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Research Article

Sustainable Agriculture for Food Security: Soil Health, Agroecology, Climate Resilience, and Just Food Systems

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Abstract

Agriculture feeds humanity, yet the dominant model of intensive, input-heavy production has degraded soils, depleted water, eroded biodiversity, and contributed substantially to climate change, while still leaving hundreds of millions of people food insecure. This critical review synthesises evidence on sustainable agriculture, soil health, agroecology, and food systems, and examines how farming can produce sufficient, nutritious food while restoring ecosystems and supporting livelihoods. It shows that yield gains since the Green Revolution were accompanied by environmental costs that now threaten long-term productivity, and that sustainable practices including crop diversification, agroforestry, conservation agriculture, integrated pest management, efficient irrigation, and improved livestock systems can improve soil, water, biodiversity, and resilience, often without sacrificing yields when adapted to local contexts. The review evaluates organic farming, agroecology, regenerative agriculture, precision agriculture, and climate-smart agriculture, and examines diets, food loss and waste, markets, gender, and governance. It argues that sustainable agriculture requires not only farm-level practices, but also transformation of food systems, including fair prices, secure tenure, extension, finance, and policies that reward stewardship. Priorities for research, measurement, and action are identified.

Keywords: *sustainable agriculture; soil health; agroecology; food security; climate resilience; biodiversity; food systems*

1. Introduction

Food is a basic human need, yet the global food system is failing on multiple fronts. About 735 million people faced chronic hunger in 2022, while more than two billion people experienced moderate or severe food insecurity, and overweight and obesity affect billions more, reflecting a system that produces enough calories in aggregate but distributes them unevenly and produces diets that are often unhealthy (FAO, IFAD, UNICEF, WFP and WHO, 2023). At the same time, agriculture occupies about half of habitable land, uses about 70 percent of freshwater withdrawals, and contributes about a fifth to a quarter of global greenhouse gas emissions, while driving deforestation, soil degradation, and biodiversity loss (Foley et al., 2005; IPCC, 2019; FAO, 2023). The challenge is therefore not only to produce more, but to produce better: more nutritious food, with less environmental harm, in ways that are fair and resilient.

Sustainable agriculture is often defined as farming that meets current food needs without compromising the ability of future generations to meet theirs, by maintaining soil, water, biodiversity, and livelihoods (FAO, 2018; Pretty, 2008). This definition is widely accepted, but its interpretation varies. For some, sustainability means efficiency: producing more per unit of land, water, or input. For others, it means agroecology: redesigning farms as ecosystems, using ecological processes, local knowledge, and diversity

(Altieri, 2002; Gliessman, 2015). For still others, it means regenerative agriculture: rebuilding soil organic matter, carbon, and biological activity (FAO, 2018). These approaches overlap, and this review treats them as complementary, not competing.

This review has four aims. First, it describes the state of global agriculture, food security, and environmental pressures. Second, it explains soil health, water, biodiversity, and climate as foundations of sustainable production. Third, it evaluates farming practices and systems, from agroecology to precision agriculture, and examines diets, food loss and waste, and value chains. Fourth, it analyses policy, markets, gender, tenure, and governance, and identifies priorities for a just transition. It draws on FAO, IPCC, and IPBES assessments, long-term experiments, meta-analyses, and case studies, with emphasis on literature published between 2000 and 2025.

A central argument is that sustainable agriculture cannot be achieved by a single technology or by asking farmers alone to change. It requires redesigning farms, landscapes, markets, and policies together, with farmers, especially smallholders, women, and Indigenous Peoples, at the centre (Altieri, 2002; FAO, 2018). Productivity, sustainability, and equity are not trade-offs to be balanced in the abstract; they must be pursued together in specific places, with attention to soils, climates, cultures, and livelihoods.

2. Global Agriculture, Food Security, and Environmental Pressures

Global agricultural production has grown dramatically since the 1960s. Figure 2 shows the rise in cereal yields, driven by improved varieties, fertilisers, pesticides, irrigation, and mechanisation during the Green Revolution (Evenson and Gollin, 2003; Pingali, 2012). Evenson and Gollin (2003) found that Green Revolution varieties contributed substantially to yield growth and to reduced food prices, especially in Asia. Pingali (2012) argued that the Green Revolution averted famine in many regions, but that its benefits were uneven, with sub-Saharan Africa and many marginal areas benefiting less, and with environmental costs that were not fully accounted for. Figure 1 summarises the composition of global production, with cereals, vegetables and fruits, and animal products dominating.

