Environmental Defense Fund

LANDSCAPE OF AGRICULTURAL INNOVATION

Catalogue of agricultural innovations

January 2026

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1. ABOUT THIS REPORT

These findings are presented in two complementary parts:

Brief for policymakers and private-sector leaders: A high-level summary of emerging innovation areas, with clear actions required from both policymakers and industry to create the market forces and enabling environment needed for ag-tech solutions to mature and scale.

Catalogue of agricultural innovations: A detailed reference that profiles each innovation category, including product examples, assessments of market readiness, geographic considerations and potential climate and environmental benefits and tradeoffs.

Note: All product and company examples are illustrative and have not been researched by EDF for verification of corporate claims of effectiveness.

Acknowledgment: This work was made possible through the support of the Platform for Agriculture and Climate Transformation, a sponsored project of Rockefeller Philanthropy Advisors.

Technological advancements are poised to help farmers stay productive in the face of more extreme and variable weather, so that they can maintain good livelihoods and feed a growing population, while reducing the climate impacts of food production. Environmental Defense Fund analyzed nearly 400 companies and innovations in the climate-smart agriculture market to evaluate their climate impacts and benefits, market readiness and environmental co-benefits.

Agriculture accounts for more than 10% of the U.S. greenhouse gas (GHG) emissions and remains the nation's largest source of methane and nitrous oxide emissions. At the same time, agriculture can play a pivotal role in helping the U.S. achieve economy-wide, net-zero GHG emissions by 2050.

Unlocking the potential of agricultural technology is key to driving a much-needed third modern agricultural revolution (Saiz-Rubio & Rovira-Más, 2020). Farmers and society need this revolution now more than ever as climate change makes food production more difficult and population growth means we need more food.

The U.S. has long been a global leader in innovation, from driving the Green Revolution's advances in agricultural science to breakthroughs in biotechnology, aerospace and renewable energy. Today, it stands as the world's leading exporter of software and technology. Building on these strengths, the U.S. can spearhead the next wave of agricultural innovation, enabling American farmers to maintain productivity in the face of a changing climate and while reducing the impact of agriculture on the environment.

The ag-tech sector represents a promising driver of U.S. economic growth, with strong signals of resilience and investor confidence even amid broader downturns in venture capital (RSFI). Regenerative agriculture and climate-smart solutions have proven particularly attractive, drawing steadily increasing private-sector commitments — from just over $2 million in corporate funding in 2018 to more than $10 million in 2023 (EDF, 2024). Globally, agrifood-tech investment reached $16 billion in 2024, with the U.S. capturing 41% ($6.6 billion) (AgFunder, 2024), underscoring America's leadership and the sector's economic potential.

This report catalogues the most promising ag tech innovations across five technology fields — **nutrient and fertilizer solutions, smart sensing and precision analytics, agronomic data and measurement platforms, biotech and genetic innovation and automation and machinery**. These valuable tools can boost farm productivity while delivering climate and environmental benefits. This review is focused primarily on field crop applications, with some livestock applications.

Policymakers and the private sector each have distinct but complementary roles to play in scaling climate-smart agricultural innovations to market and that deliver measurable climate and economic benefits.

Policymaker actions can create the enabling environment for climate-smart agriculture in the following ways.

- Strengthen federal programs: Protect and expand funding for initiatives like AgARDA, Conservation Innovation Grants (CIG) and the Regional Conservation Partnership Program (RCPP) that drive innovation.
- Advance legislation: Pass bipartisan bills such as the Precision Agriculture Loan (PAL) Act, the Innovative FEED Act and the EMIT LESS Act. Additionally, fully appropriating existing federal research programs like AgARDA could encourage further private sector innovation within the agriculture technology space.
- Build partnerships and capacity: Advance public private partnerships through programs like the Conservation Technical Assistance (CTA), provided by USDA's Natural Resources Conservation Service and other civil service and private sector partners, ensures farmers have on-the-ground support to adopt new practices and technologies.

Private sector actions can accelerate adoption and scale in the following ways.

- Invest in innovation: Steer capital and leverage technology and research across the five innovation categories to drive impactful solutions within their value chain emissions and across industries.
- Forge partnerships: Food and agriculture companies should collaborate with ag-tech companies to promote education on supplier-wide adoption of nutrient management programs and precision technologies.
- Innovate financial opportunities: The food and agriculture industry must identify innovative approaches to financing the adoption of climate-smart technologies by adding to the current toolbox of cost-share programs and advancing an array of financial incentives that directly address the barriers faced by farmers (EDF, 2022)
- Ensure scientific integrity: Align on practical, science-based MRV methods that create a common language for comparing outcomes across supply chains and regulatory districts, harmonized metrics, and joint pilots with the public sector to identify synergies and avoid unintended trade-offs to validate outcomes and build confidence for buyers and investors.

See the Landscape of agricultural innovation for further analysis of economic, market and policy barriers to adopting these solutions and the actions recommended.

2. INNOVATION CATEGORIES

TABLE 1

Landscape of high-potential climate-smart agriculture technologies

Technologies	Market readiness	Adaptation or mitigation	Where benefits occur	Adoption barriers
Innovation area: Nutrient and fertilizer solutions		**Environmental benefit:** Reduced nitrous oxide emissions, lower runoff/pollution, improved nutrient efficiency, healthier soils		
Renewables-powered nitrogen fixation and catalytic ammonia synthesis	Commercial	Mitigation	On-farm energy use & powertrain emissions, non-CO_2 field emissions, up-stream/downstream supply chain emissions	Upfront cost, technical feasibility, compatibility with existing systems
Biomass-derived fertilizers	Commercial	Mitigation	Soil organic carbon & biomass sequestration, soil nutrient balance, up-stream/downstream supply chain emissions	Technical feasibility, biophysical constraints, market or supply chain access
Enhanced-efficiency fertilizers (EEFs)	Early market	Mitigation	Soil nutrient balance, plant nutrient uptake & use efficiency, non-CO_2 field emissions	Upfront cost, farmer awareness or knowledge, time to realize benefits
Biologicals: microbial nitrogen fixation and biostimulants	Early market	Mitigation	Soil nutrient balance, plant nutrient uptake & use efficiency, yield stability and climate risk buffering	Farmer awareness or knowledge, technical feasibility, time to realize benefits
Waste streams to fertilizer	Early market	Mitigation	Soil nutrient balance, up-stream/downstream supply chain emissions, water quality protections	Technical feasibility, policy or regulatory uncertainty, biophysical constraints
Methane to fertilizer	Early market	Mitigation	Soil nutrient balance, nutrient uptake and use efficiency, non-CO_2 field emissions	Technical feasibility, farmer awareness or knowledge, data infrastructure or digital literacy
Soil amendments	Early market	Mitigation	Soil organic carbon and biomass sequestration, non-CO_2 field emissions, soil nutrient balance, yield stability and climate risk buffering	Technical feasibility, farmer awareness or knowledge, upfront cost, policy or regulatory uncertainty
Innovation area: Smart sensing and precision analytics		**Environmental benefit:** Optimized water/fertilizer use, reduced waste, early pest/disease detection, improved yields per input		
Remote sensing for precision agriculture and regenerative agriculture monitoring	Market scale	Mitigation	Field operations efficiency, soil nutrient balance, yield stability and climate risk buffering	Data infrastructure or digital literacy, upfront cost, farmer awareness or knowledge

Technologies	Market readiness	Adaptation or mitigation	Where benefits occur	Adoption barriers
In-field farmland sensors and monitoring, precision irrigation	Market scale	Mitigation	Irrigation water-use efficiency, soil nutrient balance, yield stability and climate risk buffering	Upfront cost, data infrastructure or digital literacy, farmer awareness or knowledge, technical feasibility
Variable rate application and fertigation	Market scale	Hybrid	Soil nutrient balance, plant nutrient uptake and use efficiency, irrigation water-use efficiency	Upfront cost, technical feasibility, farmer awareness or knowledge
Innovation area: Agronomic data and measurement platforms		**Environmental benefit:** Enhanced soil health, biodiversity support, climate resilience, reduced chemical dependence		
Technical assistance for climate-smart agricultural practices	Early market	Hybrid	Soil nutrient balance, non-CO_2 field emissions, yield stability and climate risk buffering	Farmer awareness or knowledge, policy or regulatory uncertainty, time to realize benefits
Agronomics and computational agroecology	Early market	Hybrid	Soil nutrient balance, field operations efficiency, yield stability and climate risk buffering, chemical-use intensity	Data infrastructure or digital literacy, technical feasibility, policy or regulatory uncertainty
Carbon market facilitators	Early market	Mitigation	Soil organic carbon and biomass sequestration, non-CO_2 field emissions, upstream/downstream supply chain emissions, soil nutrient balance	Policy or regulatory uncertainty, upfront cost, technical feasibility
Innovation area: Biotech and genetic innovation		**Environmental benefit:** Drought tolerance, pest resistance, reduced chemical inputs, higher productivity on less land		
Biological pest controls and crop protection	Market scale	Adaptation	Chemical-use intensity, soil nutrient balance, yield stability and climate risk buffering	Technical feasibility, farmer awareness or knowledge, market or supply chain access
Seed genome editing, trait discovery and selection	Early market	Adaptation	Plant nutrient uptake and use efficiency, non-CO_2 field emissions, yield stability and climate risk buffering	Policy or regulatory uncertainty, farmer awareness or knowledge
Crop microbiome engineering	Commercial	Adaptation	Soil nutrient balance, plant nutrient uptake and use efficiency, yield stability and climate risk buffering	Technical feasibility, farmer awareness or knowledge, time to realize benefits
Plant cell culturing	Commercial	Mitigation	Upstream/downstream supply chain emissions, non-CO_2 field emissions, yield stability and climate risk buffering	Upfront cost, technical feasibility, market or supply chain access

