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Implications of leading crop production practices on environmental quality and human health

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Abstract

Globally, much weight is currently being placed on agriculture to provide food for the growing population as well as feedstock for the bioenergy industry. Unfortunately, the intensification of agricultural operations to satisfy these growing needs has been associated with a number of environmental and human health risks. A review of publications on the subject was conducted and emphasis was placed on articles focusing on agriculture, environment, and public health as well as their interactions. Supporting information was also gathered from publications of various agricultural and environmental agencies. Agricultural practices with potential negative implications on the environment and human health were identified broadly as: (a) utilization of biosolids and animal manures, (b) use of agricultural chemicals, (c) management of post-harvest residue, (d) irrigation, and (e) tillage operations. Soil, water, and air contamination by nutrients, heavy metals, pathogens, and pesticides, as well as air contamination by particulate matters, noxious gases, and pathogens were among the leading environmental impacts. Some of the human-health impacts identified included neurological and reproductive defects, cardiovascular risks, cancers and other diseases (of kidney, liver, lung, and skin), skin allergies, gastroenteritis, and methemoglobinemia. Continual awareness on the impacts of the reviewed agricultural practices on environmental quality and human health and the implementation of experimentally-backed best management practices in agricultural systems remain indispensable.

1. Introduction

Environmental quality and human health are issues of global concern, particularly in this era of rapid industrialization, intense agricultural operations, and climate change. Of interest, the quest for alternative energy sources has led to the intensification of agricultural operations to offset the demand on energy crops such as sugarcane, corn, and soybean, thus, deepening the adverse impacts of agricultural activities on climate change and human health (Alcamo et al., 2005; De Fraiture et al., 2008). In most agricultural settings, management practices are often evaluated based on their economic benefits with less attention given to the environmental and public health perspectives. Attempts at addressing such shortcomings surely warrant an understanding of producers' preferences for any given crop and soil management approach since studies have shown that producers are motivated by a combination of financial, environmental, and personal incentives (Ecker et al., 2012). In the Unites States (US), efforts are being made by federal agencies such as the United States Environmental Protection Agency (USEPA) and United States Department of Agriculture (USDA) as well as their state counterparts, to create awareness of the implications of agricultural activities on environmental quality (USEPA, 2005; Elrashidi et al., 2010). Likewise, the World Health Organization (WHO) has also identified critical links between

agriculture and human health (Hawkes and Ruel, 2006). However, current data and future projections suggest the need for implementation of best management practices in agricultural systems to curb the environmental degradation and human health risks associated with modern-day agriculture (Alcamo et al., 2005; De Fraiture et al., 2008; Costello et al., 2009).

A variety of pollutants discharged from agricultural sources are notably associated with environmental pollution (USEPA, 2003; Gerba and Smith, 2005). Commonly documented pollutants from agricultural sources include nutrients, trace metals, organic carbon (OC), pesticide compounds, noxious gases, and pathogens (USEPA, 2005; Gerba and Smith, 2005; Menzi et al., 2010). Certain agricultural practices such as the application of organic amendments (animal manures and biosolids), inorganic fertilizers, and pesticides; crop residue handling; and irrigation water use have often been cited as sources as well as facilitators of the transport of the aforementioned pollutants within the environment (USEPA, 2003; Udeigwe et al., 2010).

Various health-related issues in humans have also been attributed to a number of agricultural pollutants. For instance, linkages between cancer and certain agricultural pesticides (Alavanja et al., 2003) and between respiratory diseases and particulate matters ($PM_{2.5}$ and PM_{10}) (Arbex et al., 2007), have been widely documented. Likewise, a number of human health issues relating to trace element ingestion have been noted (Uriu-Adams and Keen, 2005; Boxall et al., 2009). Pathogens present in animal manure and biosolids have been shown to cause a number of health problems in humans (Mathis et al., 2005; Sidhu and Toze, 2009), while environmental contamination by nutrients from agricultural sources has also been tied to health risks in humans (Fawell and Nieuwenhuijsen, 2003; Kalantar-Zadeh et al., 2010). Current findings have also highlighted the relationships between human exposure to agricultural contaminants and climate change; projecting that the risks of these contaminants to humans could increase considerably in the future (Boxall et al., 2009).

The intensification of agricultural practices to provide feedstock for the biofuel/biodiesel industry and food for the growing world population further deepens the aforementioned challenges. Thus, the aim of this paper was to highlight current perspectives on the impacts of key crop production practices on both environmental quality and human health. The first part of this work will discuss the key crop production practices of environmental and human health concerns, followed by a description of the principal contaminants from agricultural sources, and their impacts on the environment and human health.

2. Principal crop production practices of environmental and human concern

2.1. Biosolids and animal manure utilization

Biosolids (aerobically and/or anaerobically digested sewage sludge) and manure are historically used on agricultural soils as sources of plant nutrients, with a growing use of solid manures as amendments to increase soil organic matter (SOM) content especially on light soils and degraded landscapes (Kimetu et al., 2008). Biosolids, a by-product of municipal wastewater treatment plants, is characterized as a complex mixture of OM (USEPA, 1999); while animal manures are solid and liquid animal wastes that may be treated (by composting, aerobic or anaerobic digestion, or solid separation) or untreated before use. In the US alone, it is estimated that 8×10^6 tons of dry biosolids are produced annually and about half of these are land applied (USEPA, 1999; Iranpour et al., 2004). Land application of biosolids has increased over the years since many states now have more stringent laws governing landfill disposal; likewise, incineration of biosolids has also decreased since many incinerators are unable to meet the USEPA 503 regulations of the Clean Air Act (Epstein, 2002). In Europe, about 2.39×10^6 tons of dry biosolids which is equivalent to 37% of the total amount produced are reportedly land applied annually (Chang et al., 2002). It is reported that biosolids production is considerably more of an issue in Europe considering the amount of sludge produced to agricultural area available for beneficial use (Iranpour et al., 2004), thus, suggesting potential future environmental problems. Similarly, livestock production in the US generates over a billion tons of manure annually (USEPA, 2011), some of which are injected or surface applied and incorporation.

