Nurturing Crops, Enhancing Soil Health, and Sustaining Agricultural Prosperity Worldwide through Agronomy

Abstract

Agronomy is the science and technology of crop and soil management for producing food, fiber, feed, and fuel. As the global population continues to rise, agronomy will play an increasingly vital role in meeting escalating food demands while sustaining natural resources. This review highlights major advancements in agronomic research and practice that enhance crop yields, soil health, and agricultural sustainability worldwide. Key topics include plant breeding for improved crop varieties, optimized plant nutrition and soil fertility management, efficient water management, integrated pest management (IPM), conservation agriculture techniques, precision agriculture technologies, and climate-smart farming approaches. Modern agronomy strategies such as drought-tolerant cultivars, micro-irrigation, reduced tillage systems, site-specific input applications, and integrated cropping systems can significantly improve productivity and resilience. However, continued innovation and diffusion of agronomic knowledge is crucial to nourish growing populations while protecting environmental quality. Collaborative efforts among researchers, educators, policy makers, and farmers will be imperative to apply advanced yet context-specific agronomic solutions that sustain agricultural prosperity into the future.

Keywords: plant breeding, soil fertility, irrigation, IPM, conservation agriculture, precision agriculture, climate-smart agriculture

Introduction

The global population is projected to reach 10 billion by 2050, with much of the growth concentrated in developing regions [1]. Meeting future food demands in an environmentally and economically sustainable manner is one of the most formidable challenges facing humanity. Agronomy, the science and practice of field crop production and soil management, will play a pivotal role in producing more food, feed, fiber and fuel while maintaining natural resources [2]. Advances in agronomic research and technologies over the past century have significantly enhanced agricultural productivity. However, continued innovation and knowledge dissemination will be critical to nourish the world’s growing population under increasingly variable climate conditions. This review summarizes major advancements and future priorities across diverse agronomic strategies that can synergistically improve crop yields, soil health, resource efficiency, economic viability, and environmental stewardship in agricultural systems worldwide.

Improving Crop Genetics through Plant Breeding

Plant breeding has been essential for improving agronomic crop traits such as yield potential, growth duration, grain/fruit quality, pest resistance, and tolerance to environmental stresses [3]. Conventional breeding approaches rely on creating genetic variability through cross-hybridization and selection of superior performing progeny lines. Traditional landraces and crop wild relatives serve as important genetic resources for introducing useful diversity into breeding programs. Key targets in developing improved crop cultivars include:

- **Yield potential** – Increasing productivity per unit area and time via traits enhancing photosynthetic efficiency, growth duration, and harvest index [4].

- **Quality** – Enhancing nutrition and market values through higher protein, micronutrients, oil content, taste, and processing qualities [5].
- **Pest resistance** – Reducing yield losses from insect pests, pathogens, and weeds through genetic resistance [6].
- **Abiotic stress tolerance** – Improving yield stability under drought, flooding, heat, cold, and saline conditions through morpho-physiological adaptations [7].
- **Mechanization suitability** – Modifying plant architectures for compatibility with mechanical sowing, harvesting, and processing [8].

Table 1. Conventional breeding achievements in major crops

Crop	**Trait Improved**	**Breeding Impact**
Rice	Yield, insect resistance, salinity tolerance, grain quality	40-60% yield increase in tropical Asia since 1960s [9]
Wheat	Rust resistance, heat tolerance, dwarfing, quality	Avoidance of epidemics; doubling of global yield since 1950s [10]
Maize	Yield, pest resistance, nitrogen use efficiency	Average US yields tripled between 1940-2010 [11]
Potato	Yield, pest/disease resistance, drought tolerance	50% increase in developing world yields in past 30 years [12]
Cassava	Yield, disease resistance, vitamin A content	Up to five-fold yield increases in Sub-Saharan Africa [13]
Tomato	Shelf-life, color, flavor, pest/disease resistance	Significant improvements in storage ability, appearance, and adaptability to humid tropics [14]