Technologies	Market readiness	Adaptation or mitigation	Where benefits occur	Adoption barriers
Innovation area: Automation and machinery		**Environmental benefit:** Precision input use, lower labor intensity, reduced fuel/water use, minimized soil disturbance		
Crop protection weeding robotics and drones	Early market	Mitigation	Chemical-use intensity, field operations efficiency, on-farm energy use and powertrain emissions	Upfront cost, technical feasibility, compatibility with existing systems
Autonomous tractors and farm machinery	Early market	Mitigation	On-farm energy use and powertrain emissions, field operations efficiency, chemical-use intensity	Upfront cost, technical feasibility, compatibility with existing systems

Table 1: Key

Market readiness	A marker of "relative maturity," based on the sum of fundraising rounds for each company in that category, as well as the extent to which the product is being deployed commercially. • Pilot: Small-scale testing with early adopters or trial partner • Early market: Limited release, often targeting niche or visionary customers • Commercial: Broad release with a viable business model and revenue generation • Market scale: Rapid growth, infrastructure investment and mainstream adoption • Mature market: Saturation, stable demand and slower growth; high competition
Adaptation or mitigation	Adaptation — in human systems, the process of adjustment to actual or expected climate and its effects, in order to moderate harm or exploit beneficial opportunities. Mitigation (of climate change) — a human intervention to reduce emissions or enhance the sinks of greenhouse gases.
Where benefits occur	Part of agricultural production process where climate or adaptation benefits are realized: soil nutrient balance, nutrient uptake and use efficiency, water use efficiency, on-farm energy use, field operations efficiency, chemical-use intensity, soil carbon sequestration, non-CO_2 field emissions, water quality protection, upstream/downstream emissions, yield stability and climate-risk buffering
Adoption barriers	Starting point of general barriers to scaling the technology, including upfront cost, technical feasibility, farmer awareness, labor disruption, compatibility with existing systems, policy misalignment, biophysical constraints, market access, data infrastructure or digital literacy, time to realize benefits

2.1 Nutrient and fertilizer solutions

Fertilizer innovations target every phase of nutrient supply — from renewables-powered ammonia synthesis to on-farm fixation, biomass-derived amendments, enhanced-efficiency formulations, microbial inoculants, waste-to-fertilizer pathways, and methane-to-fertilizer systems. These approaches aim to slash the carbon and nitrous-oxide footprint of synthetic fertilizer production — 40% of total synthetic nitrogen (N) fertilizer CO_2e emissions come from production and manufacturing, estimated at 438.5 Mt CO_2e out of 1,129 Mt CO_2e globally in 2018 (Menegat, S., Ledo, A. & Tirado, R, 2022) — while boosting nutrient-use efficiency and local resilience.

NUTRIENT & FERTILIZER SOLUTIONS

- PILOT
- EARLY MARKET
- ▶ **COMMERCIAL**
- MARKET SCALE
- MATURE MARKET

- ▶ **MITIGATION**
- ADAPTION
- HYBRID

WHERE CLIMATE BENEFITS OCCUR:

- On-farm energy use and powertrain emissions
- Non-CO_2 field emissions
- Upstream/ downstream supply chain emissions

ADOPTION BARRIERS:

- Upfront cost
- Technical feasibility
- Compatibility with existing systems

Renewables-powered nitrogen fixation and catalytic ammonia synthesis

Renewables-powered nitrogen fixation and ammonia synthesis uses renewable energy sources such as solar, wind, hydro, geothermal or biomass to drive on-farm or regional systems that produce nitrogen or synthesize ammonia. This approach could help reduce fossil fuel use and enable low-carbon fertilizer production.

Literature summary

Recent research by Environmental Defense Fund revealed that fertilizer production facilities have higher nitrous oxide (N_2O) and methane (CH_4) emissions than previously estimated by the Environmental Protection Agency (Eagle, 2023 [EDF Internal Doc]). For example, mobile sensing measurements at U.S. ammonia fertilizer plants found methane emissions of 29 ± 18 Gg CH_4/yr, significantly higher than the 0.2 Gg CH_4/yr reported in EPA's database (Zhou et al., 2019). Similarly, industrial N_2O emissions from adipic and nitric acid production have been found to be substantially underestimated, with untapped abatement potential through existing low-cost technologies that could achieve 90-99% reduction efficiency (Davidson & Winiwarter, 2023).

Global-scope emissions from manufacturing nitrogen fertilizer are hard to quantify, as regional differences in energy sources and production efficiency mean manufacturing emissions are variable. However, energy generation is implied as one of the dominant drivers of synthetic N fertilizer manufacturing emissions because the Haber-Bosch process requires high temperatures (~400-500°C) and pressures (~150-300atm) (Menegat, S., Ledo, A. & Tirado, R, 2022). Moving away from ammonia production processes that use natural gas and adopting renewables-powered ammonia production sources offers an opportunity to reduce the emission intensity associated with synthetic N fertilizer production. Action to reduce N_2O and CH_4 losses from fertilizer production facilities provide near-term mitigation opportunities with existing production (Davidson & Winiwarter, 2023; Zhou et al., 2019).

Steam methane reforming (SMR) is the predominant method of industrial hydrogen production, an essential component of ammonia, and direct emissions using SMR with no carbon capture is approximately 9 kg CO_2e/kg H2 (Godfrey Nnabuifeet, 2023). When powered by renewable energy sources, direct emissions from water electrolysis can range from 2.0 kg to 4.4 kg CO_2e/kg H2 depending on the type of renewable energy source (Wei et al., 2024; Rodríguez-Fontalvo et al., 2024; Sgarbi et al., 2025). Therefore, producing fertilizers at scale using green ammonia (ammonia produced using renewable powered water electrolysis) can reduce industrial hydrogen production CO_2e emissions by over half, reducing the overall carbon intensity of crop production.

On-farm ammonia production with renewable energy

As a subset of green ammonia technology, on-farm ammonia production powered by renewable energy sources integrated into hardware units offers additional benefits beyond emissions reduction during the production phase. This decentralized approach to ammonia synthesis directly addresses transportation-related emissions by eliminating or significantly reducing the need to transport ammonia from centralized production facilities to agricultural sites.

On-farm production systems typically integrate renewable energy sources such as solar panels or wind turbines directly with smaller-scale ammonia synthesis units, creating a closed-loop system that can provide nitrogen fertilizer on demand at the point of use. This localized production model not only reduces the carbon footprint associated with fertilizer transportation but also enhances supply chain resilience and potentially reduces costs for farmers in remote locations.

PRODUCT EXAMPLES

Green Lightning: On-farm reactors powered by renewable electricity that pull nitrogen from air and convert it into liquid ammonia fertilizer

Talus Renewables: A modular, containerized system that uses renewable electricity, water and air to produce ammonia on-site for local fertilizer use

ReMo Energy: A distributed network of small-scale plants that harness renewable power to synthesize green ammonia ("ReMonia™") from air and water for nitrogen fertilizer

NUTRIENT & FERTILIZER SOLUTIONS

PILOT
EARLY MARKET
▶ **COMMERCIAL**
MARKET SCALE
MATURE MARKET

▶ **MITIGATION**
ADAPTION
HYBRID

▶ WHERE CLIMATE BENEFITS OCCUR:

- Soil organic carbon and biomass sequestration
- Soil nutrient balance
- Non-CO_2 field emissions
- Water quality protection
- Upstream/ downstream supply chain emissions

▶ ADOPTION BARRIERS:

- Technical feasibility
- Biophysical constraints
- Market or supply chain access

Biomass-derived fertilizers

Biomass-derived fertilizers are produced by converting organic materials — such as agricultural waste, animal byproducts and forest residues — into nutrient sources for plants, using biological or chemical processes tailored to the specific biomass type. This approach enables nutrient recycling, reduces reliance on fossil-fuel-based inputs and supports more circular nutrient management systems.

Literature summary

Compost application can significantly enhance soil carbon sequestration, with short-term (1 year) retention rates of up to 53 % of applied carbon, although this drops to just 2-16 % over a 20+ year horizon (Martinez-Blanco et al., 2013). However, net GHG benefits depend entirely on the counterfactual — what would have happened to that organic material under business-as-usual? If compost merely replaces stockpiling or land-spreading elsewhere, total carbon stocks may not change (Eagle & Olander, 2012). Real emission reductions and soil-C gains can only be claimed when compost displaces mineral fertilizer inputs and is diverted from a higher-emitting fate (e.g., open-air storage). This positions compost as a potentially important carbon sink in degraded soils — but only when replacing synthetic fertilizer (to decrease upstream GHGs) and minimizing nutrient losses to NH_3, NO_2, and NO_3 (Brockmann et al., 2018; Meier et al., 2015).

It is important to note that the potential to increase soil-C stocks via animal-manure application to arable land depends on various factors including how the manure would have been used otherwise (Maillard & Angers, 2014). In many cases, spreading raw manure simply relocates carbon rather than adding net soil C. Yet when applied in place of synthetic N fertilizer and managed to match crop needs, manure can reduce N_2O emissions — and upstream GHGs — by curbing excess N inputs. Our own N_2O-N-balance research shows little difference in N_2O between synthetic fertilizer and manure when both are applied to achieve the same net N balance; by quantifying actual manure nutrient content and adjusting fertilizer rates accordingly, farmers can safely lower total N applications with minimal yield impact.