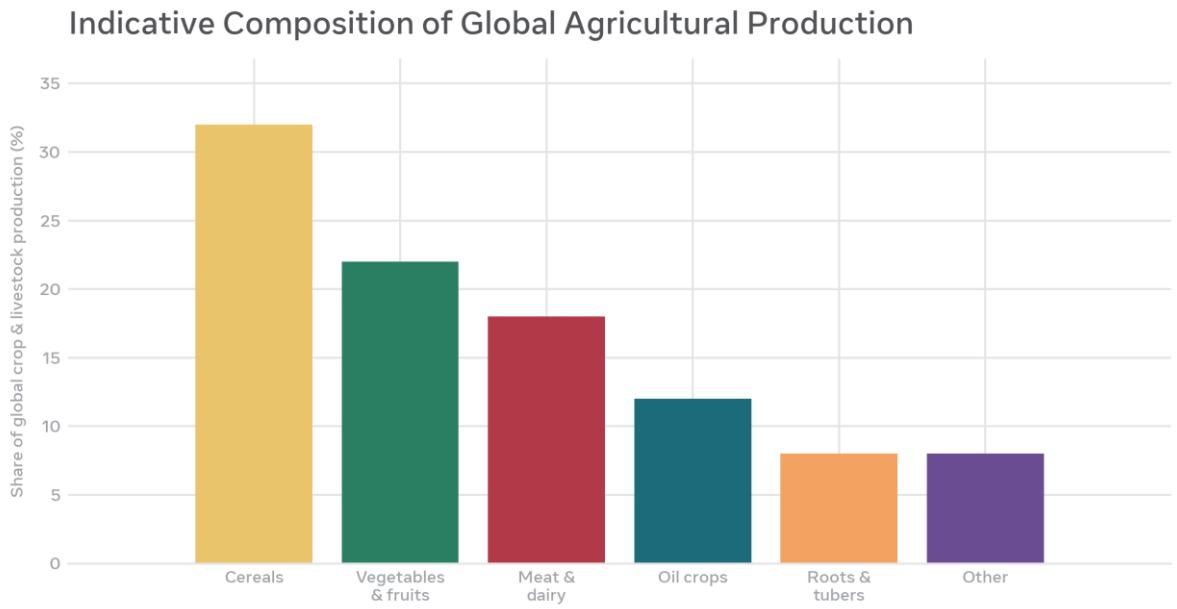

Figure 1. Composition of global agricultural production (FAO, 2023).