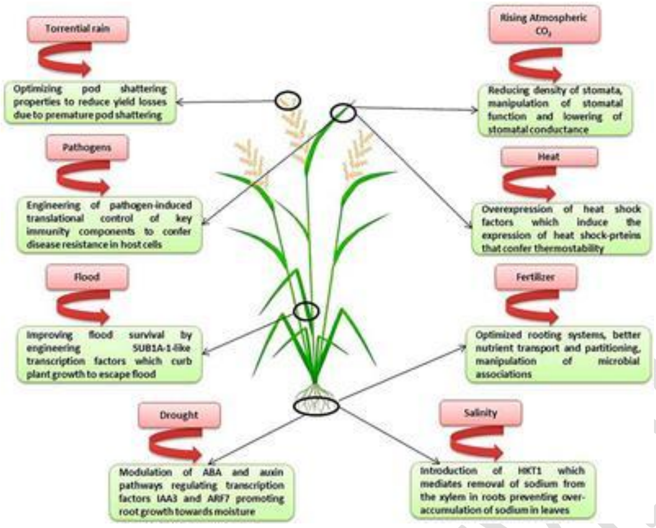

Figure 1. Conventional breeding process for developing improved crop varieties

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The Green Revolution of the mid-20th century that staved off famine in Asia and parts of Latin America resulted predominantly from semi-dwarf, fertilizer responsive wheat and rice varieties [15]. Modern breakthroughs include hybrid pigeonpea that tripled yield potential in India [16], Sub1 rice tolerant of prolonged flooding in Asia [17], and drought-tolerant maize for Africa [18]. Transgenic (genetically modified) crops enhanced with genes from other species provide a complementary approach to overcoming constraints for which natural genetic diversity is lacking, such as herbicide tolerance in soybean, insect resistance in cotton and maize, virus resistance in cassava, and vitamin fortification in rice [19]. However, high regulatory costs have often restricted adoption of transgenic crops to large commercial farms. Developing nutritionally enriched and stress resilient crop varieties amenable to sustainable, smallholder production systems remains a major priority worldwide. Continued genetic improvement through plant breeding ~~will be~~have vital for raising the yield ceiling across locations and farming systems while also enhancing product quality.

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Optimizing Soil Health and Fertility

The health and fertility of agricultural soils is foundational to crop productivity as soils supply vital nutrients, water, oxygen, and physical support to plants [20]. Depletion of organic matter and nutrients is a serious threat that diminishes soil quality and long-term productivity. Key recommendations for maintaining or enhancing soil health include:

- **Organic matter additions** – Applying manures, composts, crop residues, and green manures to replenish organic matter critical for fertility and soil structure [21].
- **Balanced fertilization** – Ensuring optimal and balanced application of nitrogen, phosphorus, potassium and other essential nutrients to meet crop needs [22].
- **Reduced tillage** – Minimizing mechanical disturbance to preserve organic matter, structure, and biodiversity of the soil food web [23].

- **Cover crops** – Growing non-cash crops to protect soil from erosion, fix nitrogen, suppress weeds, and scavenge nutrients between cropping periods [24].
- **Crop rotations** – Rotating cereals with legumes improves nitrogen fixation and breaks pest cycles [25].
- **Soil testing** – Routine analysis of soil chemical and physical properties guides appropriate amendments and fertilizer requirements [26].

Table 2. Recommended integrated soil fertility management practices

Practice	**Purpose**	**Benefits**
Farmyard manure	Organic matter addition	↑ soil fertility, water holding, structure
Compost	Organic matter addition	↑ drainage, aeration, microbial activity
Green manures	Nitrogen provision	↑ soil N, prevents erosion
Crop residues	Erosion control, organic matter	↑ water infiltration, nutrients
Vermicompost	Organic fertilizer	↑ plant growth, yield
Legume rotation	Biological N fixation	↑ soil N, break pest cycles
Balanced fertilizer	Essential plant nutrients	↑ crop yield, quality
Liming	Raise pH	Unlock bound nutrients
Biofertilizers	Nitrogen provision	↓ synthetic N fertilizer

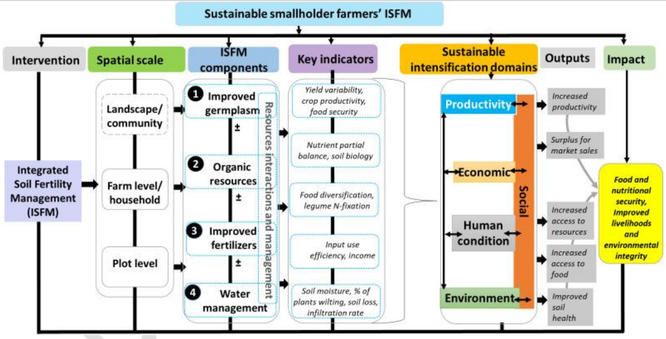

Figure 2. Impacts of balanced integrated soil fertility management on crop yields

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Knowledge-intensive systems integrating organic and inorganic inputs tailored to soil conditions can sustain long-term fertility and stable crop productivity [27,28]. For instance, combining judicious mineral fertilizer use with manures, composts, and legume rotations has repeatedly boosted crop yields across sub-Saharan Africa and South Asia [29-31]. Educating farmers on soil science principles and location-specific best management practices is instrumental to fostering good stewardship of the soil.

Efficient Irrigation Methods

Irrigation has been fundamental to enhancing and stabilizing agricultural productivity across arid and semi-arid environments that constitute over 40% of the world's land area [32]. However, conserving limited freshwater resources is imperative. Adoption of precision irrigation methods can significantly improve crop water use efficiency. Recommended approaches include [33,34]:

- **Drip irrigation** - Frequent water application in small amounts directly at the plant root zone via perforated tubing. Can reduce water use >50% and boost yields by 20-90%.
- **Alternate wetting and drying (AWD)** - Allowing rice fields to dry for short periods before re-flooding reduces water needs 25-30% with similar yields.
- **Sprinkler irrigation** – Distributing water via overhead sprinkler systems suited for many row crops and orchards if wind drift is limited.
- **Surge flow irrigation** – Intermittently applying water down furrows in pulses can decrease usage 15-30%.
- **Subsurface irrigation** - Raising groundwater tables near plant root zones then allowing downward percolation. Low labor and reduced evaporation.
- **Computerized systems** – Automated irrigation based on plant needs and environmental conditions optimizes water productivity.