Estimates that N_2O emissions can offset roughly 37 % of the SOC sink from manure on upland soils — assuming a global average rate of 115.7 kg N ha^{-1} yr^{-1} — are based on typical (often unmanaged) application practices (Zhou et al., 2017). Improved manure recycling — through composting, vermicomposting, black-soldier-fly digestion, anaerobic digestion, or simply tighter application timing and placement — offers significant potential to cut both field N_2O and upstream synthetic-N emissions.

Finally, bio-based fertilizer production requires large, standardized feedstock supplies (Chojnacka et al., 2019), but this does not mean scaling livestock numbers to meet demand. Rather, we should optimize the use of existing manure and compost resources by reintegrating livestock and cropping operations to reduce haul distances and spread available material more widely across the landscape.

PRODUCT EXAMPLES

Corigin: Aqueous solution comprised of numerous phenols, organic acids and other lightweight biomolecules sourced from almond shells

Chonex: Bio-fertilizer created by transforming layer hen manure using black soldier fly larvae

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WHERE CLIMATE BENEFITS OCCUR:

- Soil nutrient balance
- Plant nutrient uptake and use efficiency
- Non-CO_2 field emissions
- Water quality protection

ADOPTION BARRIERS:

- Upfront cost
- Farmer awareness or knowledge
- Time to realize benefits

Enhanced-efficiency fertilizers (EEFs)

Enhanced-efficiency fertilizers (EEFs) are designed to improve nutrient availability to crops while reducing nutrient losses to the environment, achieved through various mechanisms that slow nutrient release, control transformation rates or inhibit specific loss pathways.

Classification of EEFs based on mode of action:

- Slow-release fertilizers — nutrients are chemically bound in compounds that break down gradually via microbial activity, hydrolysis or oxidation. Examples: Urea-formaldehyde (releases N over weeks/months); isobutylidene diurea (hydrolyzes in water); sulfur-coated urea (physically coated to slow dissolution).

- Controlled-release fertilizers — nutrients are physically encapsulated or coated with materials that regulate release rates through diffusion, osmosis or coating degradation. Unlike slow-release products that depend on environmental conditions, controlled-release products are engineered for more predictable release patterns.

- Stabilized fertilizers with inhibitors — contain additives that suppress specific biological processes:

    - Nitrification inhibitors (e.g., nitrapyrin, DCD) — slow conversion of ammonium to nitrate

    - Urease inhibitors (e.g., NBPT) — reduce ammonia volatilization by blocking urease enzyme activity

Literature summary

Enhanced-efficiency fertilizers (EEFs) — including nitrification inhibitors, urease inhibitors, controlled-release or slow-release products — can reduce nitrogen losses and greenhouse gas emissions compared to conventional synthetic nitrogen. Nitrification inhibitors can lower nitrous oxide emissions, with potential reductions of 8 Mt CO_2e from grazing land applications alone by 2030 (Eagle et al., 2022). In one meta-analysis, nitrification inhibitors reduced N_2O emissions in North American corn systems by an average of 32% (Eagle et al., 2017). However, emerging research indicates that inhibitors may delay rather than prevent nitrogen losses unless combined with reduced total application rates. Recent studies demonstrate that the efficiency benefits of inhibitors are primarily realized when using reduced N rates, as the nitrogen retained in the system reduces the need for additional inputs (Kaur et al., 2024). This suggests that optimal use of EEFs requires adjusting total N application rates downward to account for improved retention, rather than maintaining conventional rates with inhibitor additions.

PRODUCT EXAMPLES

Phosphosolutions: A phosphorus fertilizer with a proprietary polymer coating that modulates nutrient release in response to plant uptake

Indogulft BioAg: A line of nano-encapsulated and microbial fertilizers, including nanofertilizer formulations, for targeted nutrient delivery

Biologicals: microbial nitrogen fixation and biostimulants

Microbial Nitrogen Fixation (MNF) involves the use of bacteria that convert atmospheric nitrogen into forms plants can use, reducing the need for synthetic fertilizers. Biostimulants are substances or microorganisms that improve plant growth, stress tolerance or nutrient efficiency, often supporting or partially substituting conventional inputs like nitrogen fertilizers. Some biologicals are aimed at converting nutrients into more accessible forms, facilitating plant-nutrient uptake, including phosphorus solubilization and other nutrient mobilization processes. (Note: Biocontrols are discussed in Section 2.4)

Literature summary

Biological nitrogen fixation (BNF) can reduce greenhouse gas emissions when it successfully offsets the use of synthetic nitrogen fertilizers, which are responsible for substantial CO_2 and N_2O emissions during production and application. Traditional legume-based BNF systems, when integrated into crop rotations with corresponding reductions in synthetic nitrogen application, have been associated with cradle-to-farm gate emission reductions of 30–70% compared to conventional fertilization, depending on crop type, soil conditions and actual nitrogen replacement achieved (Poch et al., 2020; Robertson & Vitousek, 2009). For example, replacing 50% of synthetic nitrogen with BNF in legume rotation systems has been associated with reductions of up to 1.2 tons CO_2e per hectare per year.

However, these emissions-reduction estimates from legume-based systems may not directly translate to newer asymbiotic BNF products entering the market. Studies are still underway to understand whether and how these commercial BNF inoculants can produce similar benefits; preliminary field trials including 61 site-years found inconsistent crop yield responses, with only two site-years showing yield increases when compared with fertilizer alone, suggesting variable efficacy in nitrogen provision and uncertain emissions reduction potential (Franzen et al., 2023). Some products may help maintain yields with lower N rates under the right conditions. Beyond nitrogen fixation, emerging biological products also target phosphorus solubilization and other nutrient mobilization mechanisms, potentially reducing the need for mineral fertilizer inputs, though comprehensive emissions data for these applications remain limited.

PRODUCT EXAMPLES

Azotic: A microbial inoculant containing nitrogen-fixing bacteria formulated for seed or soil application

BioConsortia: A suite of custom microbial products discovered and optimized via proprietary R&D to support crop health

NUTRIENT & FERTILIZER SOLUTIONS

PILOT
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- Yield stability and climate-risk buffering

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- Farmer awareness or knowledge
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- Technical feasibility
- Farmer awareness or knowledge
- Upfront costs
- Policy or regulatory uncertainty

Soil amendments

Soil amendments for climate mitigation include biochar and ground silicate or limestone rock (to support enhanced weathering (EW)). Biochar is a carbon-rich, relatively stable material created through pyrolysis of biomass under low oxygen conditions. Its primary climate benefit comes from converting organic carbon that would otherwise decompose quickly into a more durable form that can persist for decades to centuries. Some studies also suggest soil co-benefits, such as improved water-holding capacity, nutrient retention and reductions in nitrous oxide (N_2O) emissions, though these are context-dependent and not consistently realized (Raffeld & Lavallee, 2024). If biochar is being created under a carbon crediting scheme, the biochar producer is typically responsible for the verified carbon removal process and obtains the credits, rather than the farmer (Raffeld et al., 2025). The revenue from credit sales can then be used to compensate farmers for spreading biochar on their fields.

Enhanced weathering involves applying finely ground, cation-rich rocks (e.g., basalt, olivine, wollastonite, agricultural lime) to soils to accelerate natural weathering reactions. These reactions convert atmospheric CO_2 into dissolved bicarbonates and carbonates, with eventual transfer from soils via water to rivers and oceans for long-term sequestration. Farmers are already familiar with liming practices, which makes EW adoption more accessible, though the use of silicate rocks and industrial byproducts for climate purposes is newer. In acidic soils, these rock additions increase soil pH, which can increase crop nutrient efficiency, improving yields with lower fertilizer requirements (Holland et al. 2018; Beerling et al. 2023).

Both of these amendments are likely to confer climate benefits under the right contexts. However, the remaining uncertainties in quantifying those benefits mean that EDF is cautious about current crediting. For biochar we are also cautious because there may be more climate-effective uses of the biomass involved (e.g., burning it directly to replace petroleum fuel sources) than pyrolysis for biochar.

Literature summary

Biochar

Roughly 50% of feedstock carbon is lost during pyrolysis stage of biochar manufacturing. Of the carbon retained, 80-90% is considered stable on decadal to longer timescales. This translates into significant long-term storage potential when produced from sustainably sourced feedstocks. Typical "break-even" relative to uncharred biomass occurs within 5-10 years (Lehmann et al., 2021; Woolf et al., 2021). Meta-analyses suggest potential N_2O reductions of ~30-40% in the first year of application, though results vary widely by soil type, feedstock and pyrolysis temperature (Lehmann et al., 2021). Yield and soil quality improvements are most pronounced in acidic and coarse-textured soils, but long-term field evidence remains limited (Raffeld & Lavallee, 2024). Repeated annual applications of biochar are necessary to maintain soil benefits where they do manifest (Yang et al., 2025).

Voluntary carbon marketplace protocols differ in how they treat production system boundaries, permanence and baselines. The "system" includes the full life cycle of a biochar project — from sourcing and transporting biomass, through pyrolysis and co-products, to end use of the char. EDF's Comparison of Biochar Carbon Market Protocols report (Raffeld et al., 2025) compared five major standards (Verra, CAR, Puro.earth, Global Biochar C-Sink, Isometric) and found significant differences in how these boundaries are set. A major issue is the use of a zero baseline, which assumes biomass would otherwise decompose rapidly and release CO_2. This inflates credited benefits because it ignores alternative uses such as energy generation, compositing or animal bedding that also offset or store carbon. EDF flagged this as an integrity risk, and some registries now require evidence that feedstocks are not being diverted from higher-value uses (Raffeld et al., 2025).

