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Understanding arsenic dynamics in agronomic systems to predict and prevent uptake by crop plants

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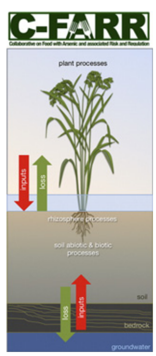
HIGHLIGHTS

- Consumption of staple foods such as rice, apple juice and vegetables grown in contaminated soil is now recognized as a tangible route of human exposure to arsenic
- Arsenic occurs in food because it is present in the soil and water and is taken up by crop plants.
- Understanding the sources of arsenic to crop plants and influence the dynamics of the agronomic arsenic cycle are key to reducing crop uptake of arsenic now, and preventing exposure in future.
- This review considers natural and anthropogenic sources of arsenic to the soil, biogeochemical cycling, rhizosphere processes, plant processes, and mitigation strategies
- This review recommends: mobilizing existing soil data so that it is readily accessible to commercial and private growers; expanding detailed soil monitoring; reconsideration, unification and enforcement of action levels for agricultural soil arsenic based on updated science, community outreach and education about the potential for arsenic in the soil, as necessary steps to protect valuable soil resources.

GRAPHICAL ABSTRACT



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ABSTRACT

This review is on arsenic in agronomic systems, and covers processes that influence the entry of arsenic into the human food supply. The scope is from sources of arsenic (natural and anthropogenic) in soils, biogeochemical

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and rhizosphere processes that control arsenic speciation and availability, through to mechanisms of uptake by crop plants and potential mitigation strategies. This review makes a case for taking steps to prevent or limit crop uptake of arsenic, wherever possible, and to work toward a long-term solution to the presence of arsenic in agronomic systems. The past two decades have seen important advances in our understanding of how biogeochemical and physiological processes influence human exposure to soil arsenic, and this must now prompt an informed reconsideration and unification of regulations to protect the quality of agricultural and residential soils.

1. Introduction

Consumption of staple foods such as rice, beverages such as apple juice, or vegetables grown in historically arsenic-contaminated soils are now recognized as tangible routes of arsenic exposure. The presence of elevated concentrations of arsenic in the soil is not a pre-requisite for dietary arsenic exposure; seen in the accumulation of arsenic by rice grown in uncontaminated soils (Norton et al., 2012). When drinking-water arsenic concentrations are low, dietary arsenic can be a significant exposure (Carlin et al., 2015). Understanding the sources of arsenic to crop plants and the factors that influence them is key to reducing human exposure now and preventing exposure in future. In addition to the abundant natural sources of arsenic, there are a large number of industrial and agricultural sources of arsenic to the soil; from mining wastes, coal fly ash, glass manufacturing, pesticide application, wastewater sludge, pharmaceutical waste, livestock dips, smelting activities to phosphate fertilizers. Plant uptake of arsenic was previously assumed to be too low to merit setting limits for arsenic in food crops, but given that measurable biological effects occur in at arsenic levels below the current maximum contaminant level (MCL) for drinking water (Bodwell et al., 2004), these low levels can still translate into significant exposures, particularly in children (Davis et al., 2012) and presumably in adults who consume a lot of rice. In response, the World Health Organization (WHO) set an advisory MCL for inorganic arsenic in white (polished) rice of 0.2 mg/kg (WHO, 2016) along with the limit of 10 μg/L in water, and the European Union set similar standards that included a lower MCL (0.1 mg/kg) for rice-containing baby foods (European Union, 2015). Currently, dietary arsenic exposure is suspected to play a role in cardiovascular disease in adults (Moon et al., 2012), and to disrupt the glucocorticoid system (involved in learning and memory) to those exposed in utero (Caldwell et al., 2014). An in depth review of the current findings on the relationship between dietary arsenic exposure and human health is provided by Davis et al. (this issue).