While more knowledge-intensive, precision irrigation systems greatly improve the plant-availability of applied water compared to traditional field flooding. Maximizing crop yield per unit of water consumed ~~will be~~ were critical for sustainably intensifying production on existing irrigated land. However, improved water harvesting and small-scale irrigation technologies also hold promise for expanding agriculture into areas with limited rainfall [35]. Overall, disseminating context-specific irrigation best practices can significantly increase water productivity in agriculture.

Employing Integrated Pest Management

Pest pressures severely constrain crop productivity worldwide by inflicting yield losses up to 40% [36]. Integrated pest management (IPM) provides an ecologically-based framework to cost-effectively manage insects, plant pathogens, and weeds using complementary tactics [37]:

- **Prevention** – Selecting resistant varieties, crop sanitation, and cultural practices that deter pests.
- **Monitoring** – Regular field scouting and economic thresholds to guide need-based application.
- **Control methods** – Deployment of biological, physical, and reduced-risk chemical controls in a combined manner that minimizes selection for resistance.

Table 3. Examples of IPM techniques for major crop pest groups

Pest Group	IPM Methods

Pest Group	**IPM Methods**
Insects	Resistant varieties, biological control agents, sex pheromones, Bt crops, biorational pesticides
Plant pathogens	Resistant varieties, seed treatments, forecasting models, sanitation, low fungicide doses
Weeds	Competitive crop cultivars, mulching, cover crops, row spacing, mechanical cultivation, targeted herbicide application

IPM increases pest regulation from natural enemies, mitigating the need for pesticide inputs. Economic analyses consistently demonstrate higher returns from IPM relative to conventional pest control [38]. However, IPM remains underutilized globally, often due to inadequate farmer training and barriers accessing biological control agents or non-chemical technologies [39]. Strengthening farmer knowledge of agroecological pest management coupled with greater availability of IPM inputs could significantly reduce reliance on hazardous pesticides that pose risks to human health and the environment [40].

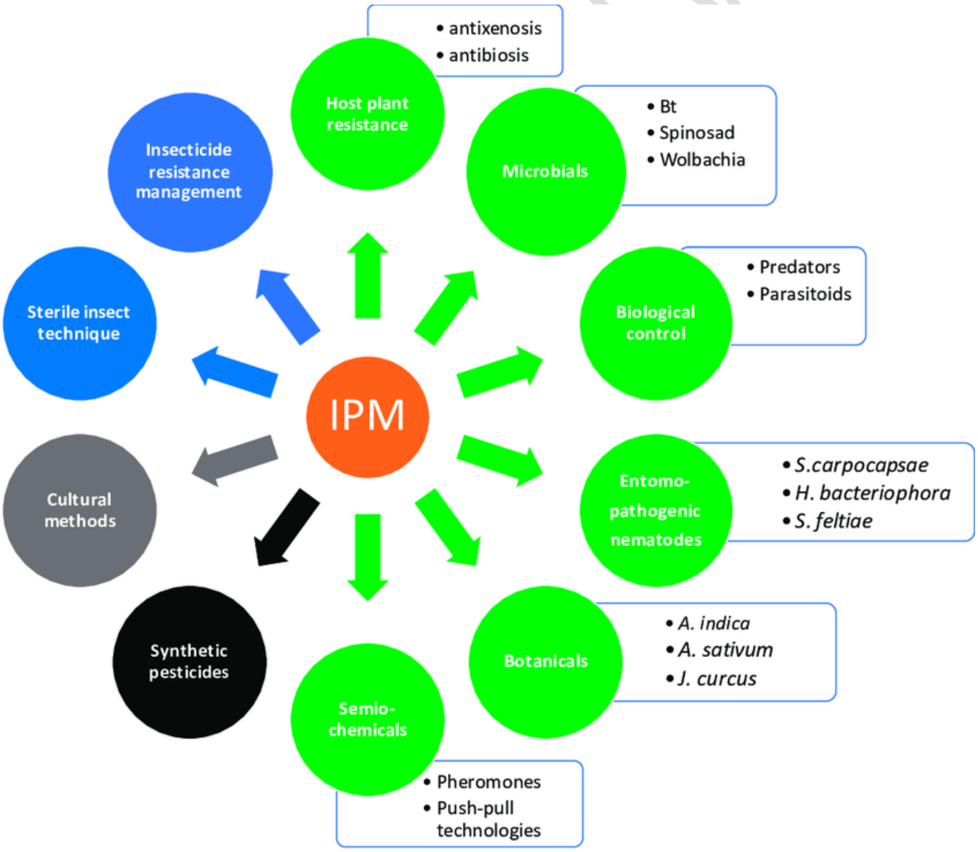

Figure 3. Potential for integrated pest management

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Implementing Conservation Agriculture