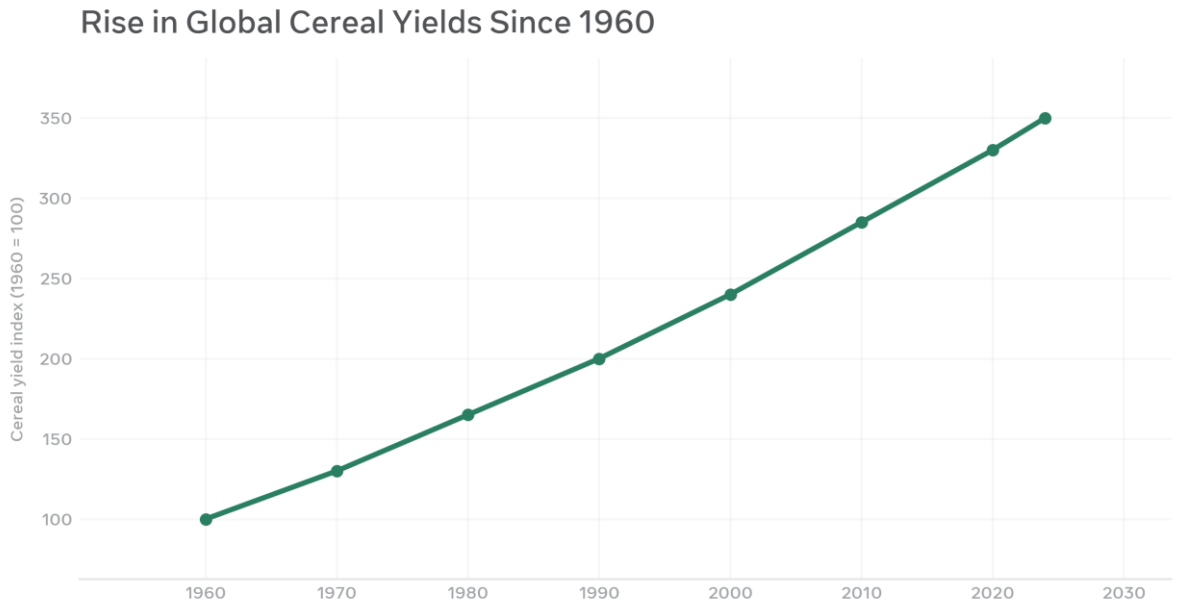

Figure 2. Rise in global cereal yields since 1960, following the pattern reported by FAO (2023) and Evenson and Gollin (2003).

Food security is defined by availability, access, utilisation, and stability (FAO, IFAD, UNICEF, WFP and WHO, 2023). Availability has improved in aggregate, but access remains constrained by poverty, conflict, inequality, and shocks, while utilisation depends on nutrition, water, sanitation, and health (FAO, IFAD, UNICEF, WFP and WHO, 2023). Stability is threatened by climate extremes, pests, market volatility, and conflict, which can disrupt production and supply chains (IPCC, 2022). The COVID-19 pandemic, conflicts, and climate extremes have reversed progress on hunger in recent years, showing how fragile food security can be (FAO, IFAD, UNICEF, WFP and WHO, 2023).

Environmental pressures are large. Agriculture is the main driver of deforestation, habitat loss, and biodiversity decline, especially through expansion of cropland, pasture, and plantations (Foley et al., 2005; IPBES, 2019). It is the largest user of freshwater, with irrigation accounting for most withdrawals in many regions, and with groundwater depletion in major aquifers (FAO, 2023). Synthetic fertilisers have increased yields but have also caused nutrient runoff, eutrophication, and nitrous oxide emissions, while pesticides have harmed pollinators, aquatic life, and human health (IPCC, 2019; FAO, 2018). Soil degradation affects about a third of global soils, through erosion, organic matter loss, salinisation, compaction, and contamination, reducing productivity and resilience (FAO, 2015; FAO, 2020).

3. Soil Health as the Foundation of Sustainable Agriculture

Soil is a living ecosystem, not merely a medium for plants. It contains bacteria, fungi, protozoa, nematodes, earthworms, and arthropods that cycle nutrients, decompose organic matter, suppress diseases, and build structure (FAO, 2020). The FAO (2020) warned that soil biodiversity loss threatens food security, because healthy soils depend on diverse communities. Soil organic matter is central: it improves water holding, nutrient supply, structure, and resilience, and it stores carbon (Lal, 2004; FAO, 2015). Lal (2004) argued that restoring soil organic matter is essential for both food security and climate mitigation, because degraded soils have lost large amounts of carbon that can be partly restored through better management.

Practices that build soil health include cover crops, crop rotation, intercropping, organic amendments, reduced tillage, and agroforestry (FAO, 2015; Pretty, 2008). Cover crops protect soil from erosion, fix nitrogen, suppress weeds, and add organic matter, while crop rotation breaks pest and disease cycles and improves nutrient use (Pretty, 2008; Altieri, 2002). Conservation agriculture, which combines minimum tillage, permanent soil cover, and crop rotation, can reduce erosion, improve water infiltration, and maintain yields, but its benefits depend on context, residues, and weed management (Pittelkow et al., 2015). Pittelkow et al. (2015) found in a global meta-analysis that conservation agriculture can maintain yields in many cases, with benefits larger in dry and degraded environments, but that it may reduce yields initially where residues are scarce or weeds are poorly controlled. This context dependence is a recurring theme: no practice works everywhere, and adaptation to local soils, climates, and livelihoods is essential.

