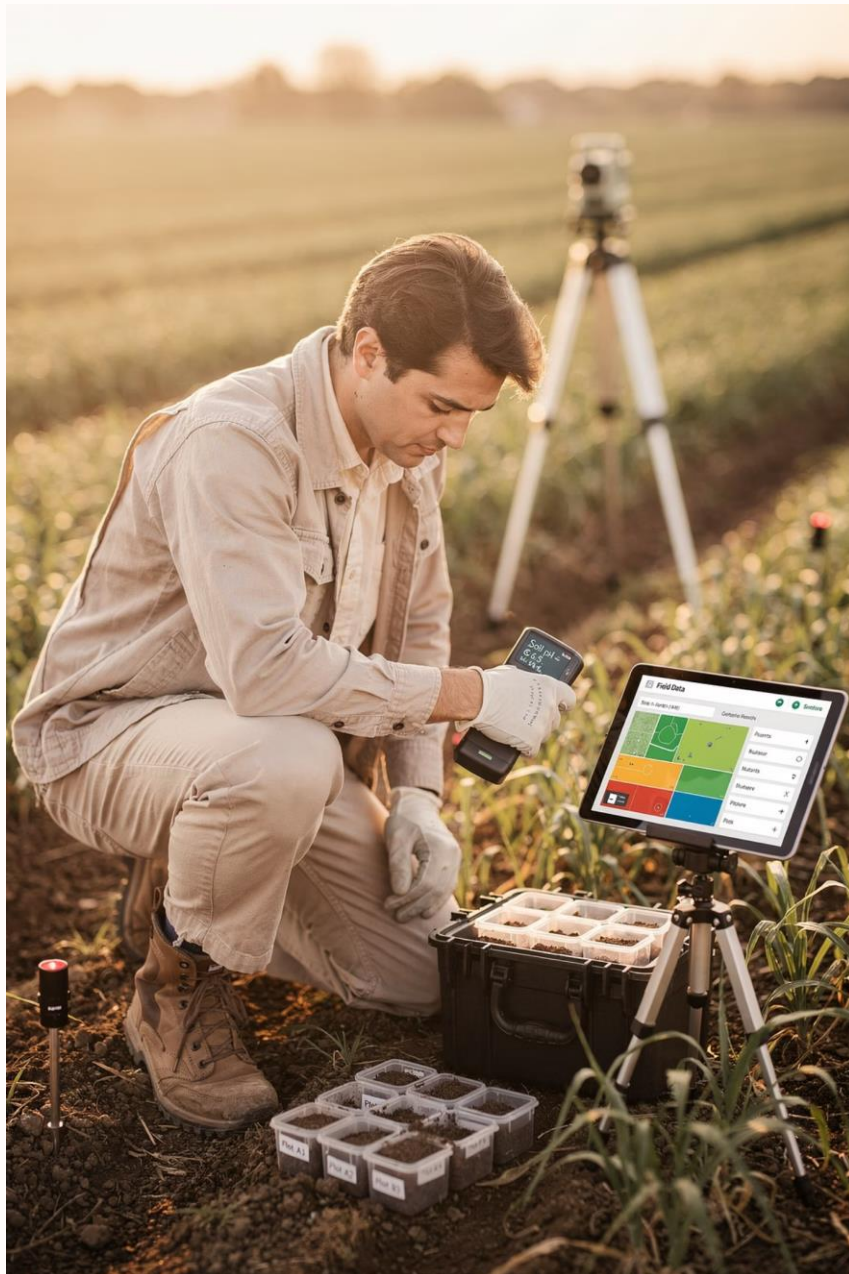
The Power of Recycled Nutrients



Side by side, the difference is unmistakable. Fields fed with recycled organic nutrients and thoughtfully managed biological inputs match — and often exceed — the performance of conventionally fertilized crops, while building long-term soil health rather than depleting it.

Innovative Nutrient Management Management Strategies

Beyond crop rotations and organic recycling, a new generation of technologies is unlocking novel ways to capture, concentrate, and redistribute nutrients with unprecedented precision and efficiency.