Conservation agriculture aims to prevent soil erosion, conserve soil moisture, enhance biodiversity, and stabilize crop yields through three linked principles [41]:

1. Continuous no-tillage – Avoiding ploughing and retaining crop residues on the surface
2. Permanent soil cover – Cover crops, mulches, and perennial plant mixes
3. Crop rotations – Temporal and spatial diversification of crops

The combination of reduced mechanical disturbance and permanent ground cover under conservation agriculture facilitates soil organic matter accumulation, water infiltration, and balanced soil biological activity [42]. No-tillage specifically decreases erosion over 90% compared to conventional tillage [43]. Benefits of conservation agriculture are most pronounced in dryland production contexts, including 30-100% yield increases under drought stress [44]. Conservation agriculture has been adopted across >180 million hectares globally, predominantly in North and South America as well as Australia [45]. Widespread implementation in Asia and Africa has been constrained by limited herbicide availability, weed control challenges, retention of crop residues for livestock, and lack of appropriate equipment for small farms [46]. However, reduced tillage techniques tailored to local constraints show considerable promise for enhancing sustainability across diverse smallholder systems [47].

Table 4. Principles and impacts of conservation agriculture practices

Principle	**Practice**	**Benefits**
No-tillage	Direct seeding without ploughing	↓ soil erosion, compaction; ↑ organic matter, infiltration
Permanent soil cover	Cover crops, crop residue retention	↓ evaporation; ↑ biodiversity, nutrient cycling
Crop rotation	Temporal and spatial diversification	↓ pests and diseases; ↑ soil N, yields

Figure 4. Global expansion of conservation agriculture systems

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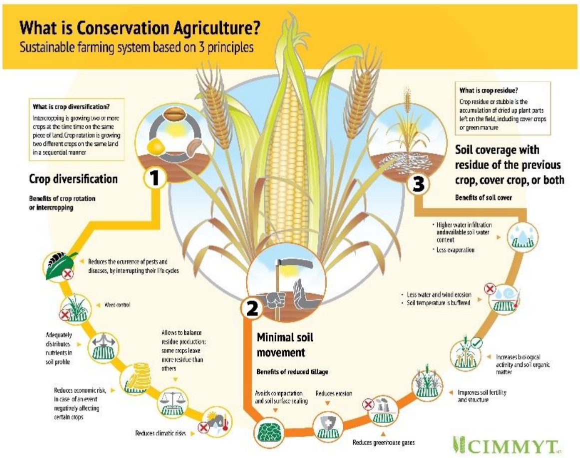


Widespread dissemination of conservation agriculture knowledge and technologies adapted to smallholder contexts can play a major role in sustainably intensifying productivity while strengthening resilience to climate change across the developing world [48].

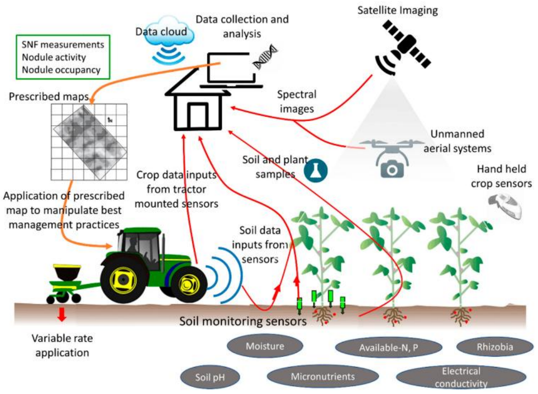
Employing Precision Agriculture Technologies

Precision agriculture aims to optimize field-level management by accounting for in-field spatial and temporal variability through information technology [49]. Major technologies include:

- **Guidance systems** – GPS-enabled tractor/implement guidance allows efficient operations and controlled traffic patterns to avoid soil compaction.
- **Variable rate application** - Matching application rates of seed, fertilizers, and chemicals to needs within sub-field zones enhances efficiency.
- **Distance and remote sensing** – Proximal (ground-based) and remote sensing informs variable rate application and detects crop stress.
- **Automated equipment** – Robotic systems for pruning, weeding, spraying, and harvesting reduce labor and improve timeliness.
- **Decision support tools** – Information systems assist real-time operational decision making and farm planning.

Adoption surveys show precision agriculture technologies are mainly utilized by large, mechanized farms in North America, Europe, and Australia currently [50]. However, applications suited for smallholder systems are expanding, including handheld nutrient sensors, micro-dosing of fertilizers, and farm management apps [51]. Most practices increase input use efficiency over uniform application, with returns on investment averaging $3-$20 for each $1 invested [52]. Barriers such as upfront costs, technical skills, maintenance, and unreliable electricity constrain broader uptake and require innovative business models for delivering precision services to smallholders [53]. Overall, precision agriculture tools have substantial yet under-realized potential to enhance crop productivity, profitability, and environmental performance across diverse farm sizes and geographies.