Enhanced weathering

The ground rock used in EW reacts with carbonic acid in soils (formed from atmospheric CO_2 dissolving in rainwater) to form bicarbonate. Long-term carbon storage results when the bicarbonate is transported via rivers to the oceans, where storage is expected to last hundreds of thousands of years. Agricultural lime is a long-standing example, though its carbon content can make the climate benefit more variable depending on local climate conditions and farming practices.

Global carbon dioxide removal potential for enhanced weathering is estimated in the literature to be 0.5–4 Gt CO_2 per year, with the Intergovernmental Panel on Climate Change citing a 2–4 Gt range (IPCC AR6 WGIII) and national-level estimates from various countries (e.g. Beerling et al., 2020) in the 0.5–2 Gt range. These estimates are model-driven and highly uncertain — EDF analysis underscores that real-world constraints such as feedstock supply, energy input, MRV losses and downstream alkalinity retention mean effective removals could fall substantially below modeled values (Buma et al., 2025).

The emergence of enhanced weathering projects is being driven by carbon markets and corporate net-zero commitments, which create financial incentives for companies to generate tradeable carbon removal credits through mineral application. Registries like Puro.earth and Isometric are beginning to pilot methodologies, while developers such as InPlanet and Eion Carbon enroll farmers and source silicate feedstocks.

Key uncertainties remain about how efficiently carbon is transported from field to soil and ocean, with potential losses from incomplete dissolution, secondary mineral formation, or carbonate precipitation in rivers and nearshore waters. Additional risks involve heavy metals in some feedstocks (e.g., nickel, cadmium), possible effects on soil organic carbon, and variability in biological interactions. At the same time, EW could deliver co-benefits by raising soil pH in acidic soils, improving nutrient availability, and reducing N_2O emissions.

PRODUCT EXAMPLES

Carbo Culture: Produces high-surface-area biochar via advanced pyrolysis, targeting both soil health and durable carbon removal

Pacific Biochar: Commercial biochar producer supplying agricultural markets in the U.S., generating credits through Puro.earth

Eoin Carbon: U.S. firm supplying basaltic rock for agricultural use, with partnerships to integrate crediting into farm supply chains

MARKET CREDITS COMPANY EXAMPLES

Isometric: Registry and MRV platform developing protocols to standardize enhanced weathering crediting and biochar

Puro.earth: Registry that issues credits to producers for both biochar and enhanced weathering projects

Waste streams to fertilizer

A process to produce fertilizers by processing large-scale industrial waste streams to recover essential nutrients such as potassium and micronutrients, with sources including battery manufacturing residues, pulp mill byproducts, fly ash, and gypsum. Some processes also capture and convert industrial CO_2 and ammonia-rich effluents into stabilized fertilizer products, turning waste into valuable agricultural inputs.

Literature summary

The carbon intensity of global N fertilizer supply chains averaged 10.48 tons of CO_2e per ton of nitrogen, inclusive of the entire supply chain. Manufacturing amounts to about 38.8% of global N fertilizer supply chain emissions (Menegat et al., 2022). The climate benefit occurs through displacing energy-intensive conventional fertilizer manufacturing (particularly Haber-Bosch processes for nitrogen) and diverting industrial waste from disposal.

The magnitude of emissions reductions varies by nutrient type and waste stream. For example, recovering potassium from industrial byproducts may yield different carbon benefits than nitrogen recovery, as conventional potash mining has a lower carbon footprint (~0.15-0.3 tons CO_2e per ton K2O) compared to ammonia synthesis (~2.4 tons CO_2e per ton N). Industrial micronutrient recovery could displace mining and processing emissions, though specific reduction potentials depend on the conventional production pathway being replaced.

Emerging processes — like recovering trace minerals and repurposing byproducts — are still under evaluation and comprehensive LCA emissions metrics remain unavailable. Standardized assessments are needed to quantify net climate benefits across different industrial waste-to-fertilizer pathways.

PRODUCT EXAMPLES

Cinis Fertilizer: A Swedish green-tech producer that upcycles industrial by-products (e.g., battery and pulp mill residues) into water-soluble potassium sulfate (SOP) fertilizer

Tracegrow: A circular-economy fertilizer producer whose RETRACER™ process recovers zinc, manganese, and other micronutrients from recycled batteries and industrial side streams to manufacture EU-certified, organic-approved micronutrient fertilizers

CCm Technologies: A carbon-capture process that converts CO_2 and other industrial waste streams into pelletized organo-mineral fertilizers containing stabilized ammonia and phosphates

NUTRIENT & FERTILIZER SOLUTIONS

PILOT
▶ **EARLY MARKET**
COMMERCIAL
MARKET SCALE
MATURE MARKET

▶ **MITIGATION**
ADAPTION
HYBRID

▶ **WHERE CLIMATE BENEFITS OCCUR:**

- Soil nutrient balance
- Upstream/ downstream supply chain emissions
- Water quality protection
- Yield stability and climate-risk buffering

▶ **ADOPTION BARRIERS:**

- Technical feasibility
- Policy or regulatory uncertainty
- Biophysical constraints

NUTRIENT & FERTILIZER SOLUTIONS

- PILOT
- EARLY MARKET
- ▶ COMMERCIAL
- MARKET SCALE
- MATURE MARKET

- ▶ MITIGATION
- ADAPTION
- HYBRID

▶ WHERE CLIMATE BENEFITS OCCUR:

- Soil nutrient balance
- Plant nutrient uptake and use efficiency
- Non-CO_2 field emissions
- Upstream/ downstream supply chain emissions

▶ ADOPTION BARRIERS:

- Technical feasibility
- Farmer awareness or knowledge
- Data infrastructure or digital literacy

Methane to fertilizer

Methane to fertilizer is a process for using methanotrophic microbes that capture methane from sources such as dairy barn exhaust, manure lagoons, or digestate, and convert it into microbial biomass. This biomass, enriched with assimilated nitrogen, can be harvested and processed into an organic fertilizer, recycling existing nitrogen within the system rather than relying on new fixation.

Methanotrophs capture methane from their environment — dairy barn exhaust, manure lagoons, slurry pits, anaerobic digestate — and then oxidize it to derive energy and carbon for growth. These microorganisms assimilate available nitrogen from their environment (ammonia, nitrate, organic nitrogen) and convert it into microbial biomass. When this biomass is harvested and processed, it can serve as an organic nitrogen fertilizer, effectively recycling existing nitrogen in the system rather than fixing new nitrogen from the air.

Literature summary

Methanotrophic microbial consortia (MMCs) employed in controlled bioreactor systems represent an emerging biotechnology for methane oxidation and nutrient recovery from agricultural and waste management operations (Windfall Bio, 2025). These specialized microorganisms utilize methane as their primary carbon and energy source through enzymatic oxidation, converting emissions from manure lagoons, landfills and flare gas into microbial biomass. The methanotrophic metabolism enables the assimilation of bioavailable nitrogen compounds present in waste streams, incorporating them into cellular proteins and other nitrogenous biomass components that can subsequently be processed into organic fertilizer products.

This biological methane oxidation approach addresses the mitigation of a potent greenhouse gas with a global warming potential approximately 80 times that of CO_2 over a 20-year timeframe, while simultaneously generating nitrogen-rich organic amendments (Segal, 2024). The technology facilitates nutrient cycling within agricultural systems by converting waste-derived nitrogen into bioavailable organic forms, thereby reducing dependence on energy-intensive synthetic nitrogen fertilizer production and its associated greenhouse gas emissions, particularly N_2O.

Process optimization is achieved through integrated monitoring systems that provide continuous data on bioreactor performance parameters, enabling operators to maximize methane oxidation rates and biomass productivity while quantifying carbon mitigation potential for emerging carbon credit markets (Breakthrough Energy, n.d.). Preliminary field trials conducted in dairy operations and waste management facilities have demonstrated technical feasibility and suggest potential scalability, though peer-reviewed performance data and life-cycle assessments remain limited (MCJ Collective, 2023). Further research is warranted to establish nitrogen conversion efficiencies, long-term system stability and economic analyses of this technology's costs and benefits.

PRODUCT EXAMPLES

Windfall Bio: Methanotroph reactor that takes methane-source as input to release nitrogen/ plant nutrient compound

2.2 Smart sensing and precision analytics

These tools integrate remote (satellite, drone) and in-field sensors with AI-driven analytics and cloud platforms to deliver real-time data on soil, crop and weather conditions. By enabling precision irrigation, variable-rate nutrient application and regenerative-practice monitoring, they help farmers optimize inputs, reduce waste and track progress toward environmental targets.

Remote sensing for precision agriculture and regenerative agriculture monitoring

By using remote imagery and data collection — such as drones and satellites, other sensors — farm managers can assess progress and changes associated with the implementation of precision and/or regenerative agriculture. Most agriculture technology companies developing remote sensing solutions are integrating predictive-modeling software into product offerings.