The use of biosolids and animal manures as soil amendments has often been associated with environmental contamination. Biosolids and manures contain considerable quantities of nitrogen (N), calcium (Ca), magnesium (Mg), potassium (K), sodium (Na), and phosphorous (P), as well as OC (Powers, 2004; Sullivan et al., 2006; Udeigwe et al., 2009; Stietiya and Wang, 2011). The devastating impact of the direct runoff of nutrients, particularly P and N, from land applied and stored manures and biosolids on surface water quality have also been cited (Rostagno and Sosebee, 2001; Hoorman et al., 2008). Biosolids and manures have also been cited as major sources of trace metals (e.g. copper (Cu), zinc (Zn), lead (Pb), cadmium (Cd), nickel (Ni)) (Iranpour et al., 2004; Schroder et al., 2008) (Table 1), and harmful pathogens (e.g. *Campylobacter* spp, *Salmonella* spp, *Escherichia coli*, *Cryptosporidim parvum*, etc) (Gerba and Smith, 2005; Sidhu and Toze, 2009) additions to soil and water. Direct discharge of gases such as methane (CH_4), ammonia (NH_3), hydrogen sulfide (H_2S), and carbon dioxide (CO_2) from stored and applied biosolids and manures (Chadwick et al., 2011; USEPA, 2011) especially manure stored in deep (anaerobic) but exposed lagoons, has also been noted for its environmental and health implications.

2.2. Use of agricultural chemicals

Commercial crop production is highly dependent on the utilization of agricultural pesticides (i.e., any chemical applied to control weeds, insects, plant disease, and rodents). It was estimated that over 11.5 billion kg of pesticide active ingredients (valued at $39.4 billion) were used worldwide in 2007, with over 2.5 billion kg (~$12.5 billion) used in the US alone (Grube et al., 2011). In the US, the agricultural sector accounts for over 70% of all conventional pesticide used. Estimates of pesticide used by the US agricultural

Table 1
Levels of trace elements that occur as impurities in common fertilizers added to agricultural soils.[a]

	Source			
	N fertilizer	P fertilizer	Manure	Sewage sludge
	mg kg^{-1}			
As	2–120	1–1200	3–25	2–30
Cd	0.05–8.5	0.1–190	0.1–0.8	<1–3400
Cr	3.2–19	66–245	1.1–55	8–41000
Cu	–	1–300	2–172	50–8000
Hg	0.3–3	0.01–2	0.01–0.4	<1–55
Mo	1–7	0.1–60	0.05–3	1–40
Ni	7–34	7–38	2–30	6–5300
Pb	2–27	4–1000	11–27	30–3600
Se	–	0.5–25	0.2–24	1–10
U	–	20–300	–	<2–5
V	–	2–160	–	–
Zn	15–570	50–1450	15–570	90–50000

[a] Adapted from Selinus, 2013.

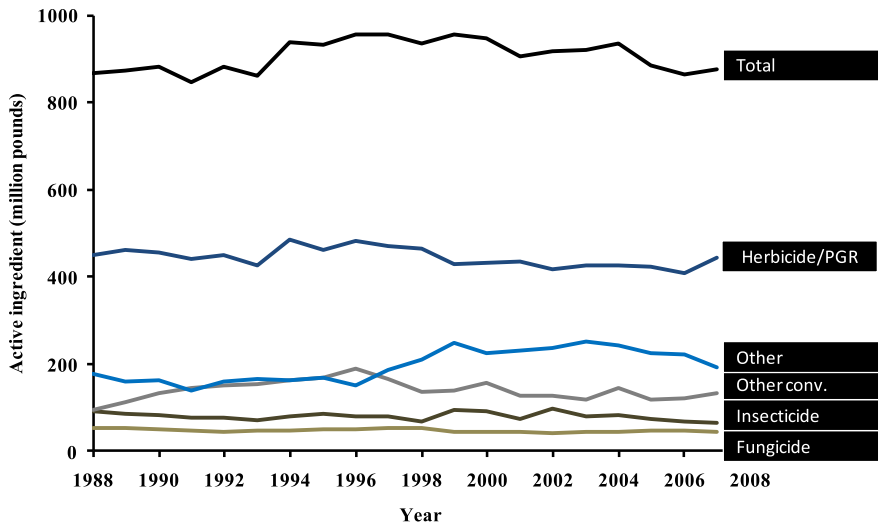

Fig. 1. Estimate of pesticides used by the U.S. agricultural sector from 1988 to 2007 (Grube et al., 2011).

sector from 1988 to 2007 are presented in Fig. 1. Among the top 25 pesticides used by the agricultural sector are 13 herbicides, three fungicides, three insecticides, five fumigants, and one plant growth regulator (Grube et al., 2011). The herbicide, glyphosate, remains the most used active ingredient (Woodburn, 2000; Grube et al., 2011). Although risk assessment research identifies glyphosate as one of the safest herbicides on human health, continuous exposure from frequent use in the US has resulted in increasing levels of this pesticide in food, drinking water, and the atmosphere (Chang et al., 2011). About 60–100% of rain and air particle samples collected during two crop growing seasons from Iowa and Mississippi contained glyphosate (Chang et al., 2011).

The dependence of modern-day agriculture on pesticides, as illustrated above, is associated with numerous environmental implications. A survey of 51 major river basins and aquifer systems by the U.S. Geological Survey's (USGS's) National Water Quality Assessment (NAWQA) program revealed that pesticides were detected 97% of the times in samples from stream water and 61% of samples from shallow groundwater in agricultural areas (Gilliom, 2007). Organochlorine compounds, most of which are no longer in use, were detected in 92% of fish tissue and 57% of sediment samples collected in agricultural areas (Gilliom, 2007). The most frequently detected pesticides in agricultural areas were among those that were most heavily used; such as glyphosate (Gilliom, 2007). The increasing dependence on herbicides and herbicide-resistant crops are also noted for weed population shifts and increasing cases of herbicide resistance (e.g. glyphosate tolerance) (Owen and Zelaya, 2005).

The use of inorganic fertilizers as sources of plant nutrients has been very productive and continues to be essential in meeting the global food demand. But application of fertilizers at rates beyond crop needs, and on soils susceptible to nutrient leaching are a subject of concern because of the associated impact on environmental quality. Records of US fertilizer consumption from 1960 to 2008 (Fig. 2) show a large jump in N (2.74–12.6 million tons), P (2.57–4.25 million tons), and K (2.15–4.66 million tons) utilization (USDA, 2013), indicating the increasing dependence on inorganic nutrient sources. Fertilizer nutrients, particularly P and N, are often cited as a major component of agricultural runoff, and have continuously ranked high as one of the major non-point source pollutants in surface waterbodies causing eutrophication (USEPA, 2003). The addition of inorganic fertilizers has also been associated with the accumulation of contaminants (occurring as impurities) such as arsenic (As), Cd, fluorine (F), Pb, mercury (Hg), in agricultural soils in many areas of the world (McLaughlin et al., 1996; Nziguheba and Smolders, 2008).