Figure 5. Potential for precision nutrient management to increase nitrogen use efficiency on smallholder farms



Adopting Climate-Smart Agriculture

Climate-smart agriculture integrates management practices that sustainably improve productivity and farmers’ adaptive capacity while reducing agricultural greenhouse gas emissions [54]. Major practices include:

- **Stress-tolerant varieties** – Cultivars with enhanced heat, drought, or flood tolerance confer yield stability under variable conditions.
- **Efficient irrigation** – As discussed previously, precision irrigation preserves freshwater supplies and expands production.
- **Integrated nutrient management** – Balancing organic and inorganic nutrient sources enhances soil health and resilience.
- **Conservation tillage** – Reduced disturbance increases soil organic matter, rainwater retention, and carbon sequestration.
- **Diversified agroforestry** – Strategic integration of trees and shrubs bolsters resilience through microclimate regulation, soil conservation, and product diversification.

Table 5. Examples of climate-smart practices for mitigation and adaptation

Climate Impact	**Mitigation Practice**	**Adaptation Practice**
Increasing CO_2	Conservation tillage	Heat tolerant varieties
Rising temperatures	Reduced methane rice	Short-duration cultivars
Altered precipitation	Agroforestry	Water harvesting, micro-irrigation
Extreme events	Integrated pest management	Stress resilient varieties

Widespread implementation of climate-smart agriculture across contexts is estimated to have global mitigation potential of 5.5-6.0 Gt CO_2-eq year−1 by 2030, representing over 15% of total agriculture and land-use change emissions [55]. Realizing this potential requires

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extensive investment in research and incentives to evaluate context-specific portfolios of climate-smart practices. Partnerships among researchers, extension agents, communities, and policy makers will be critical for accelerating climate adaptation and building resilient food systems worldwide.

Figure 6. Potential for climate-smart agriculture adoption to increase yields and resilience

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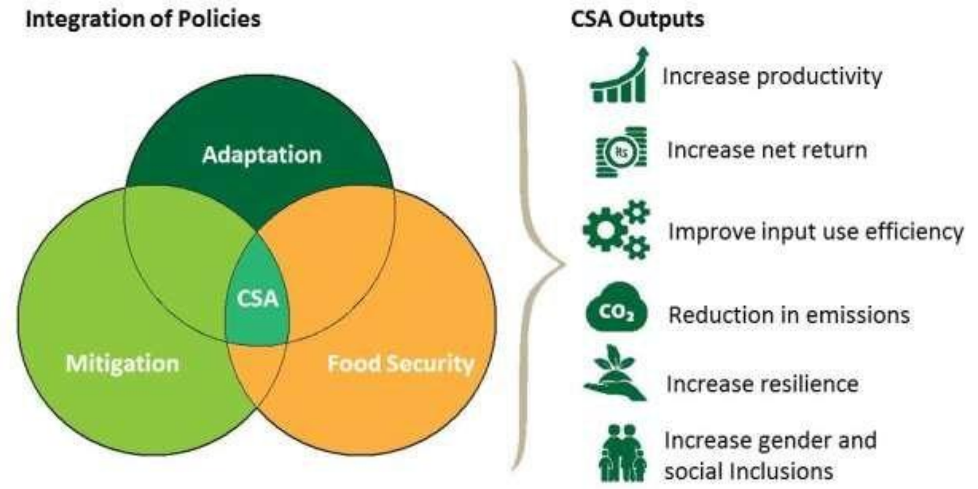

Moving Forward: Priorities and Prospects

In coming decades, agronomic innovations must ~~center~~centre on sustainably meeting escalating food demands while regenerating natural resources. Continued genetic improvement of major staple crops will be imperative, with emphasis on conservation breeding approaches that tap locally-adapted varieties to enhance nutritional quality and stress resilience [56]. Replicating conservation agriculture successes from larger farms across smallholder systems can support sustainable intensification [57]. Scaling proven IPM tactics through farmer field schools also holds enormous potential to reduce reliance on hazardous pesticides [58]. Emerging precision technologies should prioritize increasing access for smallholder farmers to catalyze widespread benefits.

Results

Agronomy encompasses the scientific principles for efficient crop and soil management supporting sustainable agriculture worldwide. Advances across agronomic research domains including plant-soil interactions, cropping systems, crop physiology, breeding, biotechnology and more enable agricultural productivity gains while protecting environmental quality.

Optimizing Plant Nutrition

Proper plant mineral nutrition is key to achieve genetic yield potentials. Site-specific nutrient management (SSNM) guidelines tailor fertilizer rates to soil properties and yield goals, enhancing uptake efficiency (58). Dynamic SSNM models integrate soil test data, crop needs and real-time plant signals for improved N recommendations (59). Controlled release fertilizers including polymer-coated, OMXC and IBDU formulations minimize nutrient losses while synchronizing supply to crop demand (60-62).

In acidic tropical soils, Limy fertilizers containing calcium and magnesium carbonates restore soil pH for better nutrient availability besides providing essential cations (63). Seed priming techniques enhance nutrient absorption and early vigor in crops including wheat, rice and maize leading to higher yields (64-66). Stimulating beneficial plant-microbe associations through mycorrhizal fungi or microbial amendments enhances nutrient acquisition, stress resilience and yields (67-69). Such integrated soil fertility management approaches optimize crop nutrition for sustainable intensification.