In the United States, regulations on arsenic are distributed to several agencies. The Environmental Protection Agency (EPA) developed the MCL for arsenic in drinking water (10 μg/L) in 2006; a level supported by the World Health Organization, Canada and the European Union. In the state of New Jersey (USA) the limit is 5 μg/L, and in Australia, 7 μg/L. Many other nations still adopt a level of 50 μg/L (Bahrain, Bangladesh, Bolivia, China, Egypt, India, Indonesia, Oman, Philippines, Saudi Arabia, Sri Lanka, Vietnam, Zimbabwe) (Yamamura et al., 2001), with the exception of Mexico (35 μg/L). In the USA, The Food and Drug Administration (FDA) is responsible for setting action levels for arsenic in food, which includes apple and pear juice at 10 μg/L, in line with EPA's drinking water MCL. In Canada, the Canadian Food Inspection Agency issued alerts on excessive arsenic in rice and pear products in 2014. Consistent with the European Commission's limit for arsenic in rice used in food production for infants and young children, the FDA is proposing an action level of 0.1 mg/kg for inorganic arsenic in infant rice cereal (FDA, U., 2016). Foods in Australia and New Zealand may not contain >1 mg/kg dry mass of arsenic, and salt for food use must not contain >0.5 mg/kg. Japan has a limit of 15 mg/kg of arsenic in paddy soils (Japan, 2016). Likewise, Thailand has an agricultural arsenic soil quality standard of 3.9 mg/kg. Within the USA, states differ widely in their action levels for arsenic in soil, for instance New Jersey has a cleanup criterion of 20 mg/kg and Florida has a cleanup target level of 2.1 mg/kg and 12 mg/kg for industrial sites (Henke, 2009).

Arsenic occurs in food because it is present in soil and water and is taken up by plants. This review article brings together the latest scientific information on arsenic in agronomic systems, describing its sources in soils and the processes that influence the uptake of arsenic by crop plants. The intention of this review is to prompt a reconsideration and unification of government regulations on action levels for arsenic in agricultural soil; raise awareness of how both former and ongoing inputs of arsenic to soil can result in food contamination and impacts to human health and finally, to indicate the way forward for mitigation strategies that safeguard valuable soil resources.

2. Natural sources of arsenic in soil

Below toxic concentrations, the higher the total soil arsenic concentration (the sum of all arsenic species, regardless of bioavailability) the higher the crop uptake of arsenic. This is true of anaerobic cultivation systems such as rice (Adomako et al., 2009; Lu et al., 2009; Williams et al., 2007), aerobic horticultural systems (Norton et al., 2013) as well as conventional (aerobic) agriculture (Williams et al., 2007). The global average total soil arsenic concentration is 5 mg/kg, (equivalent to parts per million), but there is large variation between and within geographical regions (Koljonen et al., 1989). Where soils have formed on arsenic-rich bedrock, or downstream of these bedrocks, very high concentrations of natural arsenic can result. Concentrations of up to 4000 mg/kg arsenic have been measured in soils from the arsenopyrite belt (iron arsenic sulfide, FeAsS) in Styria, Austria (Geiszinger et al., 2002), for instance. There are approximately 568 known minerals that contain arsenic as a critical component (IMA, 2014). Arsenic is present in many rock-forming minerals because it can chemically substitute for phosphorus (V), silicate (IV), aluminum (III), iron (III) and titanium (IV) in mineral structures. Global mapping data of total arsenic concentrations in topsoil is not available, although large-scale regional maps are available for soil arsenic concentrations in Europe (Lado et al., 2008) and the USA (Shacklette and Boerngen, 1984). European data predicts that most soils range <7.5–20 mg/kg arsenic, with a median of 6 mg/kg (Lado et al., 2008). This prediction comes from block regression-kriging; a spatial prediction technique based on regressing soil arsenic concentrations against auxiliary variables, and is useful because it uses a particularly high resolution (block size of 5 km^2). On a continental scale, large zones of soils with approximately 30 mg/kg arsenic have been found in southern France, the north-eastern Iberian Peninsula and south-west England, with the two latter being zones of extensive natural mineralization associated with base and precious metal mining activities. The United State Geological Survey (USGS) soil sampling of the contiguous USA reports a mean soil arsenic concentration of approximately 5 mg/kg with 5 and 95 percentile values of approximately 1.3 and 13 mg/kg respectively (Smith et al., 2014). Large regional patterns are apparent in the data, for example the soils of New Hampshire have soil arsenic concentrations of approximately 10 mg/kg arsenic, and Florida, 3.5 mg/kg. The sampling density goal for the USA surface soils and stream sediments database is 1 per 289 km^2 (USGS, 2016), but is currently at only 1 sample per 1600 km^2. This contrasts with smaller regional surveys such as the recently published Tellus database for