Soil degradation is reversible in many cases, but it takes time and investment. Erosion can be reduced through terracing, contour farming, hedgerows, and vegetation, while salinisation can be addressed through drainage, salt-tolerant crops, and improved irrigation (FAO, 2015). Soil testing, nutrient management, and integrated soil fertility management, which combines organic and inorganic inputs, can improve nutrient use efficiency and reduce losses (Pretty, 2008; FAO, 2018). Monitoring soil health requires indicators beyond yield, including organic matter, structure, biodiversity, and water holding, which are not yet measured systematically in many countries (FAO, 2020).

4. Water, Biodiversity, and Climate in Farming Systems

Water management is critical for sustainable agriculture. Irrigation has enabled high yields in arid and semi-arid regions, but it has also depleted aquifers, salinised soils, and reduced river flows (FAO, 2023). Efficient irrigation, including drip, deficit irrigation, and scheduling based on soil moisture and weather, can save water while maintaining yields, but it requires investment, knowledge, and governance to avoid rebound effects where saved water is used to expand irrigated area (FAO, 2023). Rainwater harvesting, mulching, and soil health practices can improve water use in rainfed systems, which produce most food in sub-Saharan Africa and many other regions (FAO, 2018).

Agricultural biodiversity, including crop varieties, livestock breeds, pollinators, natural enemies, and soil organisms, underpins resilience (IPBES, 2019; FAO, 2019). The FAO (2019) State of the World's Biodiversity for Food and Agriculture warned that biodiversity that supports food production is declining, with loss of crop varieties, livestock breeds, pollinators, and soil organisms. Pollinators support about three-quarters of leading food crops, and their decline threatens yields and nutrition (Potts et al., 2016). Diversified farming, including intercropping, agroforestry, and hedgerows, can support pollinators and natural enemies, reduce pest pressure, and improve resilience, while also providing fruits, timber, fodder, and income (Altieri, 2002; Gliessman, 2015).

Climate change affects agriculture through heat, drought, flooding, pests, and shifting seasons (IPCC, 2022; Lobell et al., 2011). Lobell et al. (2011) found that warming has already reduced yields of maize and wheat in many regions. Adaptation includes drought- and heat-tolerant varieties, diversified crops, agroforestry, improved water management, weather information, and insurance (IPCC, 2022). Mitigation in agriculture includes reducing methane from livestock and rice, nitrous oxide from fertilisers, and carbon dioxide from land-use change, while enhancing carbon storage in soils and trees (IPCC, 2019; Smith et al., 2014). The IPCC (2019) found that sustainable land management can reduce emissions, enhance resilience, and support livelihoods, but that it must be designed to avoid trade-offs with food production and biodiversity.

Table 1. Sustainable farming practices and their benefits and limits (Pretty, 2008; Altieri, 2002; FAO, 2018).

Practice	What it does	Benefits	Limits and context
Crop diversification / rotation	Rotate and intercrop species	Pest control, nutrients, resilience	Needs markets, knowledge, labour
Cover crops	Cover soil in off-season	Soil, water, weeds, carbon	Seed, water, termination cost
Agroforestry	Trees in farms and landscapes	Shade, soil, carbon, income	Land, tenure, long establishment
Conservation agriculture	Minimum tillage, cover, rotation	Soil, water, erosion control	Weeds, residues, initial yield risk
Integrated pest management	Monitor, biological, targeted control	Less pesticide, biodiversity	Knowledge, monitoring, labour
Efficient irrigation	Drip, scheduling, deficit	Water saving, yields	Cost, energy, governance

5. Farming Systems: Agroecology, Organic, Regenerative, and Precision Agriculture

Agroecology applies ecological principles to farming, emphasising diversity, synergy, recycling, and social equity (Altieri, 2002; Gliessman, 2015). Gliessman (2015) described agroecology as a science, a practice, and a movement, linking farm design with food system transformation. Evidence from meta-analyses and case studies shows that agroecological practices can improve yields, especially for smallholders in marginal environments, while improving soil, biodiversity, and resilience (Altieri, 2002; Pretty et al., 2006). Pretty et al. (2006) found in a review of resource-conserving agriculture that yields increased in many cases, especially where soils were degraded and inputs were low, although results varied by crop and context.