Literature summary

The integration of remote sensing technologies with predictive modeling can enable targeted, efficient input application based on continuously updated data streams (Sishodia et al 2020; Roy and George 2020). Coupling remote-sensing data collection with scalable cloud and AI pipelines can help overcome data-intensity/overflow issues in precision-ag technologies (Wolfert et al., 2017; Sishodia, Ray & Singh, 2020). Sensors can be configured for collection frequency and tracking needs, allowing for structured decision-making, supporting positive outcomes on the integration of farm management practices.

Remote sensing technologies can be employed in the monitoring of cover cropping, no-till, nutrient optimization and other practices that can contribute to regenerative agriculture outcomes, like soil carbon sequestration and soil health (Rehberger et al 2023; Schattman et al 2023).

PRODUCT EXAMPLES

Miraterra: A proximal-and-remote sensing platform (the Digitizer) combining spectroscopy, modeling and AI to digitize soil, plant and feed properties

Taranis: An AI-driven crop-intelligence platform that fuses aerial imagery (drones, satellites) with machine-learning analytics for leaf-level field monitoring

SMART SENSING AND PRECISION ANALYTICS

PILOT
EARLY MARKET
COMMERCIAL
▶ **MARKET SCALE**
MATURE MARKET

▶ **MITIGATION**
ADAPTION
HYBRID

▶ **WHERE CLIMATE BENEFITS OCCUR:**

- Field operations efficiency
- Soil nutrient balance
- Soil organic carbon and biomass sequestration
- Water quality protection
- Yield stability and climate-risk buffering

▶ **ADOPTION BARRIERS:**

- Data infrastructure or digital literacy
- Upfront cost
- Farmer awareness or knowledge

In-field farmland sensors and monitoring

Sensors and monitoring systems that are equipped in-field to monitor diverse variables like soil water content, plant disease, soil microbes and nutrients, temperature, atmospheric molecular content and many more. Generally, in-field sensing hardware has integration with monitoring or database software, with some newer models introducing integration of artificial intelligence for data analysis and system-level outcome modeling.

Literature summary

In-field sensor and monitoring systems — capable of tracking variables such as soil moisture, nutrient content, microbial communities, plant stress and atmospheric conditions — can enable more precise, adaptive and efficient input use (Balasundram et al 2023; Parra- López et al. 2024). AI-integrated platforms using tools like drones and crop analytics now enable real-time decision-making for soil, crop health and input efficiency (Environmental Defense Fund, 2023). However, adoption barriers such as digital literacy gaps, upfront costs and data privacy concerns remain, especially in low-resource farming environments.

PRODUCT EXAMPLES

Arable Crop Intelligence System: A single solar-powered internet enabled smart device (Mark 3) that measures weather, plant, soil, irrigation and crop imagery to provide in-field insights

GroGuru: A subscription-based service using wireless underground probes (WUGS) and AI to continuously monitor root-zone moisture and deliver irrigation guidance

SMART SENSING AND PRECISION ANALYTICS

PILOT
EARLY MARKET
COMMERCIAL
▶ **MARKET SCALE**
MATURE MARKET

▶ **MITIGATION**
ADAPTION
HYBRID

▶ **WHERE CLIMATE BENEFITS OCCUR:**

- Irrigation water-use efficiency
- Soil nutrient balance
- Plant nutrient uptake and use efficiency
- Field operations efficiency
- Water quality protection
- Yield stability and climate-risk buffering

▶ **ADOPTION BARRIERS:**

- Upfront cost
- Data infrastructure or digital literacy
- Farmer awareness or knowledge

SMART SENSING AND PRECISION ANALYTICS

PILOT

EARLY MARKET

COMMERCIAL

▶ **MARKET SCALE**

MATURE MARKET

MITIGATION

ADAPTION

▶ **HYBRID**

▶ WHERE CLIMATE BENEFITS OCCUR:

- Irrigation water-use efficiency
- Soil nutrient balance
- Plant nutrient uptake and use efficiency
- Field operations efficiency
- Water quality protection
- Yield stability and climate-risk buffering

▶ ADOPTION BARRIERS:

- Upfront cost
- Technical feasibility
- Data infrastructure or digital literacy

Precision irrigation

Also known as targeted or controlled irrigation, precision irrigation systems are a method of delivering water and nutrients directly to the roots of plants, ensuring they receive the right amount at the right time and place. Generally, precision irrigation improves irrigation efficiency, optimizes crop growth when compared to certain irrigation styles (i.e. flood, sprinkler) and minimizes water and nutrient loss.

Literature summary

Precision irrigation and input efficiency practices are included in EDF's vision to reduce CO_2 emissions from agriculture by 135 MMT by 2030 (Eagle et al., 2022). Precision irrigation tools like "digital controllers and remote monitoring" are helping optimize water application (EDF, 2023). Studies show that precision systems, particularly those integrating AI and IoT, can reduce water use by 20–40% and energy-related CO_2 emissions by up to 55–90% compared to conventional irrigation, especially where diesel or electric groundwater pumping is common (Gonzalez Perea et al., 2021; Qin et al., 2024). Additionally, automated, sensor-based irrigation helps sustain soil health and prevent nitrate leaching through more efficient nutrient delivery (Anjum et al., 2023; Lakhiar et al., 2024).

PRODUCT EXAMPLES

N-Drip: A low-pressure, gravity-fed drip irrigation kit that retrofits onto existing flood systems to deliver water and soluble nutrients directly to plant roots

Agrow Analytics: A cloud-based service that combines satellite and on-site sensor data with weather forecasts to generate field-specific irrigation guidance

SMART SENSING AND PRECISION ANALYTICS

PILOT

EARLY MARKET

COMMERCIAL

▶ **MARKET SCALE**

MATURE MARKET

MITIGATION

ADAPTION

▶ **HYBRID**

▶ **WHERE CLIMATE BENEFITS OCCUR:**

- Soil nutrient balance
- Plant nutrient uptake and use efficiency
- Irrigation water-use efficiency

▶ **ADOPTION BARRIERS:**

- Upfront cost
- Technical feasibility
- Farmer awareness or knowledge

Variable rate application and fertigation

This technology applies fertilizer at different rates across a field through an irrigation system based on specific location and field conditions.

Literature summary

Variable rate application and fertigation technologies significantly increase nitrogen and water use efficiency while reducing environmental externalities. EDF's climate roadmap includes fertigation as part of improved cropland nutrient management that reduces demand for synthetic fertilizer and upstream emissions (Eagle et al., 2022). Variable rate application, including drone and satellite-based fertilizer mapping, further supports these gains by accounting for field heterogeneity, reducing excess nitrogen inputs and limiting nitrogen leaching and nitrous oxide emissions (Sood et al., 2025; EDF, 2023). Together, these precision fertilization practices mitigate the carbon and nitrogen intensity of agricultural systems, although implementation remains constrained by infrastructure costs, technical complexity and uneven farmer adoption.

PRODUCT EXAMPLES

SoilOptix: A high-resolution soil-mapping tool that creates detailed layers of soil properties (nutrients, density, organic content) to inform variable-rate applications

EOS Data Analytics: A crop-monitoring platform that uses multi-spectral satellite imagery to visualize in-field variability and suggest variable-rate input zones

2.3 Agronomic data and measurement platforms

These solutions guide farmers through practice design, on-farm trials and carbon-credit participation — bridging the gap between technology potential and practical, system-wide adoption of climate-smart practices. They combine technical assistance, computational agroecology platforms and carbon-market facilitation into a cohesive service model.

AGRONOMIC DATA & MEASUREMENT PLATFORMS

PILOT

▶ **EARLY MARKET**

COMMERCIAL

MARKET SCALE

MATURE MARKET

▶ **MITIGATION**

ADAPTION

HYBRID

▶ **WHERE CLIMATE BENEFITS OCCUR:**

- Soil nutrient balance
- Soil organic carbon and biomass sequestration
- Non-CO_2 field emissions
- Water quality protection
- Yield stability and climate risk buffering
- Upstream/downstream supply chain emissions

▶ **ADOPTION BARRIERS:**

- Farmer awareness or knowledge
- Policy or regulatory uncertainty
- Time to realize benefits

Technical assistance for climate-smart agricultural practices

Technical assistance for climate-smart practices provides farmers with advisory support to implement holistic farming and grazing systems that enhance resilience and sustainability. This includes guidance from consultancy agencies, companies, individuals, or certified crop advisors to promote practical, on-farm adoption of climate-smart methods.

Literature summary

Technical assistance consultants are important intermediaries who support the adoption of agroecological diversification. While consultants are not the source of biophysical change, they help producers operationalize frameworks that have been associated with improved soil carbon sequestration, reduced nitrogen losses and enhanced plant and soil health (Rhodes, 2017; Schreefel et al., 2020; Newton et al., 2020). Literature also emphasizes that consultants can help farmers navigate complex transitions by integrating social, financial and technical knowledge into tailored on-farm strategies, thus enabling climate-smart transformations even amid uncertainty and institutional resistance (Anderson et al. 2020; Gosnell et al., 2020).

