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Contribution of atmospheric deposition to soil provisioning ecosystem services in the contiguous United States: Part 1. Calcium

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Abstract

Soil provisioning ecosystem services may be impacted by the atmospheric deposition of calcium ions (Ca^{2+}). Atmospheric deposition can serve as an input of Ca^{2+} to soils; however, deposition varies spatially across the United States (U.S.). This study ranked an estimated provisioning value of soil ecosystem services due to atmospheric Ca^{2+} deposition within the contiguous U.S. by state and region. The total provisioning ecosystem value of atmospheric calcium deposition was $65M (i.e., 65 million U.S. dollars) based on an average 2014 price of $10.42 per U.S. ton of agricultural limestone ($CaCO_3$) or nearly $355M based on an average 2014 price of $33.00 per U.S. ton gypsum ($CaSO_4 \cdot 2H_2O$). The highest ranked regions for total value of Ca^{2+} deposition were: 1) Northern Plains, 2) Midwest and 3) South Central while the highest ranked regions based on area-normalized values were: 1) South Central, 2) Midwest and 3) Northern Plains. The highest ranked states for total value of Ca^{2+} deposition were: 1) Texas, 2) Kansas and 3) New Mexico while the highest ranked states based on area-normalized values were: 1) Kansas, 2) Iowa and 3) Illinois. The results of this study begin to provide an estimated value of the importance of atmospheric calcium deposition when assessing ecosystem services. The potential impacts on society from this research include adding calcium deposition into the ecosystem services framework for the United Nations (UN) Sustainable Development Goals.

Keywords: Agriculture, Calcium, Fertility, Fertilization, Food security, Gypsum, Land use, Market failure, Soil inorganic carbon (SIC), STATSGO

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Natural systems provide life-supporting and life-enhancing services, which are called "ecosystem services" (Heal, 2000). Ecosystem services, as defined by the Millennium Ecosystem Assessment (2005), are the "benefits people obtain from ecosystems. These include provisioning services such as food and water; regulating services such as flood and disease control; cultural services such as spiritual, recreational, and cultural benefits; and supporting services, such as nutrient cycling, that maintain the conditions for life on Earth." In economic terms, ecosystems provide various goods (physical products) and services (processes and conditions that benefit human life), which are included in the frameworks for ecosystem services (Brown et al., 2007). Frameworks for ecosystem services are increasingly used for economic and environmental policy making with regards to atmospheric emissions and air quality management (Daily et al., 2009; Smart et al., 2011; Maes et al., 2012). A key group of ecosystem services relate to the provision of food and fiber, and are therefore called "provisioning" ecosystem services (Heal, 2000).

According to Heal (2000), many of the services provided by the natural environment (including the atmosphere and atmospheric deposition) do not go through the market (Fig. 1). The atmosphere is considered to be a "public good", which is nonrival and nonexcludable.

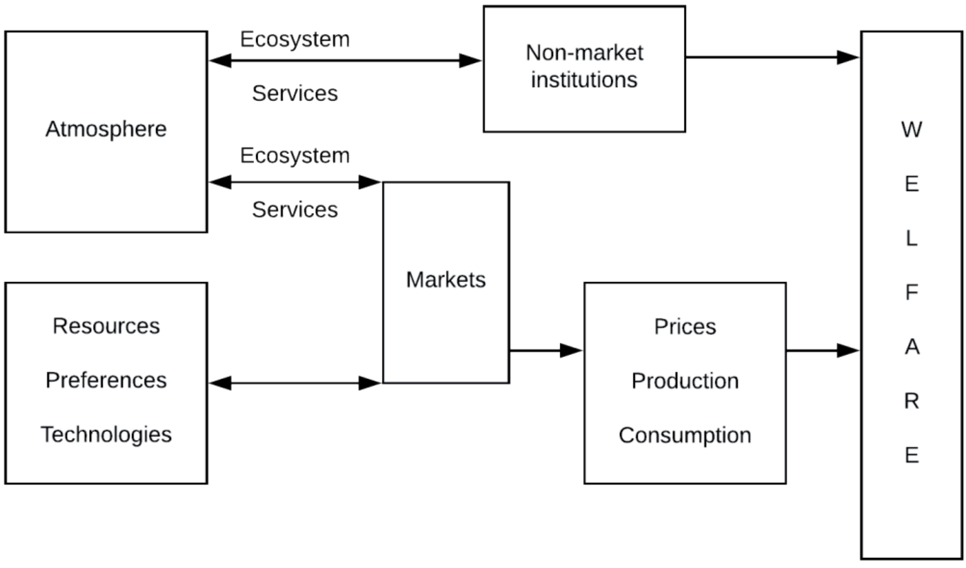

Fig. 1. Conceptual diagram of how the market transforms resources into goods and services that meet human demand. Non-market institutions are sometimes needed to mediate the interactions between humans and the environment (Adapted from Heal, 2000)