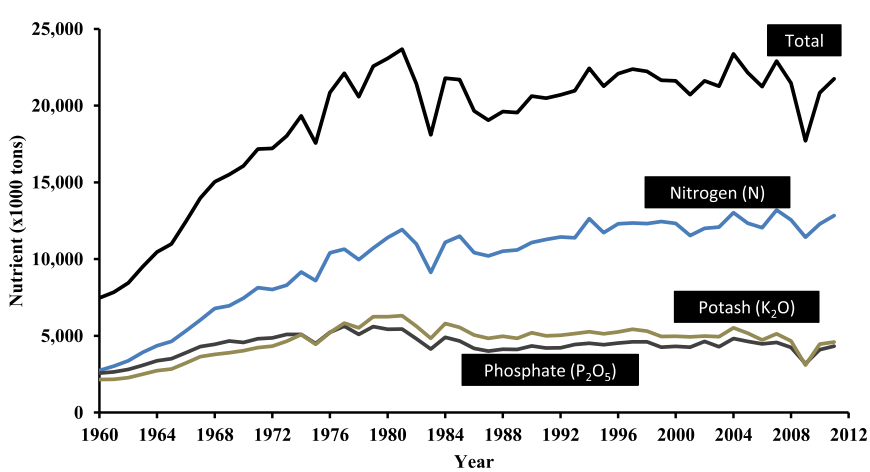

Fig. 2. Nitrogen, phosphorus and potassium fertilizer consumption in the U.S. from 1960 to 2011 (USDA, 2013).

2.3. Crop residue management

Management of pre-planting and post-harvest residues is a critical aspect of most crop production systems. The type of residue management practices employed can have significant impact on environmental quality, crop yield, and the subsequent utilization of land resources (Cheesman, 2004; Graham et al., 2007). In most agricultural settings, residues resulting from the production of crops are generally retained on the soil surface (as in no-till), plowed in (as in conventional tillage), or burnt. In regions with relaxed environmental regulations, burning of residues is often preferred by producers because of the immediate impact on farm operations, disease and weed management, and yield (McCarty and Hartmann, 2010).

Burning of crop residues is practiced in all 50 states in the US (McCarty et al., 2009a). Using satellite monitoring, it was estimated that over 1.2 million ha of croplands are burnt annually in the contiguous United States with the most cropland burning recorded in Florida (sugarcane), Arkansas (wheat, corn, soybean), Idaho (wheat), California (rice, cotton, wheat, and orchard), and Texas (sugarcane) (McCarty et al., 2009b). Within the continental US, crop residue burning is projected to emit 6.1 Tg of CO_2, 8.9 Gg of CH_4, 232.4 Gg of carbon monoxide (CO), 10.6 Gg of nitrogen dioxide (NO_2), 4.4 Gg of sulfur dioxide (SO_2), as well as 28.5 Gg of PM_{10} (particulate matter of less than 10 μm in diameter), and 20.9 Gg of $PM_{2.5}$ (particulate matter of less 2.5 μm in diameter) annually (Gg = gigagram = 10^9 g, Tg = teragram = 10^{12}g) (McCarty et al., 2009b). Particulate matter and trace gases emitted by burning impact air quality and public health on local and regional scales (Adler, 2010). In the US, annual $PM_{2.5}$ emission estimates from April to December were 3.49×10^5 (2002), 3.30×10^5 (2003), 1.80×10^5 (2004), and 2.24×10^5 (2005) tons, with the lead contributing states being Oregon (24.7%), Montana (23.7%), California (17.7%), and Louisiana (10.2%) for 2002, 2003, 2004, and 2005, respectively (Zhang et al., 2008). Biomass burning also contributes to land degradation by destroying OM and by the formation of hydrophobic compounds which could impede water infiltration. Soils under burning have an increased susceptibility to runoff (DeBano et al., 1998; Udeigwe et al., 2010). The short- and long-term impact of burning on desirable soil properties (e.g. OM content, fertility status, microbial activity, water holding capacity, etc.) (Pietikäinen and Fritze, 1993; DeBano et al., 1998; Udeigwe et al., 2010) and the associated impact on air and water quality remain undeniably a huge environmental threat.

2.4. Irrigation

Agriculture accounts for over 80% of US consumptive water use and even higher (90%) in the Mountain regions (Idaho, Montana, Wyoming, Arizona, New Mexico, Colorado, Nevada, and Utah) (Gollehon and Quinby, 2006).

About 54.9 million acres of irrigated farmland was reported in the 2008 Farm and Ranch Irrigation Survey by the USDA, a 4.6% increase from 2003 (USDA, 2008). In 2000, 85% of total agricultural withdrawals of irrigation water occurred in a 19-state area within the Mountain, Plains, and Pacific regions (Gollehon and Quinby, 2006). States with the largest area of irrigated land are Nebraska, California, Texas, Arkansas, and Idaho (USDA, 2008). In the year 2000, 59% of total irrigation withdrawals were from surface water sources and the rest from groundwater supplies (Gollehon and Quinby, 2006). However, the trend within the past decade indicates an increasing dependence on groundwater, which supplies most of the irrigation water in the eastern 37 states noted for the greatest irrigation growth (Gollehon and Quinby, 2006).

Excessive irrigation often facilitates surface water runoff from agricultural fields which is highly undesirable because of the associated impacts on receiving waterbodies (Westermann et al., 2001). Surface runoff often carries sediments (or suspended solids), pesticides, pathogens, nutrients, dissolved salts, and metals into surface and groundwater sinks which could impact the biodiversity of aquatic species as well as reduce the recreational values of impacted waterbodies (Beman et al., 2005). Saline and metal-contaminated water used for irrigation could over time lead to the accumulation of the associated pollutants in soils, thereby impacting crop productivity as well as inducing land degradation (Wahla and Kirkham, 2008; Wiedenfeld, 2008). Likewise, the increasing contaminant levels in declining aquifers as evidenced in some semi-arid/arid regions of the US such as the Southern High Plains (Scanlon et al., 2005) are also reflecting in the soils of groundwater-irrigated fields (Udeigwe et al., 2015). Incidences of accumulation of toxic elements and compounds in crops have also been traced to contaminated irrigation water (Arora et al., 2008; Dahal et al., 2008).