PRODUCT EXAMPLES

Continuum Ag: A soil-analytics service that combines lab data with on-farm sampling to generate carbon intensity scores and guide regenerative practice adoption

CIBO Technologies: An AI-powered platform that models farm-management practices to estimate supply-chain emissions and support regenerative ag programs

AGRONOMIC DATA & MEASUREMENT PLATFORMS

PILOT

EARLY MARKET

COMMERCIAL

▶ **MARKET SCALE**

MATURE MARKET

MITIGATION

ADAPTION

▶ **HYBRID**

▶ WHERE CLIMATE BENEFITS OCCUR:

- Soil nutrient balance
- Plant nutrient uptake & use efficiency
- Irrigation water-use efficiency
- Field operations efficiency
- Chemical-use intensity
- Soil organic carbon and biomass sequestration
- Non-CO_2 field emissions
- Water quality protection
- Yield stability and climate-risk buffering

▶ ADOPTION BARRIERS:

- Data infrastructure or digital literacy
- Technical feasibility
- Policy or regulatory uncertainty

Agronomics and computational agroecology

Agronomics and computational agroecology refer to the development and application of digitized, integrated land management systems that leverage data-driven computational models to optimize decision-making in agriculture. These systems combine agronomic science and advanced analytics to support adaptive management of farmland. Examples of typical use cases are crop assurance and prioritization, dynamic regulatory compliance and targeted input use.

Literature summary

Agronomics and computational agroecology offer promising frameworks to support the transition toward lower-emission food systems by bringing together predictive modeling technology and ecological/farm data to predict potential crop/farm system outcomes. Many company solutions also claim to provide data- ormodel-based advice on issues key to farm outcomes such as: crop prioritization, soil health deficiencies, dynamic fertilizer use across fields and more. While these systems do not themselves sequester carbon or reduce nitrogen losses, they enable the scaling and contextual application of agroecological principles — such as nutrient cycling, polyculture and input reduction — by integrating ecological modeling with farm-level data streams (Raghavan et al., 2016; Tonle et al., 2025). These approaches have been shown to support crop diversification strategies and resilient planting systems that may improve soil carbon retention and plant health (Meynard et al., 2003; Raghavan et al., 2016). At a high level, one key barrier to the implementation of predictive modeling technologies in agriculture is accurately representing system complexity across dimensions of difference: cropping systems, region, operational structures, ecological health. This poses a need for the study of data quality in building models, performance outcomes and reliability, and the implications of predictive modeling structures on long-term outcomes in agriculture.

PRODUCT EXAMPLES

Acclym: Models environmental and field data to analyze the effects of strategic decisions and monitor regulatory compliance and sustainability reporting

AgZen: Adjustable fertilizer spray systems that alter automatically using AI-driven analysis of conditions and crop

Climate FieldView: Technology to scout field and analyze data in real-time to build crop-prescriptions claiming to improve yield

Carbon market facilitators

Companies that enable farmers to participate in carbon markets provide the tools and infrastructure to translate on-farm sequestration activities into marketable credits. These providers offer end-to-end services — from designing field protocols and supplying monitoring hardware to integrating carbon accounting software and navigating registry requirements — so that growers can enroll in programs without shouldering the full burden of complex measurement, reporting and verification.

Literature summary

Enabling farmer participation in agricultural carbon programs presents a promising yet intricate opportunity for reducing GHG emissions and bolstering soil carbon storage. The USDA reports that voluntary carbon credits from agriculture and forestry projects rose to 7.9 million metric tons of CO_2-equivalent in 2022, although agriculture's share remains modest compared to forestry (USDA, 2023). Barriers such as complex quantification methods, high transaction costs and uncertain revenue streams constrain many growers from entering these markets. Service providers that lower entry hurdles through technical assistance, streamlined data collection and shared infrastructure can significantly expand farmer engagement; the long-term success of carbon markets hinges on improving credit integrity and reducing upfront costs for participants.

EDF has conducted and facilitated substantial research on both the protocols for soil carbon crediting (Oldfield et al. 2022) and the MMRV necessary for documenting changes in soil carbon and N_2O (Oldfield et al. 2024). The high uncertainty associated with both measurement (Even et al. 2025) and modeling (Lavallee et al. 2024) have resulted in EDF's decision to support further research to refine estimation but not to support a carbon market in soil-based GHG mitigation through adoption of conservation practices (e.g., cover crops, tillage) at this time (Eagle et al. 2022). We do support crediting where direct GHG emissions are reduced through farm operations (Eagle et al. 2022).

PRODUCT EXAMPLES

Regrow: A sustainability platform that uses remote sensing and modeling to help farms track greenhouse-gas emissions and participate in carbon-credit programs

Agricapture: A data-driven system that integrates satellite imagery and soil tests to measure and document on-farm carbon and methane changes for verified credits

AGRONOMIC DATA & MEASUREMENT PLATFORMS

PILOT
▶ **EARLY MARKET**
COMMERCIAL
MARKET SCALE
MATURE MARKET

▶ **MITIGATION**
ADAPTION
HYBRID

▶ **WHERE CLIMATE BENEFITS OCCUR:**

- Soil organic carbon and biomass sequestration
- Non-CO_2 field emissions
- Upstream/ downstream supply chain emissions
- Soil nutrient balance

▶ **ADOPTION BARRIERS:**

- Policy or regulatory uncertainty
- Upfront cost
- Technical feasibility

2.4 Biotech and genetic innovation

These approaches harness advanced biological tools — peptide- and pheromone-based biocontrols, CRISPR/Cas genome editing, trait discovery, crop-microbiome engineering and plant cell culture — to enhance crop resilience, nutrient efficiency and production of high-value compounds. They offer targeted, low-input alternatives to conventional pesticides and breeding methods.

BIOTECH AND GENETIC INNOVATION

PILOT
▶ **EARLY MARKET**
COMMERCIAL
MARKET SCALE
MATURE MARKET

▶ **MITIGATION**
ADAPTION
HYBRID

▶ **WHERE CLIMATE BENEFITS OCCUR:**
- Chemical-use intensity
- Soil nutrient balance
- Yield stability and climate risk buffering

▶ **ADOPTION BARRIERS:**
- Technical feasibility
- Farmer awareness or knowledge
- Market or supply chain access

Biological Pest Controls and Crop Protection

As introduced in Section 2.1, biocontrols are further detailed here. Biological pest controls and crop protection rely on natural organisms or substances — such as beneficial microbes, plant extracts, pheromones or insect-killing peptides— to manage agricultural pests, diseases and weeds. Crucially, only a fraction of pests currently have an effective, commercially available biocontrol; each agent works through highly specific biochemical or ecological interactions with its target species. Because of this precision, a biocontrol that suppresses one pest will not necessarily affect another and alternative management tactics remain necessary where no suitable biocontrol exists. When the match is right, however, these targeted solutions help preserve non-target beneficial organisms and slow the evolution of resistance relative to broad-spectrum chemical pesticides.

Literature summary

Biological pest-control strategies are widely supported in the literature for their potential to reduce pesticide reliance and mitigate environmental impacts. Compared to synthetic pesticides, these biological tools can enhance natural pest regulation without significantly harming beneficial organisms or contributing to chemical resistance (Bianchi et al., 2006). That said, only a subset of economically important pests currently have a well-matched, commercially viable biocontrol agent. This is because each organism or substance acts through highly specific biochemical or ecological pathways — a product effective against one target seldom works on even closely related species. Diversified landscapes and the use of microbial biocontrol agents are associated with increased pest suppression, lower crop damage and greater biodiversity — particularly in systems where habitat complexity supports predator-prey dynamics (Groen Kennisnet, 2020). However, challenges remain in ensuring consistent field performance and economic scalability, especially in regions or cropping systems where no suitable biocontrol has yet been developed, highlighting the need for region-specific deployment and better integration into whole-farm systems (Leontopoulos et al., 2020).

PRODUCT EXAMPLES

Vestaron: A line of peptide-based bioinsecticides inspired by spider venom, designed to target specific pests while being compatible with beneficial organisms

Provivi: A producer of pheromone-based pest disruption products formulated for large-scale crops to interfere with insect mating cycles

BIOTECH AND GENETIC INNOVATION

PILOT

▶ **EARLY MARKET**

COMMERCIAL

MARKET SCALE

MATURE MARKET

MITIGATION

▶ **ADAPTION**

HYBRID

▶ **WHERE CLIMATE BENEFITS OCCUR:**

- Plant nutrient uptake and use efficiency
- Non-CO_2 field emissions
- Yield stability and climate risk buffering

▶ **ADOPTION BARRIERS:**

- Policy or regulatory uncertainty
- Farmer awareness or knowledge

Seed genome editing, trait discovery and selection

Seed genome editing, trait discovery and selection refer to advanced biotechnological methods used to identify and precisely modify genetic traits in crops to enhance performance, resilience or nutritional value. These tools can accelerate specific trait selection traditionally accomplished by plant breeding, by using gene editing methodologies that target specific genes associated with desirable traits — such as pest resistance. Using gene editing to develop resilience and enhanced productivity under changing climate regimes is more difficult as multiple gene pathways require coordinated manipulation.

Literature summary

Seed genome editing, trait discovery and selection are increasingly important tools in improving the climate-resilience of crop species, enabling the precise modification of plant genomes to enhance traits such as drought tolerance, nitrogen-use efficiency and pest resistance. The literature highlights that CRISPR/Cas systems, applied across over 70 crop species, can offer targeted, efficient and increasingly transgene-free editing platforms (Timofejeva & Singh, 2023). Moreover, trait discovery from crop wild relatives (CWRs) provides a complementary strategy, especially under climate stress, with identified marker-trait associations supporting adaptation to heat and salinity stress in crops like wheat and lentils (Gupta & Bansal, 2023). Genomic methods such as GWAS and high-throughput sequencing have expanded the resolution and speed of trait mapping (Rasheed et al., 2017), while classical selection theory continues to underpin heritability estimates and long-term gains in breeding programs (Moeinizade et al., 2020).