Organic farming avoids synthetic fertilisers and pesticides, relying on organic inputs, crop rotation, and biological control (Reganold and Wachter, 2016). Reganold and Wachter (2016) reviewed evidence and found that organic systems often have lower yields than conventional systems, by about 19 to 25 percent on average, but can be more profitable, have lower environmental impacts per unit of land, and support greater biodiversity. The yield gap is smaller for some crops and in some contexts, and larger for others, and it depends on management, soils, and climate (Reganold and Wachter, 2016). Organic farming is not automatically sustainable: it can still degrade soils, use excessive tillage, or rely on long-distance transport, and its benefits depend on practices, not only on certification (Reganold and Wachter, 2016).

Regenerative agriculture emphasises rebuilding soil health, biodiversity, and ecosystem function, often through cover crops, livestock integration, and minimal disturbance (FAO, 2018). Its principles overlap with agroecology and conservation agriculture, but its definition is less standardised, and claims about carbon sequestration and yields are sometimes overstated (FAO, 2018). Evidence suggests that regenerative practices can improve soil organic matter

and water holding, but that carbon gains are finite, reversible, and context-dependent (Lal, 2004; IPCC, 2019). The term should therefore be used with clear practices, measurement, and safeguards, not as a marketing label.

Precision agriculture uses sensors, GPS, drones, satellites, and data analytics to apply water, fertiliser, and pesticides more precisely, reducing waste and environmental harm (FAO, 2023). It can improve nutrient use efficiency, detect pests early, and optimise irrigation, but it requires connectivity, investment, and data governance, and it can exclude smallholders if not designed inclusively (FAO, 2023). Climate-smart agriculture, which aims to increase productivity, adaptation, and mitigation together, includes many of these practices, but it has been criticised for vagueness and for prioritising productivity over equity and ecology (IPCC, 2019). The review argues that labels matter less than outcomes: practices should be judged by their effects on yields, nutrition, soil, water, biodiversity, climate, and livelihoods, not by their branding.

6. Livestock, Diets, Food Loss and Waste, and Value Chains

Livestock systems vary widely, from pastoralism and smallholder mixed farming to intensive feedlots (FAO, 2023; Gerber et al., 2013). Gerber et al. (2013) estimated that livestock supply chains account for about 14.5 percent of global greenhouse gas emissions, through enteric fermentation, manure, feed production, and land-use change. Improving feed, manure management, animal health, and grazing can reduce emissions per unit of product, but total emissions also depend on demand and herd sizes (Gerber et al., 2013). Pastoralism, which uses rangelands unsuitable for crops, supports millions of livelihoods and can maintain grassland ecosystems when well managed, but it is threatened by land grabs, conflict, and climate change (FAO, 2023).

Diets shape environmental impacts. Shifting toward diets with more plants, fruits, vegetables, legumes, and whole grains, and less emission-intensive animal products, can reduce greenhouse gas emissions, land use, and water use, while improving health, especially in high-consuming countries (Willett et al., 2019; IPCC, 2019). Willett et al. (2019) proposed a planetary health diet that is healthy and environmentally sustainable, but noted that it must be adapted to cultures, incomes, and nutritional needs, and that access to diverse, affordable foods is essential. Dietary change should not be framed as individual blame; it requires food environments, prices, education, and policies that make healthy, sustainable foods accessible (FAO, IFAD, UNICEF, WFP and WHO, 2023).

Food loss and waste are large and avoidable. Gustavsson et al. (2011) estimated that about one-third of food produced for human consumption is lost or wasted, with losses in production and storage in low-income regions and waste in retail and consumption in high-income regions. Reducing loss and waste can improve food security, reduce emissions, and save land and water, through better storage, cold chains, processing, date labelling, and consumer behaviour (Gustavsson et al., 2011; FAO, 2023). Value chains matter: smallholders often face low prices, high transport costs, and limited storage, while large retailers and processors capture much of the value (FAO, 2023). Short supply chains, cooperatives, and fair trade can improve incomes and reduce waste, but they require infrastructure, finance, and trust (FAO, 2018).

7. Gender, Tenure, Markets, and Governance

Women produce a large share of food, especially in smallholder systems, yet they face barriers to land, credit, extension, and markets (FAO, 2011; FAO, 2023). The FAO (2011) found that closing the gender gap in farm productivity and agrifood systems could increase yields, reduce hunger, and improve nutrition, by giving women equal access to resources. Gender-responsive extension, finance, and technology, which account for time, mobility, and decision-making, are essential, not optional (FAO, 2023). Youth also matter: many young people leave farming because of low incomes, drudgery, and lack of opportunities, yet they bring innovation, digital skills, and entrepreneurship that can transform food systems if supported (FAO, 2018).