2.5. Tillage systems and operations

Various landuse practices, particularly those involving heavy machinery operations have been associated with significant surface soil alterations that eventually impact soil quality, crop productivity (Hamza and Anderson, 2005), as well as water quality and quantity (Fleige and Horn, 2000; McVay et al., 2006). Heavy machinery operations under certain soil types (e.g. heavy-textured soil) and wet conditions negatively impact soil structure, leading to compaction and reduced infiltration rates. Thus, under intense rainfall or irrigation, surface runoff could occur, leading to loss and/or landscape redistribution of sediments, OC, and nutrients, and other contaminants (Neely et al., 1989; Ritter and Shirmohammadi, 2000; Allan, 2004). The NRCS National Resource Inventory reported 960 and 765 million tons of soil erosion loss from cropland by water (sheet and rill) and wind, respectively, in 2007 (NRCS, 2007). These numbers stress the need for conservation tillage operations and practices resulting in retention of surface residues (>50% for no-till and 30–50% for minimum till) as opposed to conventional tillage practices (<30% surface residues) that involve multiple tillage passes and more surface soil disturbance which are implicated in soil degradation, as well as air and water quality impairments (Tan et al., 2002; Liebig et al., 2004). From an agronomic perspective, nutrient and OC losses are often associated with sediment loss, particularly in fields that are conventionally tilled. Van Oost et al. (2007), in evaluating the contribution of agricultural soil erosion to global carbon cycle showed that a significant amount (0.47–0.61 Pg C/year) of soil organic carbon (SOC), resulting from agricultural erosion, moves laterally over the earth's surface, with about 0.32 Pg C/year resulting from cropland alone.

3. Major contaminants from agricultural sources and their environmental implications

3.1. Soil- and water-borne contaminants

Nutrients, trace elements, pesticides, pathogens, and radioactive materials are among the principal contaminants of agricultural origin. The close association/interaction of soil and water in the environment facilitates the mobility and transfer of contaminants between the two systems; as a result, most soil-borne contaminants are also associated with water quality impairment.

Nutrients, particularly N and P, from agricultural sources, have often been documented as key soil- and water-borne contaminants (David and Gentry, 2000; Kleinman et al., 2002; Hart et al., 2004). Frequently documented anthropogenic sources of nutrient input to

agricultural soils include inorganic fertilizers, animal manures, biosolids, and crop residues (Pritchard et al., 2010; Holm et al., 2010; Stacey et al., 2010). Prolonged land application of these materials beyond plant needs could lead to accumulation of excess nutrients in soils and the subsequent release to waterbodies. Primary forms of N in soil and water systems include nitrite (NO_2^-), nitrate (NO_3^-), ammonia (NH_4^+), nitrous oxide (N_2O), nitric oxide (NO), elemental N (N_2) and organic N (Sawyer et al., 2003; Havlin et al., 2013) and these forms are chiefly controlled by the chemistry (pH, redox potential, etc.) and microbial activity of the medium (Havlin et al., 2013; Sawyer et al., 2003). Phosphorus in soil–water system could broadly be grouped into orthophosphate ($H_2PO_4^-$, HPO_4^{-2}), organic P, and complexed P (Fe/$AlPO_4$ and $CaHPO_4$). Mobility and bioavailability of P in the environment is generally controlled by soil minerals, pH, other ions, OM, P saturation, time, and temperature (Sparks, 2003; Sposito, 2008). Phosphorus and N are often transported during surface runoff (dissolved and sediment-bound P and N), leaching (dissolved P and N) and preferential flow (dissolved N) from contaminated soils to surface waterbodies (Follett and Hatfield, 2001; Radcliffe and Cabrera, 2006). Soil and water contamination by potassium is considered a lesser threat to environmental quality and health and is not often cited (Baert et al., 1996).

Heavy metals such as Cu, Cd, Ni, Zn, Cr, cobalt (Co), manganese (Mn), and Hg, as well as other elements such as As, S, aluminum (Al), and iron (Fe) have often been found in toxic amounts in many agricultural soils (Adriano, 2001). Atmospheric deposition and anthropogenic sources such as sewage sludge/biosolids, animal manures, composts, agricultural chemicals (fertilizers and lime), irrigation water, and industrial wastes, are the frequently cited sources of metal input to agricultural soils in England and Wales (Nicholson et al., 2003). The fate of these elements in soil–water systems is influenced by factors such as pH, redox potential, clay minerals, and OM (Adriano, 2001; Sposito, 2008). Over time, metals such as Cu, Fe, Mn, and Zn could accumulate in soils, sorbed by plants (into the food chain) (Arora et al., 2008), or move through surface runoff and leaching to surface and groundwater (Rattan et al., 2005).

The presence of radioactive elements in soil and water systems has also been tied to a number of agricultural materials. Phosphate fertilizers and phosphogypsum (a by-product from phosphate fertilizer plants commonly used as a source of Ca amendment to soils) have been documented as potential sources of uranium (U), thorium (Th), radon (Rn), polonium (Po), and radium (Ra) (Papastefanou et al., 2006; Santos et al., 2006; Abril et al., 2009). Phosphogypsum applied at the rate of 20 Mg ha^{-1} was associated with the additions of 3.0, 15, and 12 MBq ha^{-1} of ^{238}U, ^{226}Ra, and ^{210}Po, respectively, to the treated soils (MBq = megabecquerel, 10^6 Bq). The exhalation of ^{222}Rn from a stack of phosphogypsum and treated soils was found to be correlated with the concentration of ^{226}Ra (Abril et al., 2009). The application of fly ash to agricultural soils to add plant micro- and macro-nutrients has also been associated with the introduction of radioactive elements such as ^{238}U, ^{232}Th, ^{226}Ra, ^{228}Ra, ^{222}Rn and ^{220}Rn to the soil (Mandal and Sengupta, 2003; Papastefanou, 2008), although the levels were reported to be within the permissible limits (Pandey and Singh, 2010).