Micronutrients are equally vital for plant growth and yield formation. Foliar application of micronutrients offers a rapid means of deficiency correction and higher yields compared to soil application in crops such as wheat, rice, maize, soybean and cotton (70-74). However, effectiveness depends on nutrient source, concentration, adjuvants, timing, environmental conditions and genotype (75). Site-specific micronutrient management incorporating soil-plant testing, mapping and fertilizer amendments increases yields by 15-30% in India, China, Thailand and Pakistan (76,77). Breeding crop cultivars efficient at acquiring micronutrients addresses deficiencies through genetic enhancement (78).

Managing Soil Constraints

Alleviating soil physical, chemical and biological constraints is key to sustainable crop production. Gypsum and biosolids application to sodic and saline-sodic soils improves soil structure and hydraulic conductivity while displacing sodium ions to support crop growth (79,80). Raised beds enhance root zone drainage and aeration for higher yields in puddled rice soils (81). Minimum tillage practices conserve soil structure and moisture while reducing compaction issues compared to intensive ~~plow~~plough-based methods (82). Controlled traffic confinement systems minimize soil compaction damage from heavy machinery while enabling efficient field operations (83).

Biochar and organic amendments mitigate soil acidity while increasing cation exchange capacity to improve nutrient retention and availability in highly weathered soils (84,85). Elemental sulfur rapidly corrects alkalinity problems impeding crop growth in calcareous soils while oxidizing to sulfuric acid (86). Bioremediation hastens degradation of soil contaminants through engineered microbes, plants or amendments to restore productivity faster than natural attenuation (87). Bio-hydrophobic substances reduce waterlogging damage in flood-prone soils by repelling excess moisture while retaining available water for plants (88).

Ecological Weed Management

Integrated weed management systems optimize efficiency and sustainability of control practices. Combining preventive, cultural, mechanical and chemical measures lowers dependence on herbicides and mitigates resistance risks (89). Competitive crop cultivars, narrow plant spacing, high vigor seeds, stale seedbeds and optimum sowing time suppress weed interference while enhancing yields (90,91). Thermal, electrical and flaming methods provide energy-efficient non-chemical weed control options for organic systems (92,93). New sprayer technologies including variable rate, precision guidance and auto section control enable targeted herbicide application to weed patches minimizing usage (94).

Cover crops such as rye, buckwheat, clovers and cowpea smother weeds while improving soil properties and nitrogen availability to subsequent crops (95). Allelopathic cover crop residues chemically suppress weed seed germination and growth through release of phytotoxins (96). Living mulches like white clover control weeds in cropping strips while fixing nitrogen and reducing soil erosion between crop rows (97). Inter-row cultivation, mowing and undercutting sever weed roots and shoots while avoiding crop damage in widely spaced crops (98). Integrating multiple tools strengthens long-term ecological weed management.

Advancing Tillage and Residue Management

Conservation tillage practices that optimize soil protection and water efficiency underpin sustainable crop production intensification. No-till systems entirely eliminate soil disturbance and incorporate residues, conserving soil organic carbon and structure while reducing erosion (99,100). Strip tillage confines disturbance to narrow planted rows creating favorable seedbeds amid undisturbed inter-row zones retaining mulch cover (101). Mulch-till combines single-pass shallow tillage with controlled traffic, retaining protective corn or wheat stover residue (102). Such conservation tillage systems curb erosion, enhance water storage, and sustain yields compared to intensive conventional plowing (103,104).

However, lack of crop residue management in conservation tillage can aggravate certain problems. Thick residue layers increase evaporative loss in dry regions while hindering soil warming and drying during early cool wet seasons (105). Controlled residue burning or removal from strips covering 25-50% of the field helps overcome these challenges while retaining protected soil zones (106). Vertical tillage tools fracture surface compaction while creating rougher, cloddy seedbeds that resist wind and water erosion compared to full-width aggressive tillage (107). Integrating diverse reduced tillage equipment like paraplows and strip processors facilitates continuous direct seeding into diverse previous residues (108). Overall, evidence affirms conservation tillage with strategic residue management optimizes tradeoffs for sustainable crop production across varied environments.

Harnessing Biological Synergies through Intercropping

Intercropping involves growing two or more crop species simultaneously on the same field to unlock complementary interactions for increased total productivity per land area. Cereal-legume intercrops commonly give higher total yields than growing component crops separately through enhanced light and nutrient use efficiencies (109,110). Maize-common bean intercrops in Africa showed 40-60% greater land equivalent ratios versus sole crops (111). Pigeonpea hedgerows provide soil moisture and nutrients to intercropped cereals via hydraulic lift and litter decomposition in semi-arid regions (112).