PRODUCT EXAMPLES

CoverCress: A CRISPR-edited pennycress variety developed as a winter cash crop that integrates seamlessly into existing crop rotations

Moolec Science: A molecular farming company that inserts animal genes into plants to produce functional proteins (e.g., myoglobin) within crop seeds

BIOTECH AND GENETIC INNOVATION

PILOT
EARLY MARKET
▶ **COMMERCIAL**
MARKET SCALE
MATURE MARKET

MITIGATION
▶ **ADAPTION**
HYBRID

▶ **WHERE CLIMATE BENEFITS OCCUR:**

- Soil nutrient balance
- Plant nutrient uptake and use efficiency
- Non-CO_2 field emissions
- Soil organic carbon and biomass sequestration
- Yield stability and climate risk buffering

▶ **ADOPTION BARRIERS:**

- Technical feasibility
- Farmer awareness or knowledge
- Time to realize benefits

Crop microbiome engineering

Crop microbiome engineering refers to the intentional design, manipulation and application of microbial communities that live in and around plants to improve agricultural performance. This approach harnesses the natural interactions between microbes and crops to enhance nutrient availability, boost stress resilience, suppress pathogens and reduce reliance on synthetic inputs.

Literature summary

Crop microbiome engineering involves the strategic manipulation and application of beneficial microbial communities associated with plants — especially in the rhizosphere and endosphere — to enhance crop productivity, nutrient efficiency and stress tolerance. Evidence across the literature shows these microbes play pivotal roles in nitrogen fixation, phosphorus solubilization, disease suppression and mitigation of abiotic stresses such as drought and salinity, ultimately reducing dependence on synthetic inputs and lowering the carbon and nitrogen footprint of agriculture (Upadhayay et al., 2023; Singh et al., 2020). However, while microbial products are among the fastest-growing sectors in agricultural inputs, challenges such as inconsistent field performance, poor colonization and limited understanding of plant-microbe interactions under variable conditions persist and must be overcome for widespread adoption (Singh et al., 2020; Trivedi et al., 2024).

PRODUCT EXAMPLES

Quorum Bio: A synthetic-biology platform that engineers custom microbial strains to produce growth-promoting or protective compounds for crops

Ceragen: A developer of tailored microbial inoculants optimized for controlled-environment agriculture systems like hydroponics and vertical farms

Plant cell culturing

This method involves growing plant cells or tissues in controlled, sterile environments to produce high-value compounds or propagate clean planting material. It can produce substitutes for crop farmers and field-grown pharmaceuticals without the less water use and land requirements.

Literature summary

Plant cell culturing presents a transformative approach to agricultural production by significantly reducing nitrogen and carbon intensity through controlled, input-efficient systems. Evidence shows that plant cell culture techniques bypass traditional soil-based nitrogen application strategies and minimize greenhouse gas emissions by eliminating fertilizer overuse and land conversion pressures (Al-Harbi, 2019). Moreover, such systems offer year-round, resource-efficient outputs with reduced dependency on water and land — core contributors to agriculture's carbon footprint (Räty, 2017). While early-stage designs face scalability and public perception hurdles, the evidence converges on their strong potential to enhance soil and plant health resilience by decoupling high-value crop traits from variable agroecosystem stresses (Hocquette et al., 2024).

PRODUCT EXAMPLES

California Cultured: A fermentation-based approach that grows cocoa and coffee cells in bioreactors to create clean, land-efficient ingredients

Ayana Bio: A plant-cell culture service that produces botanical bioactives at scale in controlled bioreactors, bypassing traditional field cultivation

BIOTECH AND GENETIC INNOVATION

- PILOT
- EARLY MARKET
- ▶ **COMMERCIAL**
- MARKET SCALE
- MATURE MARKET

- ▶ **MITIGATION**
- ADAPTION
- HYBRID

▶ WHERE CLIMATE BENEFITS OCCUR:

- Upstream/downstream supply chain emissions
- Non-CO_2 field emissions
- Irrigation water-use efficiency
- Soil organic carbon and biomass sequestration
- Yield stability and climate risk buffering

▶ ADOPTION BARRIERS:

- Upfront cost
- Technical feasibility
- Market or supply chain access

2.5 Automation and machinery

These systems deploy AI-enabled robotics, autonomous tractors and unmanned aerial vehicles for tasks like weeding, spraying, seeding and harvesting. By precisely applying inputs and operating continuously with minimal labor, they reduce fuel use, compaction and chemical overuse — driving both productivity gains and emissions reductions.

AUTOMATION AND MACHINERY

PILOT
▶ **EARLY MARKET**
COMMERCIAL
MARKET SCALE
MATURE MARKET

▶ **MITIGATION**
ADAPTION
HYBRID

▶ **WHERE CLIMATE BENEFITS OCCUR:**

- Chemical-use intensity
- Field operations efficiency
- On-farm energy use and powertrain emissions
- Soil nutrient balance
- Yield stability and climate risk buffering

▶ **ADOPTION BARRIERS:**

- Upfront cost
- Technical feasibility
- Compatibility with existing systems

Crop protection weeding robotics and drones

Crop protection weeding robotics and agricultural drones leverage advanced AI, computer vision and precision spraying to identify, target and eliminate weeds or apply inputs with minimal chemical use and environmental impact. These autonomous or semi-autonomous systems can operate in real-time across varied field conditions, enabling data-driven, ultra-localized weed control and crop monitoring that significantly reduces herbicide application and promotes sustainable soil and ecosystem health. Robotics platforms typically perform mechanical or laser-based weeding, while aerial drones support early disease detection, crop scouting and variable-rate treatment to optimize overall input efficiency and crop outcomes.

Literature summary

Crop protection weeding robotics and drones demonstrably reduce agriculture's nitrogen and carbon intensity by enabling ultra-precise weed targeting and minimizing input overuse. Robotic and UAV-based systems can decrease herbicide application by up to 85%, while maintaining weed removal rates of 90–94.5%, and limiting crop damage to under 2%, significantly lowering life-cycle chemical input intensity and reducing greenhouse gas emissions associated with blanket spraying and tillage (Jiang et al., 2023; Upadhyay et al., 2024). Deep learning, real-time kinematic GPS and sensor fusion technologies underpin high-accuracy crop–weed discrimination and autonomous navigation, helping mitigate the spread of herbicide-resistant weed biotypes and promoting ecosystem resilience (Pandey et al., 2021; Lytridis and Pachidis, 2024). While the literature agrees on strong sustainability gains, adoption remains constrained by technological, economic and infrastructural barriers, including high upfront costs, limited interoperability with legacy systems and the need for farmer training and supportive regulation (Vijayakumar et al., 2025).

PRODUCT EXAMPLES

Carbon Robotics: A robotic weeder that pairs machine-vision with laser technology to autonomously identify and eliminate individual weeds

Verdant Robotics: An autonomous platform using real-time computer vision to target weeding, thinning and spot-applications of inputs within crop rows

AUTOMATION AND MACHINERY

- PILOT
- ▶ **EARLY MARKET**
- COMMERCIAL
- MARKET SCALE
- MATURE MARKET

- ▶ **MITIGATION**
- ADAPTION
- HYBRID

WHERE CLIMATE BENEFITS OCCUR:

- On-farm energy use and powertrain emissions
- Field operations efficiency
- Soil nutrient balance
- Chemical-use intensity
- Yield stability and climate-risk buffering

ADOPTION BARRIERS:

- Upfront cost
- Technical feasibility
- Compatibility with existing systems

Autonomous tractors and farm machinery

Autonomous tractors and farm machinery integrate AI, GPS-based navigation and sensor fusion to perform tasks such as seeding, spraying, mowing, tillage and harvesting with minimal or no human intervention. These systems enhance operational efficiency by enabling 24/7 fieldwork, reducing labor dependency and optimizing input use through real-time environmental data and precision control. Designed for interoperability and scalability, they support sustainable farming by minimizing fuel use, compaction and over-application of agrochemicals while enabling consistent, data-rich operations across diverse cropping systems.

Literature summary

Autonomous tractors and farm machinery can significantly reduce agriculture's carbon and nitrogen intensity by enhancing input precision, lowering diesel use and mitigating soil compaction. Electric autonomous tractors offer emissions reductions and lower operating costs by cutting fuel use and minimizing soil compaction, while addressing labor challenges (Environmental Defense Fund, 2023). These systems enable around-the-clock operation and improve efficiency in spraying, mowing and seeding by integrating GPS-guided autonomy, obstacle detection and task scheduling, as demonstrated in large-scale citrus orchard trials covering over 3,700 acres (Moorehead et al., 2011). Widespread adoption faces barriers including equipment interoperability, complex field conditions and the need for reliable AI-based perception and control systems (Shockley et al., 2021; Qu et al., 2024; Kutter et al., 2018). More research is needed to measure the ecological and farm-system outcomes of autonomous farm machinery over the medium- to long-term use. Most evidence of emissions reduction potential is presently associational and has not yet been addressed through peer-reviewed study.

PRODUCT EXAMPLES

Monarch Tractor: An all-electric, software-enabled tractor that can operate with or without a driver and integrates telematics for remote fleet management

Gridtractor: A charging-and-electrification service for farm vehicles that enables vehicle-to-grid energy management and infrastructure leasing

3. APPENDIX FOR TAGS

3.1 Market readiness

Market readiness is a marker of "relative maturity" based on the sum of fundraising rounds for each company in that category. If a category has raised much higher funding rounds, it also means that they are raising debt. Debt issuers have a lower risk tolerance, associating higher funding rounds with more secure market maturity as raising debt brings certain validation to standardized product-market fit.