Pesticides (including pesticide degradates) frequently detected (between 1992 and 2001) in US surface waters (streams) are among those which are heavily used and include the herbicides: atrazine (its degradate-deethylatrazine), metolachlor, cyanazine, alachlor, acetochlor, simazine, prometon, tebuthiuron, 2,4-dichlorophenoxyacetic acid (2,4-D), and diuron, and the insecticides; diazinon, chlorpyrifos, and carbaryl (Gilliom et al., 2006). The pesticides detected in groundwaters are mostly the highly mobile and persistence compounds and includes atrazine (and deethylatrazine), metolachlor, prometon, and simazine (Gilliom et al., 2006). In fish and sediments, historically reported organochlorine pesticides, their degradates and by-products include dichlorodiphenyltrichloroethane (DDT) group compounds, chlordane compounds, dieldrin, and heptachlor epoxide (degradate of heptachlor) (Gilliom et al., 2006). Pesticides in groundwater, and most residues present in surface water enter via the soil (Arias-Estévez et al., 2008). Pesticide occurrence and concentration in soil, surface and groundwater reflect their geographical distributions (e.g. the US Corn Belt), and are influenced by a combination of factors such as climate, agricultural management practices (tillage, irrigation, drainage, etc.), soil characteristics, climate, and hydrogeology (Gilliom et al., 2006). The environmental fate of pesticides is controlled by a combination of biological, chemical and physical factors which include degradation (chemical and microbial), sorption, desorption, volatilization, leaching, runoff, and plant uptake (Wheeler, 2002; Arias-Estévez, 2008).

Pathogens commonly associated with the agricultural use of sewage sludge/biosolids and animal manure include: *Salmonella* spp, *Shigella* spp, Listeria monocytogenes, *Helicobacter pylori*, *Campylobacter* spp, *Coxsackievirus*, hepatitia A virus, rotavirus, *Cryptosporidium*, *Giardia lamblia*, *Toxoplasma gondii*, *Escherichia coli*, *Leptospira* spp, *Cyclospora*, *Microsporidia*, and *Brucella* spp (Gerba and Smith, 2005; Gerba et al., 2011). These pathogens are introduced into soil–water systems, and subsequently to the food chain when untreated and/or improperly treated wastes are surface applied to agricultural soils, and also by direct discharge from storage units (Gerba and Smith, 2005; Pepper et al., 2006). A summary of pathogen densities in primary and secondary sludge are presented in Table 2. The environmental fate of most pathogens is influenced by a number of variables. Soil moisture favors microbial survival, and clay enhances their adsorption to soil surfaces, reducing die off and facilitating transport (Santamaría and Toranzos, 2003). Pathogen survival tends to be lower in sandy soils due to poor water holding capacity (Santamaría and Toranzos, 2003). Other factors that affect pathogen survival include pH, OM content, and temperature of the medium (Demoling et al., 2007). Microbial transport from soil to water systems is facilitated by factors such as water saturation, soil texture, and rainfall (Santamaría and Toranzos, 2003; Maier et al., 2009).

Table 2
Pathogen densities in primary and secondary sludges.[a]

Pathogen	Density in primary Sludges (/g of dry wt)	Density in secondary Sludges (/g of dry wt)
Virus		
Various enteric viruses	10^2–10^4	3×10^2
Bacteriophages	10^5	–
Bacteria		
Total coliforms	10^8–10^9	7×10^8
Faecal coliforms	10^7–10^8	8×10^6
Enterococci	10^6–10^7	2×10^2
Salmonella spp	10^2–10^3	9×10^2
Clostridium spp	10^6	–
Mycobacterium	10^6	–
Protozoa		
Giardia spp	10^2–10^3	10^2–10^3
Helminths		
Ascaris spp	10^2–10^3	10^3
Trichuris vulpis	10^2	$< 10^2$
Toxocara spp	10–10^2	3×10^2

Primary sludge: settled solids obtained after gravity sedimentation of wastewater. Secondary sludge: product obtained after further biodegradation by microorganisms.

[a] Adapted from Lepeuple et al. (2004), after Straub et al. (1993).

3.2. Air-borne contaminants

Air pollutants such as particulate matters ($PM_{2.5}$, PM_{10}), oxides of N, C and S, as well as NH_3, CH_4, H_2S, volatile organic compounds, and pathogens have been commonly tied to biomass burning and surface application of biosolids and animal manures (McCarty et al., 2009a; Chadwick et al., 2011) as well as emissions from feedlots (Beauchemin and McGinn, 2005; Flesch et al., 2007). Conventional tillage, a practice that involves maximum surface disturbance achieved by disking, plowing, and other techniques utilized to loosen the soil and bury crop residues, also impact air quality by the release of fine dust and debris into the atmosphere (Holland, 2004; Baker et al., 2005; Kasumba et al., 2011). The composition of PM depends on several factors but studies have shown that the major components are transition metals, ions (such as sulfate, nitrate), organic compounds, reactive gases, biologic materials, and soil particles (Valavanidis et al., 2008). Particulate matter composition could vary depending on the type of agricultural practices. For instance, PM from livestock units could consist of 90% organic materials, composed of microorganisms (bacteria, fungi, viruses, etc), feed, skin, and fecal particles (Seedorf and Hartung, 2000; Cambra-López et al., 2010). On the other hand, particles emitted through burning of crop residues often contain sulfur, organic components and black carbon (Adler et al., 2011), gaseous compounds (e.g. CO and volatile organic compounds), and particulate compounds (Saarikoski et al., 2007). Particulate emission from disking and harvesting could contain more of carbonaceous materials and soil particles. The chemical components of particulate matter could also vary greatly depending on the type of crop residue. Particulate matter emission from burning of wheat residues were shown to consist of 31% K (by weight) and 36% Cl, while PM emitted from the combustion of rice residues was composed of 84% carbonaceous materials (Hays et al., 2005). Recent studies have reported the detection of polycyclic aromatic hydrocarbons, polychlorinated dibenzo-p-dioxins, and polychlorinated dibenzofurans associated with the burning of agricultural product residues (Estrellan and Iino, 2010).

Biomass is primarily composed of C, oxygen (O), hydrogen (H), N, P, S, and K. Consequently, gaseous compounds such as CO, CO_2, NO, NO_2, N_2O, carbonyl sulfide (COS), CH_4, methyl chloride (CH_3Cl) are common products of biomass burning discharged to the atmosphere. During burning of plant residue, C is released mostly in the form of CO_2, CO, partially oxidized organic carbon compounds, and particulate carbon, while nitrogen (mostly occurring as an amino group), is released typically as N_2, NO, N_2O, NH_3, and hydrogen cyanide (HCN), and sulfur is released as SO_2, COS, SO_4 (non-volatile sulfate) (Levine et al., 2010). Carbon dioxide, N_2O, CH_4 are noted as greenhouse gases (Levine et al., 2010), while NOx, CO, and CH_3Cl are often cited as ozone precursor gases (Hodzic et al., 2007). According to the 2010 U.S. Climate Action Report, agriculture contributes 12% of total greenhouse gas emission (US Department of States, 2010). Apart from biomass burning, microbial decomposition of organic residues is also a common pathway of CO_2, NH_3, CH_4, and H_2S emission to the environment (Møller et al., 2004; Chadwick et al., 2011). Methane release from livestock production is one of the most important sources of CH_4 contribution to the atmosphere. However, natural wetlands and rice paddies under anaerobic conditions are also important pathways of atmospheric gas discharge (Levine et al., 2010).