Intercropping also enhances resource capture in time through staged maturity patterns. Relay-strip intercropping wheat and cotton increased total productivity by 32% over single crops (113). Sequential intercropping increased rice yields and nitrogen recovery following mustard cover crops harvested for edible greens (114). Growing short-duration legume smother crops amid fruit orchard rows offers diversified income while suppressing weeds and improving soil fertility before the main crop matures (115,116). Such spatio-temporal niche differentiation unlocks diverse biological synergies through strategic intercropping.

Efficient Precision Irrigation Management

Optimizing crop irrigation through water-saving technologies and practices enhances water productivity and sustainability. Regulated deficit irrigation delivering partial water requirements during drought-tolerant stages conserves water with smaller yield penalties than uniformly reducing applications in field crops (117). Subsurface drip irrigation localized in crop root zones minimizes evaporative loss while enabling precision delivery and reduced leaching compared to surface irrigation (118). Soil moisture sensors and plant traits like canopy temperature guide need-based irrigation scheduling to avoid over-application

(119,120). Variable rate precision systems integrate sensor feedback to apply optimal water across heterogeneous field conditions (121).

Recycling and reusing drainage through collection and pumping back to fields increases water productivity while safely removing salts in irrigated systems (122). Aquifer storage and recovery systems inject surplus water into underground aquifers during wet months, recapturing it via wells in drier seasons or droughts (123). Rainwater harvesting techniques including check dams, farm ponds and directing catchment runoff into fields improves crop water availability in rainfed systems (124). Integrating such technologies and practices enables ‘more crop per drop’ across diverse agro-ecosystems and farming scales.

Overcoming Abiotic Stresses through Smart Breeding

Developing stress-resilient crop varieties is key to stabilize productivity facing increased climate risks and soil degradation. Breeding targets physiological traits enhancing water productivity like deeper roots, reduced stomatal conductance, higher leaf chlorophyll and 13C discrimination under water deficits (125,126). Stay-green traits maintain photosynthesis and senesce slowly under terminal drought for improved yield in sorghum, maize, wheat and other cereals (127). Osmotic adjustment, sugar accumulation and proline boost drought tolerance through maintaining cell turgor in pulses, cereals, cotton and potato (128-130). Heat stress tolerance also requires selecting for membrane stability, chlorophyll retention and processes regulating pollen viability (131).

Marker-assisted recurrent selection allows precise accumulation of multiple quantitative trait loci governing complex stress resistance (132,133). Canopy temperature and spectral reflectance offer high-throughput phenotyping tools to screen diverse germplasm for desired drought adaptive traits (134). Doubled haploid breeding accelerates development of pure line varieties combining abiotic stress resilience with higher yielding ability (135). Climate modelling helps target relevant stresses and environments to prioritize in breeding programs (136). Such strategic genomics-guided breeding creates resilient, locally adapted varieties essential for sustainable crop production under climate change.

Boosting Yields through Improved Agronomic Practices

Achieving genetic yield potential relies on best agronomic management optimizing plant stand, resource capture and stress avoidance. Wider optimal row spacing coupled with higher plant populations expands light interception to increase corn and cotton yields (137,138). Planting single uniform stands rather than skip-row patterns enhances yield by reducing interplant competition in sorghum and cotton (139,140). Banded subsurface fertilizer placement beside crop rows increases nutrient availability and reduces losses, improving yields compared to surface broadcast methods (141).

Raised beds and furrow-irrigated systems enhance drainage and aeration while aligning plant rows on tops of beds for improved productivity in rice-wheat systems (142). Plastic mulching increases soil temperatures and moisture while suppressing weeds to boost early yields of vegetables, fruits and field crops (143). High density mango, citrus and apple orchards optimize light interception through geometry-based pruning and compact architecture (144-146). Integrating such agronomic enhancements realizes the full genetic potential of advanced crop varieties.

Controlling Insect Pests and Diseases

Sustainable integrated pest management deploys ecological, cultural and targeted chemical controls for effective protection. Crop rotation, intercropping, resistant varieties and predator release suppress pest and disease epidemics by breaking carryover of inoculum across seasons (147). Just-in-time diagnostic tools guide timely intervention only when monitoring indicates economic thresholds are exceeded (148). Precision targeted spraying, pheromones, sterile insects and bio-pesticides minimize nontarget effects and risks compared to broadcast chemical applications (149-152).

Seed treatments, systemic acquired resistance inducers and plant ~~defense~~defence activators provide prophylactic protection against early season crop infections (153-155). Predictive weather and disease forecasting models enable pre-emptive fungicide timing before high-risk infection periods (156). Cultural tactics like pruning infected shoot tips, deep ploughing to bury pathogens and removing alternate weed hosts limit survival and dispersal avenues (157). Balancing multiple tactics fosters long-term ecological and food safety in pest management programs.

Enhancing Benefits of Crop Rotations

Strategic crop sequencing through rotations offers ecological services beyond pest and disease control that enhance productivity. Rotating maize with soybean increased yields of both crops compared to monocultures in the US Midwest by interrupting pest cycles and nitrogen depletion (158). Cotton rotated with peanut suppressed nematodes while improving soil physical properties and water retention that increased yields (159). Introducing meadow fescue and red clover in winter wheat rotations enhanced yield through beneficial rotation effects on soil structure, nitrogen and weeds (160).