Secure tenure is fundamental. Farmers who have secure rights to land are more likely to invest in soil, trees, and water, while insecure tenure discourages long-term stewardship (FAO, 2018). Indigenous Peoples and local communities, who steward diverse farming systems and agrobiodiversity, often lack secure rights, despite their contributions to conservation and food security (Garnett et al., 2018). Policies should secure tenure, support community land management, and respect Indigenous knowledge, which includes crop diversity, soil management, and climate adaptation developed over generations (Altieri, 2002; Garnett et al., 2018).

Markets and finance shape incentives. Subsidies that favour synthetic inputs, monocultures, or overproduction can harm soil, water, and biodiversity, while payments for ecosystem services, agroecological premiums, and green finance can reward stewardship (IPCC, 2019; FAO, 2018). Extension services, farmer field schools, and peer learning are critical for spreading sustainable practices, because knowledge, not only inputs, is a limiting factor (Pretty et al., 2006; FAO, 2018). Governance must be coherent: agricultural, environmental, health, trade, and social policies often work at cross-purposes, and aligning them is essential for sustainable food systems (FAO, 2018; IPCC, 2019).

Table 2. Social and governance levers for sustainable agriculture (FAO, 2011; FAO, 2018; Pretty et al., 2006).

Lever	What it does	Why it matters	Example

Secure tenure	Protect land and resource rights	Encourages long-term investment	Community land titles, women's land rights
Gender equity	Equal access to resources	Raises yields, reduces hunger	Gender-responsive extension, credit
Extension & learning	Farmer field schools, peer learning	Spreads knowledge, builds skills	Farmer field schools, cooperatives
Fair markets	Fair prices, storage, transport	Improves incomes, reduces waste	Cooperatives, short supply chains
Finance	Credit, insurance, payments	Enables investment, manages risk	Microcredit, weather insurance
Policy coherence	Align agriculture, health, environment	Reduces trade-offs	National food system strategies

8. Research Gaps and Future Directions

Several gaps deserve priority. First, long-term, systems-level research is needed, because many benefits of sustainable practices, such as soil carbon, biodiversity, and resilience, emerge over years, not in single-season trials (Pretty et al., 2006; Reganold and Wachter, 2016). Second, research on yields, nutrition, and livelihoods together is needed, because a practice that increases yields but reduces nutrition or income is not sustainable (FAO, 2018). Third, research on scaling is needed: what works on a small farm or pilot may not work at landscape or national scale, and scaling requires markets, institutions, and policies, not only technology (Altieri, 2002; Gliessman, 2015). Fourth, research on climate adaptation, including heat, drought, and pests, is needed, especially for crops and regions that are under-researched (IPCC, 2022; Lobell et al., 2011). Fifth, research on soil biodiversity, measurement, and monitoring is needed, because soils are poorly understood and under-monitored (FAO, 2020). Finally, transdisciplinary research co-produced with farmers, Indigenous Peoples, and communities is needed, because sustainable agriculture is context-specific and knowledge-intensive (Altieri, 2002; FAO, 2018).

9. Conclusion

Sustainable agriculture is not a single practice or a return to the past; it is a forward-looking transformation of farming and food systems to produce nutritious food, restore soils, water, and biodiversity, reduce emissions, and support livelihoods (FAO, 2018; Pretty, 2008). Evidence shows that agroecological, soil-building, diversified, and efficient practices can improve resilience and sustainability, often while maintaining or improving yields, especially where soils are degraded and inputs are low (Altieri, 2002; Pretty et al., 2006). But farm-level change alone is insufficient. Diets, food loss and waste, markets, tenure, gender, finance, and governance must also change, so that farmers are rewarded for stewardship and consumers can access healthy, sustainable food (FAO, IFAD, UNICEF, WFP and WHO, 2023; Willett et al., 2019). The path forward is to build food systems that are productive, resilient, equitable, and regenerative, so that agriculture nourishes people and the planet together.

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Conflict of Interest

The authors declare no conflict of interest.

Data Availability

This review is based on published literature cited in the reference list. No new experimental data were generated. Figures present values from the cited sources.

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