Air-borne pathogen release to the atmosphere has been associated with the processing (Shammas and Wang, 2009) and surface application of biosolids and animal manures. The fungus, *Aspergillus fumigatus* among other airborne pathogens, has been detected in significant amounts during biosolid composting (Shammas and Wang, 2009). *Thermophilic actinomycetes* such as *Saccharopolyspora faeni* and *Thermoactinomyces vulgaris*, and the fungus *Aspergillus fumigates* have also been reportedly released during animal manure composting (Epstein et al., 2001; Recer et al., 2001). Air-borne mesophilic, xerophilic and thermophilic microorganisms (bacteria and fungi) were detected in significant amounts (4.4×10^2–1.7×10^6 CFU/m^3, CFU = colony forming units per cubic meter) in the air from poultry litter burning plants, with *Aspergillus niger*, *Eurotium herbariorum* and *Scopulariopsis brevicaulis* species among the dominant fungi observed in air (Wultsch et al., 2010).

4. Contaminant impacts on human health

The development of maximum permissible concentrations

Table 3
Contaminants commonly linked to agricultural sources and their permissible limits in soil and drinking water.

Contaminant	MPC (mg kg^{-1}) for soil/MCL (mg L^{-1}) for drinking water			References
	USEPA	EC	WHO	
Nutrients				
Phosphorus	–/–	–/–	–/–	
Nitrogen	–/44.3[a]	–/50.0[a]	–/50.0[a]	Selinus, 2013
Heavy/trace elements				
Nickel	210/–	30–75/0.02	–/0.02	Kabata-Pendias, 2010; Kumar and Puri, 2012; Selinus, 2013
Cadmium	20.0/0.005	1–3/0.005	–/0.003	Kabata-Pendias, 2010; Kumar and Puri, 2012; Selinus, 2013
Copper	750/1.3	50–140/2.0	–/1.0	Kabata-Pendias, 2010; Kumar and Puri, 2012; Selinus, 2013
Lead	150/0.015	50–300/0.01	–/0.01	Kabata-Pendias, 2010; Kumar and Puri, 2012; Selinus, 2013
Arsenic	–/0.01	–/0.01	–/0.01	Kabata-Pendias, 2010; Kumar and Puri, 2012; Selinus, 2013
Pesticides				
Total	–/–	–/0.005	–/–	Hamilton et al., 2003
Air-bone particulates				
PM_{25}	(12.0)[b]	–/–	–/–	USEPA, 2013
PM_{10}	(150)[b]	–/–	–/–	USEPA, 2013

MPC; Maximum Permissible Concentration.
MPL; Maximum Contaminant Limit.
USEPA; United States Envirormental Protection Agency.
EC; European Commission.
WHO; World Health Organization.
[a] Nitrogen measured as nitrate (NO_3).
[b] unit expressed in μg of partiuclate matter in m^3 of air.

Table 4
Contaminants commonly linked to agriculture-related activities/sources and their associated impacts on human health.

Contaminant	Agriculture-related source/activities	Human exposure	Associated health implications	Reference
Nutrients	Land applied and stored sewage sludge/ biosolids, animal manures and inorganic fertilizers; and crop residues	Ingestion of contaminated food and water		
Phosphorus			Cardiovascular risks	Kalantar-Zadeh et al., 2010
			Could worsen chronic kidney diseases	
Nitrogen			Methemoglobinemia	Wolfe and Patx, 2002; Fawell and Nieuwenhuijsen, 2003
			Carcinogenic effect (bladder, prostate, ovary, stomach, and liver)	Weyer et al., 2001; Fawell and Nieuwenhuijsen, 2003
Heavy/trace metals	Sewags sludgs/ biosolids; animal manures; agrochemicals (e.g. fertukuzers and lime); irrigation water; and industrial wastes.	Ingestion of contaminated food and water		
Nickel			Allergic skin reaction	Das et al., 2008
			Carcinogenic, neurologic, reproductive, developmental, and immunologic effects	Gupta et al., 2006; Das et al., 2008
Cadmium			Nephrotoxic (kidney tubular damage; and renal failure)	Kobayashi et al., 2008; Järup and Åkesson, 2009
Copper			Oxidative stress; liver disease; and neurological defects.	Gaetke and chow, 2003; Uriu-Adams and Keen, 2005
			Linked to Alzheimer's disease and Wilson's disease	Miranda et al., 2000; Opazo et al., 2002; Muller et al., 2004
Lead			Imitates calcium and interacts with protein	Lidsky and Schneider et al., 2003; Meyer et al., 2008
			Neurological and intellectual impairments	Meyer et al., 2008; Payne, 2008
Arsenic			Accumulates in tissues (skin, hair, and nails)	Kapaj et al., 2006
			Cardiovascular diseases; renal disease; and chronic lung disease,	Lee et al., 2002
			Cancer (of the lungs, skin, liver, bladder and kidney)	Morales et al., 2000
			Neurological and reproductive effects	Milton et al., 2005
			Spontaneous abortion, stillbirth and infant mortality	Hopenhayn-Rich et al., 2000
Pathogens	Sewage sludge/ biosolids; and animal manuresq	Consumption of contaminated food and water; and inhalation of contaminated air		
Bacteria				
Campylobacter; Salmonella; *Shigella*			Gastroenteritis	Sidhu and Toze, 2009
Helicobacter pyroli			Gastric ulcer and gastric cancer	Engstrand, 2001
Legionella			Respiratory illness	Sidhu and Toze, 2009
Protozoa				
Giardia and *Cryptosporidium*			Gastroenteritis	Adam, 2001

(*continued on next page*)

Table 4 (*continued*)