Slurry Separation and Pyrolysis

Performance in the Field

- **Liquid fractions** demonstrate superior plant nitrogen recovery versus raw slurries — LFD achieving **28% apparent nitrogen recovery (ANR)** in wheat versus 18% for conventional broadcast digestate
- **Biochar outcomes are feedstock-dependent:** some biochars show no immediate agronomic benefit or N₂O mitigation, while others may affect crop yields — careful feedstock selection is essential
- The approach enables nutrient transport to phosphorus-deficient regions far from livestock production areas

The Technology

Mechanical separation divides liquid biowastes into nutrient-rich liquid and solid fractions. The solid fraction can then be converted through **pyrolysis** into biochar — a stable, carbon-rich material ideal for long-distance phosphorus transport and soil amendment.

A largely untapped frontier in circular agriculture is the recovery of carbon, nitrogen, and phosphorus from human sanitation streams — a resource currently lost to wastewater treatment at enormous scale.

The Opportunity

A hypothetical fully circular system recovering **100% of C, N, and P** from human excreta could supply a meaningful share of crop nutrient requirements while simultaneously cutting emissions from both fertilizer production and sanitation infrastructure.

Climate Benefits

Displacing synthetic nitrogen fertilizer — which is energy-intensive to produce — with recovered human-derived nutrients could deliver **significant greenhouse gas reductions** across the full fertilizer lifecycle.

Regional Variation

The capacity to deliver crop nutrients and mitigate GHG emissions varies considerably by region, depending on population density, crop nitrogen demand, and the maturity of collection and processing infrastructure.



Biochar and separated liquid fractions represent a paradigm shift in how we think about agricultural "waste." Through pyrolysis and mechanical separation, low-value biowaste streams are transformed into high-value soil amendments and precision fertilizers — the circular economy made tangible.

Measuring Circularity and Its Impact

You cannot manage what you cannot measure. A robust set of circularity indicators now allows farmers, researchers, and policymakers to quantify exactly how efficiently nutrients are cycling — and where the biggest opportunities for improvement lie.



A suite of complementary metrics captures different dimensions of nutrient cycling efficiency across farm and regional food systems.

NUE & PUE

Nutrient Use Efficiency and **Phosphorus Use Efficiency** are foundational metrics for assessing how effectively applied nutrients are converted into crop output — and how much is lost to the environment.

CyCt & UseCt

Cycle Count and **Use Count** are advanced indicators expressing how many times a given nutrient atom completes a full biological cycle or passes through the top trophic compartment of the food system.

Output/Input Ratio

The **O/I ratio** provides an overall measure of system efficiency — the ratio of nutrient outputs (in food and products) to nutrient inputs (in fertilizers and feed). A ratio approaching 1.0 signals a near-closed system.