Rotating nitrogen-fixing pulses and green manures with non-legumes augments soil fertility to reduce fertilizer requirements of subsequent crops (161). Deep-rooted oilseeds, pulses and tap-rooted forages scavenge nutrients from soil layers beneath shallow-rooted cereals, recycling them to topsoil through decomposition (162). Diverse crop sequences disrupt problematic soil biology including pathogens, nematodes and allelopathic compounds (163). Overall, strategic rotations sustain multi-faceted agronomic benefits central to ecological farming systems.

Improving Soil Health through Crop Diversification

Strategically diversifying cropping systems can improve soil health and stability of food production. Crop rotations and intercropping provide temporal and spatial diversity that disrupts pest and disease cycles, increases soil organic matter, and enhances nutrient use efficiency [164]. For example, a meta-analysis of global studies found that crop rotations increased yields in rain-fed systems by 7-26% for corn, 6-13% for wheat, and 9-31% for rice compared to monocultures [165].

Integrating grain or forage legumes into rotations with cereals and other crops has pronounced benefits for soil nitrogen levels and yields. A review across Africa showed that maize rotated with legumes yielded 18-53% higher than continuous maize [166]. Intercropping maize with pigeonpea enhanced system productivity by 28-53% and nitrogen use efficiency by 30-35% [167]. Legumes contribute 50-200 kg N ha-1 to the soil through biological nitrogen fixation, reducing fertilizer requirements for subsequent crops [168].

Cover crops grown during fallow periods likewise augment soil organic matter, suppress weeds, and scavenge excess nutrients [169]. For example, cereal rye cover crops were found to reduce nitrate leaching by over 60% compared to bare fallow across the U.S. Midwest [170]. Cover crop mixtures can maximize ecosystem services. A blend of barley and peas maintained complete soil cover and increased organic matter input 4-fold versus bare fallow [171]. Overall, intentionally planned crop rotations and covers tailored to soil and climatic contexts can significantly enhance the productivity, profitability and sustainability of agricultural systems.

Discussion

The document provides a comprehensive overview of agronomic principles and practices that can enhance agricultural productivity and sustainability. Optimizing plant nutrition is key, through site-specific nutrient management, controlled release fertilizers, seed priming techniques, and stimulating beneficial plant-microbe associations (58-69). Foliar micronutrient application offers an efficient deficiency correction strategy, with effectiveness depending on various factors (70-75). Site-specific micronutrient management further increases yields by 15-30% (76,77).

Alleviating soil constraints like salinity, acidity, compaction, and contamination via amendments, tillage, and bioremediation facilitates plant growth (79-88). Integrated weed management combining preventive, cultural, mechanical and chemical controls reduces herbicide usage and resistance risks (89-98). Conservation tillage methods like no-till and strip tillage enhance soil protection, water efficiency, soil organic matter, and sustain yields (99-104). Strategic residue removal or burning can alleviate issues in cool, wet conditions (105,106). Vertical tillage tools create erosion-resilient seedbeds while avoiding aggressive full-width tillage (107). Diverse reduced tillage equipment facilitates continuous no-till planting (108).

Intercropping increases total productivity through enhanced resource use efficiencies and spatio-temporal niche differentiation (109-116). Optimizing irrigation via regulated deficit approaches, subsurface drip, sensor-based scheduling, variable rate precision technologies, drainage recycling, and aquifer storage and recovery enhances water productivity (117-124). Breeding for deeper roots and drought-adaptive processes imparts climate resilience (125-136). Realizing genetic yield potentials relies on optimizing agronomic factors like plant density, row spacing, fertilizer placement, raised beds, and orchard design (137-146).

Sustainable integrated pest management utilizes ecological, cultural and targeted chemical controls (147-155). Predictive models and removal tactics limit pest and disease spread (156,157). Rotations offer multifaceted agronomic benefits like enhanced soil quality, fertility and water retention beyond pest disruption (158-163). Crop diversification via rotations, intercropping and integration of legumes and cover crops enhances productivity and sustainability by disrupting pest cycles, increasing soil organic matter and nutrient use efficiency(164-184).

Conclusion

Agronomy provides the scientific foundation to nourish crops, invigorate soils, and sustain global food production through integrated soil fertility, water, pest, and crop management. As this review highlights, site-specific techniques that tailor nutrient, irrigation, and cultivation practices to local contexts optimize plant growth and soil conservation. Strategic crop diversification via rotations and intercropping disrupts pest pressures while benefiting soil biology. Continued agronomic advances that harness genetic yield potentials within ecological boundaries are essential to intensify production sustainably amid climate change and natural resource constraints. Knowledge-intensive, precision technologies must be adapted to strengthen resilient, ~~biodiverse~~bio diverse smallholder systems that underpin global food security. Overall, agronomic innovation in context-specific integrated crop-soil management is key to meet rising nutritional needs without compromising the environment.

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