Contaminant	Agriculture-related source/activities	Human exposure	Associated health implications	Reference
Enterocytozoon bieneusi and *Encephalitozoon intestinalis*			Diarrhea	Mathis et al., 2005
Helminth *Ascaris lumbricoides; Toxocara; Capillaria; Trichuris*			Helminth infections	Von Sperling et al., 2003; Schwartzbroad and Banas, 2003
Pesticides	Applied and stored pesticides	Ingestion of contaminated food (crop, livestock, fish),and water; and inhalation of particulates and volatiles		
e.g., organophosphate, chlorinated pesticides, 2,4-D, atrazine, butylate, diazinon, phorate, carbofuran, lindane, chlordane/heptachlor, chlordane, toxaphene, dieldrin, etc.			Cancers (leukemias and lymphoma)	López et al., 2007
			Parkinson's disease	Ascherio et al., 2006
			Increased risk of diabetes, hyperglycemis, and hyperinsulinemia	Cranmer et al., 2000
			Prostate cancer risk	Alavanja et al., 2003
			Rectal cancer, lung cancer, melanoma	Purdue et al., 2007
Air-borne particulates	Biomass burning	Inhalation of contaminated air		
$PM_{2.2}$ and PM_{10} Airborne pathogens e.g., Aspergillus fumigatus, etc.			Respiratory and heart problems	Macnee and Donaldson, 2003; Lee et al., 2007
			Asthma; allergic rhinitis; upper and lower respiratory disease	Arbex et al., 2007; Tecer et al., 2008
Oxides of C, N, and S; NH_3; CH_4			Alteration in respiratory physiology	Pijnenburg and De Jongste, 2008; Iqbal et al., 2010

(MPC) or maximum contaminant limits (MCL) (Table 3) for water and soil is vital for environmental and human health protection, particularly in intense agricultural regions where these permissible levels may be threatened. A summary of contaminants from agriculture-related activities and the potential human health implications associated with them is presented on Table 4. High P intake, through contaminated food or water, could worsen the condition of individuals with chronic kidney disease, and has also been tied to cardiovascular risks (Kalantar-Zadeh et al., 2010). Inorganic P forms are more readily absorbed by the intestine compared to organic P (Uribarri, 2006; Kalantar-Zadeh et al., 2010). Human ingestion of nitrate-contaminated food and water could endanger health by the direct formation of methemoglobin (resulting from nitrate oxidation of the Fe in hemoglobin from Fe^{2+} to Fe^{3+}) (Wolfe and Patz, 2002; Fawell and Nieuwenhuijsen, 2003). Methemoglobinemia (or blue baby syndrome), often caused by elevated level of methemoglobin in the blood, is particularly critical in infants under 6 months and often manifested through shortness of breath, cyanosis, loss of consciousness, nausea, vomiting, fatigue, dizziness, etc. (Knobeloch et al., 2000; Boxall et al., 2009). Nitrate ingestion is also linked to the formation of carcinogenic nitroso compounds which are associated with bladder, prostrate, ovarian, stomach, and liver cancers (Weyer et al., 2001; Fawell and Nieuwenhuijsen, 2003).

Nickel exposure is known for its neurologic, reproductive, developmental, immunologic, and carcinogenic effects as well as allergic skin reaction on humans (Das et al., 2008). Nickel toxicity in human occurs primarily through the reduction of glutathione (an antioxidant that defends cellular components from the harmful effect of reactive free radical and peroxides) and the bonding to sulphydryl groups of proteins (Das et al., 2008). Exposure to nickel could cause the formation of free radicals in various human and animal tissues leading to increased lipid peroxidation and alteration of DNA bases (Das et al., 2008). Nickel toxicity in peripheral tissues in the lungs, kidney, and liver has also been documented (Gupta et al., 2006; Das et al., 2008).

Human ingestion of cadmium occurs primarily through food. Cadmium is known for its nephrotoxicity, inducing kidney tubular damage, which on higher or prolonged exposure could advance to impaired glomeruli, leading to reduced filtration rate and consequently renal failure (Kobayashi et al., 2008; Järup and Åkesson, 2009). Increased cancer risks and mortality have also been associated with exposure to cadmium (Järup and Åkesson, 2009). Copper toxicity in humans could result in oxidative stress, a disorder involved in many human diseases, and eventually tissue damage (Gaetke and Chow, 2003; Uriu-Adams and Keen, 2005). Chronic Cu toxicity has also been linked to neurological defects and liver disease (Uriu-Adams and Keen, 2005). Copper toxicity has also been linked to a number of human diseases such as Wilson's disease (Müller et al., 2004) and to Alzheimer's disease (Miranda et al., 2000; Opazo et al., 2002).

Lead entry into the human body system could occur through ingestion and/or inhalation. The toxicity of lead is linked to its potential to inhibit or imitate the action of calcium as well as its interaction with proteins (Lidsky and Schneider, 2003; Meyer et al., 2008). Absorbed lead easily binds with the red blood cells and moves to soft tissues, affecting almost every organ and system in the body. Over 90% of lead in the adult body system is found in the

bones and teeth, while about 70% of lead in children is deposited in their bones (Meyer et al., 2008). Exposure to lead is also associated with neurological and intellectual impairments and can lead to death (Meyer et al., 2008; Payne, 2008). The adverse health effects of lead are more pronounced in children (Lidsky and Schneider, 2003).

Human exposure to arsenic has been associated with a number of health concerns. Arsenic has been shown to accumulate in tissues such as skin, hair, and nails and has been linked to vascular disease, renal disease, chronic lung disease, cancer (of lungs, skin, liver, bladder and kidney), as well as to neurological and reproductive effects (Morales et al., 2000; Lee et al., 2002; Milton et al., 2005). Arsenic exposure has also been linked to the impairment of intellectual function and retarded growth in children (Wasserman et al., 2004). Consumption of arsenic contaminated water has also been shown to be associated with spontaneous abortion, stillbirth and infant mortality (Hopenhayn-Rich et al., 2000).

Pathogens from agricultural sources invade the human body system through the consumption of contaminated food and water, and inhalation of contaminated air. Human noroviruses, rotaviruses, and astroviruses are the major causes of gastroenteritis in adults and children worldwide (Kirkwood et al., 2004). Bacterial pathogens such as *Campylobacter*, *Salmonella* and *Shigella*, are also linked to bacterial gastroenteritis (Sidhu and Toze, 2009). *Helicobacter pyroli* is associated with gastric ulcer and gastric cancer (Engstrand, 2001). *Legionella* (a non-enteric pathogen) is linked to life threatening respiratory illness in the elderly (Sidhu and Toze, 2009). Other bacterial pathogens such as *Yersinia enterocolitica*, *Aeromonas* spp. and *Burkholderia cepacia* may cause gastroenteritis in children and certain adults (Peng et al., 2002; Sidhu and Toze, 2009). Protozoan pathogens such as *Giardia* and C*ryptosporidium* are also linked to gastroenteritis (Hörman et al., 2004). Human pathogenic microsporidia (*Enterocytozoon bieneusi* and *Encephalitozoon intestinalis*) are noted for causing diarrhea, particularly in individuals with low immunity (Mathis et al., 2005). Helminth infection caused by *Ascaris lumbricoides*, *Toxocara*, *Capillaria*, *Trichuris*, etc. are also prevalent in biosolids, sewage sludge, and wastewater impacted areas (Von Sperling et al., 2003; Schwartzbrod and Banas, 2003.