Categorical variables key definitions

Research	**Initial R&D and proof of concept**
Pilot	Small-scale testing with early adopters or trial partner
Early market	Limited release, often targeting niche or visionary customers
Commercial	Broad release with a viable business model and revenue generation
Market scale	Rapid growth, infrastructure investment and mainstream adoption
Mature market	Saturation, stable demand and slower growth; high competition

Source: EDF Row Crop N-efficiency Innovations – JWEITZ Climate Tech Solutions Map 2024, Jonathan Weitz, 2024.

3.2 Climate impact: mitigation, adaptation or hybrid

On 20 March 2023, IPCC released AR6 Climate Change 2023: Synthesis Report to inform the 2023 Global Stocktake under the United Nations Framework Convention on Climate Change.

The AR6 report represents the most current, globally recognized synthesis of scientific understanding, offering internationally acknowledged definitions of adaptation and mitigation within the context of climate change and multilateral scientific cooperation. Each innovation outlined in the current report is categorized as either:

Adaptation

"Adaptation. In human systems, the process of adjustment to actual or expected climate and its effects, in order to moderate harm or exploit beneficial opportunities. In natural systems, the process of adjustment to actual climate and its effects; human intervention may facilitate or obstruct adjustment to expected climate and its effects. See also: Adaptation options, Adaptive capacity, Maladaptive actions (Maladaption)." Intergovernmental Panel on Climate Change. (2023). Annexes and index (page 120)

Mitigation

"Mitigation (of climate change). A human intervention to reduce emissions or enhance the sinks of greenhouse gases." Intergovernmental Panel on Climate Change. (2023). Annexes and index (page 126).

Hybrid

Assigned to innovations exemplifying implementation that falls simultaneously into categories of adaptation and mitigation.

3.3 Where climate benefit occurs

Categorical variables — key definitions and examples

Soil nutrient balance	Practices and technologies that keep nitrogen and other nutrients in the root zone and in plant/soil pools to cut nitrous oxide formation and nutrient losses — optimizing rate, source, timing and placement of nutrients to reduce emissions (IPCC; Shcherbak 2014; Abalos 2014; Lei 2022)	Examples: Next-gen fertilizers (enhance efficiency fertilizers, coated urea); AI-guided variable-rate N; biologicals with controlled mobilization of nitrogen/phosphorous; nutrient rate control to avoid overlap/overapplication
Plant nutrient uptake and use efficiency	Innovations that increase crop uptake and utilization efficiency of nutrients, thereby lowering fertilizer needs and loss pathways (Sathee 2022; Schütz 2018)	Examples: phosphorous-solubilizing microbes; inoculants/biostimulants; AI that detects in-season deficiency and prescribes sidedress
Irrigation water-use efficiency	Sensor/ET/AI-driven scheduling and efficient application methods reduce water applied per unit yield and cut energy for pumping. Controlled scheduling repeatedly saves water with neutral/positive yield effects (Qin & Dian 2024; Datta 2022; Song 2022)	Examples: AI irrigation advisors; soil moisture/ET controllers; micro-irrigation with pressure management; variable-frequency drives on pumps
On-farm energy use and powertrain emissions	Shifting field operations to more efficient/hybrid/electric drivetrains and optimizing duty cycles reduces fuel use and life-cycle GHG (dependent on grid mix and duty). LCAs and reviews show potential GWP reductions for battery-electric/hybrid vs diesel systems (Lagnelöv 2021; Wei 2024; Fargnoli 2024)	Examples: Battery-electric tractors (small/medium class); hybrid tractors; autonomy that optimizes implement load; smart route planning to cut idle/overlap
Field operations efficiency	Pass and overlap reduction. Digital/precision tools that lower the number of passes, eliminate overlap, and tighten spatial targeting reduce fuel, input use, and associated emissions while maintaining output. Evidence shows context-dependent environmental gains (Wolfert 2017; Bahmutsky 2024)	Examples: Section control on sprayers/planters; AI path planning; controlled traffic/autonomous swarms with smaller implements
Chemical-use intensity	Herbicide/pesticide load. Targeted (site-specific) detection and treatment, as with machine-vision weeding or precision spot-spray, reduces total active ingredient applied for equivalent control, lowering embodied and drift-related impacts; Substantial herbicide savings reported (Gerhards 2022; Sapkota 2023)	Examples: AI robotic weeders (mechanical/laser); camera-guided inter-row cultivators; spot-spray booms ("see-and-spray")

Soil organic carbon and biomass sequestration	Practices that increase soil organic matter and stabilize carbon (e.g. residue retention, diverse rotations, reduced disturbance, living roots) deliver mitigation and co-benefits for water holding and nutrient cycling, per NRCS soil-heath principles and IPCC AFOLU (USDA NRCS 2021; IPCC 2022)	Examples: Cover-crop-aware planting algorithms; biologicals that boost root biomass; reduced-tillage compatible robotics
Non-CO_2 field emissions	N_2O/CH_4 hotspots. Interventions that suppress biophysical pathways of N_2O (nitrification/denitrification) or CH_4 (anaerobic micro-zones) at the field scale, through nitrogen management, soil aeration, and water control directly reduce potent GHGs. Evidence characterizes nitrogen response curves and inhibitor efficacy. (Shcherbak 2014; Lei 2022)	Examples: Behavior change tools, monitoring systems, or avoided emissions enabled by the product
Water quality protection	Runoff/leaching/eutrophication. Actions that cut nutrient and sediment export to waterways (optimizing N/P rates and timing, keeping soils covered, targeting applications) protect water quality; agriculture is a dominant driver of eutrophication, and soil-health practices reduce nutrient loading (Ritchie 2022; USDA NRCS 2013)	Examples: Variable-rate nutrient maps; edge-of-field buffers paired with precision inputs; AI alerts for rainfall-risk timing
Upstream/ downstream supply chain emissions	Adjacency. While farm-gate dominates for many commodities, upstream (fertilizer manufacture, input transport) and downstream logistics can be material in LCAs for certain systems; tracking these clarifies where innovations (e.g., reduced fertilizer intensity) yield indirect GHG cuts (Fan 2022; Menegat 2022)	Examples: Lower-N input footprints via NUE gains; localized input sourcing; electrified short-haul; on-farm logistics
Yield stability and climate-risk buffering	Enabling. Innovations that stabilize yields across climate variability (drought/heat/flood tolerant genetics; smarter water/nutrient timing) support adaptation and can enable mitigation per unit output. Resilience is emphasized alongside mitigation gains aligned with productivity (FAO 2013; IPCC 2022)	Drought-tolerant seeds microbiome; AI early-warning and dynamic prescriptions; resilient rotations paired with precision inputs

3.4 Adoption barriers

To better understand the factors that influence the real-world deployment of climate-smart agricultural innovations, this report includes a standardized framework for identifying adoption barriers. These barriers are categorized using a set of predefined, reusable tags based on common constraints found across peer-reviewed literature, practitioner interviews and policy frameworks. For each innovation analyzed, the three most pertinent, pressing and measurable relevant barrier categories are assigned based on its functional design, environmental context and evidence from adoption studies. This taxonomy is intended to support cross-innovation comparisons, highlight systemic bottlenecks and inform program design, as well as policy development and investment strategies to increase innovation uptake.

Adoption barrier category definitions

Upfront cost	Refers to the initial capital investment required for purchase, installation, or infrastructure development. High upfront costs may deter adoption, particularly for smallholders or operations with thin margins
Technical feasibility	Covers operational complexity, system reliability, or contextual limitations in how the technology functions under different farming conditions. Barriers in this category often relate to fragility, maintenance demands, or inconsistent performance in varied environments
Farmer awareness or knowledge	Describes the extent to which farmers are informed about the innovation, understand how to use it effectively, or trust its agronomic value. Limited awareness, misinformation, or lack of extension services may hinder adoption
Labor disruption	Captures whether the innovation replaces, displaces, or demands significant changes in labor routines. Technologies that automate or shift roles may create friction due to job concerns, retraining needs, or changes in seasonal labor flows
Compatibility with existing systems	Assesses how easily the innovation can be integrated into current farming practices, machinery, cropping systems, or supply chains. Low compatibility often results in added friction, retrofit costs, or management complexity
Policy or regulatory uncertainty / misalignment	Encompasses the absence of clear incentives, compliance requirements, or supportive policy environments that would encourage adoption. Uncertainty or misalignment with subsidy programs, environmental regulations, or standards can suppress uptake
Biophysical constraints (e.g., climate, soil, topography)	Includes environmental limitations like soil type, rainfall variability, temperature extremes, or topography that reduce the suitability or effectiveness of the innovation in certain regions; Regardless of whether characteristics have been modified by human activities (e.g., constructed drainage, leveled fields)

Market or supply chain access	Describes logistical or economic challenges in obtaining inputs for innovation or accessing markets where outputs can be sold at a premium. This barrier is particularly relevant when adoption depends on supply-side infrastructure or buyer incentives
Data infrastructure or digital literacy	Relevant to tech-enabled innovations, this barrier captures challenges related to internet access, device availability, platform usability, or users' comfort with digital tools and data interpretation
Time to realize benefits	Reflects the lag between adoption and tangible returns such as yield improvement, cost savings, or environmental performance. Long payback periods may reduce adoption, especially under short-term financial pressure

Barriers adapted from:

(OECD, Wreford, A., A. Ignaciuk and G. Gruère, 2017), (MDPI, Barbosa Junior, M et al, 2022)