The Stark Reality

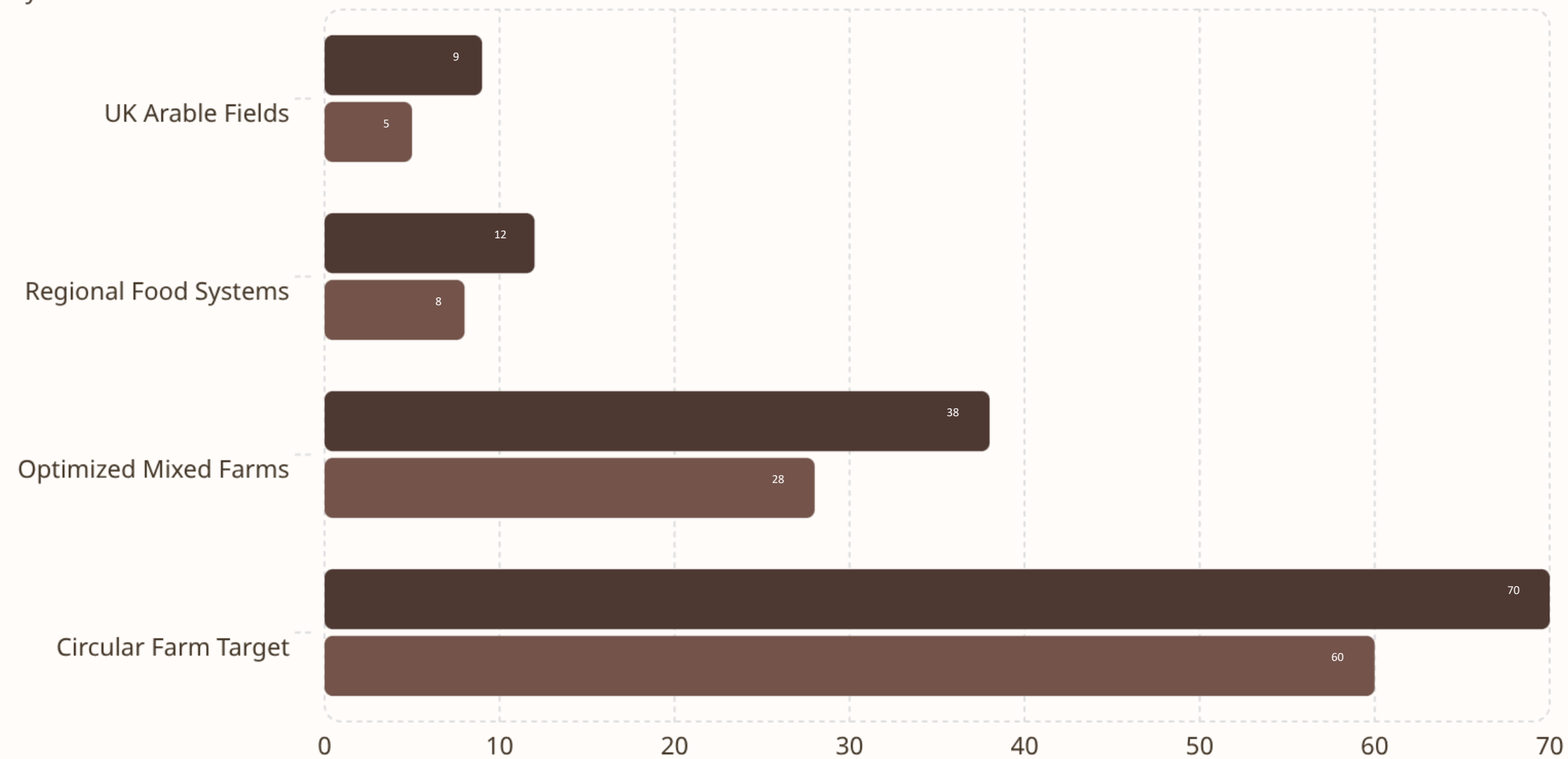
Analyses of real-world case studies consistently show that nutrient flows in today's agricultural systems are **almost entirely linear** — far from the circular ideal. Despite decades of awareness, most nutrients still travel in one direction: from mine or factory, through the farm, and into the environment.

The Numbers Tell the Story

In UK arable systems, cycled nutrient flows contribute just **9% for nitrogen** and **5% for phosphorus** of total nutrient throughput — meaning over 90% of nutrients follow a linear, one-way pathway.

At the regional food system level, the picture is similarly stark: cycled flows constitute a very small percentage of total nutrient flows reaching consumers. The gap between the circular ideal and current reality represents both a challenge and a profound opportunity.

System





The Future of Circular Agriculture

Achieving truly circular nutrient flows at scale requires more than farm-level changes. It demands a redesign of entire food systems — from field to fork and back again — tailored to the unique conditions of each region.

There is no universal blueprint for circular agriculture. The optimal mix of practices depends on local soils, climate, available organic resources, and regional food system structure.

Assess Local Context

Map available nutrient streams, biophysical conditions, and current leakage hotspots to identify the highest-impact interventions for each specific farm and region.

Match Livestock to Land

Align livestock production density with the carrying capacity of local feed and residual streams — ensuring manure production never exceeds the land's capacity to absorb and cycle it productively.

Redesign Food Systems

Restructure regional food systems to shorten nutrient loops — connecting urban organic waste streams back to nearby farmland and reducing the distance nutrients travel between production and consumption.

The Unbroken Circle: A Vision for Sustainable Agriculture

A fully functional circular nutrient economy is not a distant utopia — it is a practical, achievable goal built from proven technologies and regenerative principles available today.

Public Health

Cleaner waterways, better air quality, and reduced toxic chemical exposure for farming communities and downstream populations.

Food Security

Resilient, nutrient-rich soils that can sustain high yields without dependence on finite, imported mineral fertilizer resources.

Climate Mitigation

Reduced greenhouse gas emissions from fertilizer production, application, and leakage — contributing meaningfully to global decarbonization targets.