Pesticides from agricultural sources have been associated with a number of health hazards in humans. Frequent exposure to low levels of organophosphate has been linked to risks of cancers (leukemias and lymphoma) and other biochemical effects (López et al., 2007). Alavanja et al. (2003) reported an association between the use of chlorinated pesticides and methyl bromide and prostate cancer risk. Parkinson's disease has been associated with exposure to pesticides (Ascherio et al., 2006). Findings by Saldana et al. (2007), suggest that exposure to the herbicides 2, 4-D, atrazine, and butylate, and the insecticides diazinon, phorate, or carbofuran during the first trimester of pregnancy could increase the risk of gestational diabetes mellitus. Increased risk of type 2 diabetes, hyperglycemia, and hyperinsulinemia has also been linked to pesticide exposure (Cranmer et al., 2000). Studies have also shown that exposure to organophosphate and organochlorine insecticides is linked to alteration in the activities of enzymes involved in glucose metabolism and increase in insulin and blood glucose levels in animals (Abdollahi et al., 2004). Possible associations between (a) non-Hodgkin lymphoma and lindane, (b) leukemia and chlordane/heptachlor, (c) rectal cancer and chlordane, (d) melanoma and toxaphene, (e) lung cancer and dieldrin have also been reported (Purdue et al., 2007), although no clear relationships between cancer risk and organochlorines were observed.

Particulate matters (particularly PM_{10}) released during agricultural residue burning if inhaled, can easily penetrate into the lungs inducing and/or exacerbating respiratory and heart problems (MacNee and Donaldson, 2003; Lee et al., 2007). Awasthi et al. (2010) has also shown that small particles ($PM_{2.5}$ and PM_{10}), which are the main components of the smoke produced by crop residue burning impact pulmonary function tests in children. Likewise, the increase in the concentration of suspended particles produced during the burning of sugarcane residues was correlated with the number of hospital admissions of asthmatic patients in Brazil (Arbex et al., 2007). Increases in atmospheric concentrations of PM were also reflected in significant increases in asthma, allergic rhinitis, upper and lower respiratory disease admissions; while a 10 $\mu g/m^3$ increase in $PM_{10-2.5}$ led to 18% rise in asthma admission (Tecer et al., 2008). Exposure to oxides of C, N, and S, emitted through a number of agriculture-related activities such as biomass burning and application of animal manure and biosolids, has also been linked to alteration in respiratory physiology, illnesses and death (Pijnenburg and De Jongste, 2008; Iqbal et al., 2010).

5. Conclusions and perspectives

This work explored the main agricultural activities of environmental concerns; air, water, and soil-borne contaminants from agricultural origins; and the associated human ailments linked to some of these pollutants. The use of biosolids, animal manure, and agricultural chemicals; and practices such as burning of post-harvest residues, irrigation, and tillage operations are vital to the economic production of food and fiber. However, they also pose a number of environmental and health challenges, thus, emphasizing the need for the adoption of research-based best management practices in our pursuit for sustainable agriculture. The weight placed on agriculture to provide food for the growing population as well as feedstock for alternative energy sources, has unfortunately led to the intensification of some of these aforementioned practices. However, there is hardly any argument that the need for food in most parts of the world currently outweighs the risks associated with these practices.

Although not the focus of this paper, the changing climate could exacerbate the environmental and human health implications of agricultural intensification. For instance, increasing temperature could lead to more evaporative losses of water, thus creating more droughty conditions that could expose surface soils to the erodible forces of wind and water. Excessive rainfall could increase the chances of surface runoff of agricultural chemicals and applied nutrient to receiving waterbodies. The depletion of groundwater quantity and quality as a result of low recharge potential, which is partly due to low precipitation and increasing dependence, is also resulting in increasing contaminant levels in most groundwater-irrigated agricultural soils. In the same line with our discussion, previously identified consequences of the changing climate on agriculture include increased (a) use of pesticides and biocides as farming practices intensify, (b) potential of contaminant transport to water supplies, (c) mobilization and bioavailability of soil contaminants, and thus, (d) human exposure to agricultural chemical contaminants and pathogens.

Evidence gathered in the course of this review suggests the need for the continual implementation of research-backed measures to meet the pace of intensification of agricultural activities. Several key management practices can be reemphasized and employed to mitigate the effects of current and future practices of organic amendment and agricultural chemical uses, residue burning, conventional tillage, etc., that accentuate their negative impact on the environment and human health: (1) Application rates of manure and biosolids must follow basic guidelines, which account for inherent soil nutrient content, crop nutrient requirement, and availability of the added nutrient. Effort should also be made to

synchronize nutrient release from these organic amendments with nutrient demand pattern of the crop in question. (2) Incorporation of manure and biosolid immediately after application is recommended to minimize rapid loss of NH_3 through volatilization and pathogen release to the environment. (3) An alternative option to burning crop residue and stubble is to harrow and bale from the fields for off-field use as feed or beddings for livestock. Alternative uses of crop residues such as in energy production can be vital in residue recycling. (4) Since industrial fertilizer production depends on using large quantities of fossil fuels, and production of greenhouse gases such as CO_2, fertilizer input can be reduced by improving nutrient use efficiency of crops, which is achievable by using soil test recommendations to make applications at the right time, place, and rate, using the right source. Continuous and extensive research is also needed on the applicability and use of precision agriculture technologies to improve fertilizer and herbicide use efficiencies. (5) More research-fortified integrated pest management approaches that integrate the life cycles of pests and their interaction with the environment, crop planting date, and population, as well as crop rotations are amongst practices that are useful in mitigating pest infestation, survival, and pesticide use frequency.

No single set of recommendations can solve all environmental problems, hence, adhering to the core concept of sustainable agriculture, which not only considers the economic returns from various practices but also the impact on the environment and future, is vital to our pursuit of a more environmentally-friendly agriculture. Thus, the promotion of this concept should remain one of the ultimate goals of our agricultural and environmental agencies.

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