Atmospheric deposition, on the other hand, is not always a "public good" since it can be deposited in the soils within "private boundaries" (e.g., a farm), and therefore should be considered a "private good" for which consumption is "rival" and "excludable" (Heal, 2000). Current scientific research supports this notion by quantifying atmospheric deposition within specific soils and geographic boundaries, which can be further linked to "public" and "private" domains. Atmospheric deposition can be a source of ecosystem goods (e.g., nutrients) and services (e.g., soil build-up) (Tozer & Leys, 2013). For example, the long-term productivity of the Amazon rainforest depends on the atmospheric deposition of nutrients (especially phosphorus, P) from the Saharan desert (Okin et al., 2004). Yu et al. (2015) reported that the "imported" dust could provide about 0.022 (0.006–0.037) Tg P of phosphorus per year, equivalent to 23 (7–39) g P $ha^{-1}yr^{-1}$ to fertilize the Amazon rainforest. Swap et al. (1992) estimated annual importation of dust in the order of 13 Mtons (190 kg ha^{-1} yr^{-1}) into the northeastern Amazon Basin with the deposition of trace species, such as phosphate in the range of 1-4 kg ha^{-1} yr^{-1}. Atmospheric inputs of elements can sustain the productivity of highly weathered soils in the Hawaiian rainforests where marine aerosols supply cations and phosphorus which are deposited from Central Asian dust (Chadwick et al., 1999). Sankey et al. (2012) documented transport of biologically important nutrients by wind in an eroding cold desert.

Since the atmosphere is commonly viewed as a public good, it is often excluded from the market and consequently its atmospheric deposition is not defined in the goods category. This study argues that atmospheric calcium deposition in the soils and within geographic areas may be important in providing provisioning ecosystem services because it can provide "private" goods (e.g., Ca^{2+}, $CaCO_3$, $CaSO_4•2H_2O$) and services (e.g., provisioning: food, fiber, etc.), which can be incorporated into the market. Economic valuation of atmospheric calcium deposition is useful for policy and management since privately owned goods can lead to economic efficiency (Heal, 2000).

Calcium is a life-supporting good, which plays a crucial role in soils, plants, and human nutrition as well as in the microbial geochemical cycle (Havlin et al., 1999; Zavarzin, 2002; Wang & Li, 2008). Calcium flocculates clay particles and organic matter in soils, leading to enhanced soil structure, texture and porosity which, in turn, result in better soil aeration and drainage (Schlesinger, 1997; Brady & Weil, 2004). Calcium is required in large amounts for many plants because it is important in cellular processes as well as for cell wall health and strength (Havlin et al., 1999; USDA/NRCS, 1999; USDA/ARS, 2006). Goddard et al. (2009) quantified continental United States atmospheric wet calcium deposition and related it to the "regulating services" with regards to the potential formation of soil inorganic carbon (SIC) stocks, but did not provide a monetary valuation of these goods and services. Groshans et al. (2018a,b) proposed to account for SIC in the ecosystem services framework for the United Nations sustainable development goals and used liming replacement costs to assess the value of SIC at the farm and country scales.

For soils with calcium deficiencies, the two most common soil amendments used for supplementing calcium are agricultural limestone ($CaCO_3$) and gypsum ($CaSO_4•2H_2O$). In general, limestone would be the amendment of choice for acidic soils when calcium addition is accompanied by the desire to increase soil pH. If soil pH does not need to be increased, however, then gypsum would likely be the calcium amendment used because it is not a liming material (USDA/ARS, 2006; Chen & Dick, 2011). Gypsum is also typically used to remediate sodic soils (Brady & Weil, 2004). In contrast with common agricultural liming materials such as limestone, gypsum is more readily soluble in water and therefore can dissolve and move calcium deep into the soil to alleviate the adverse effects of aluminum or sodium at depth (USDA/ARS, 2006).

The impacts of atmospheric deposition on agriculture are significant. However, studies estimating the economic impacts of atmospheric deposition on agriculture are lacking. For instance, atmospheric deposition of Ca^{2+} ions changes the nutrient contents in soil, which in turn affects both quantity and quality of agricultural outputs (Chen & Dick, 2011). And yet, while agricultural outputs all have their prices in the market, the economic value of the atmospheric deposition of Ca^{2+} ions has not been recognized in the market. This amounts to a market failure, as the market has failed to reflect the full benefits of the atmospheric deposition of Ca^{2+} ions. It is vitally important, however, to determine the economic valuation of such atmospheric deposition, as doing so will provide a way to justify the efficient actions and policies necessary to maintain a sound system of atmospheric deposition.

Previous research focused primarily on either quantifying the atmospheric nutrient deposition to various ecosystems or on negative economic impacts of atmospheric deposition (e.g., dust storms) but overlooked the potential positive economic impacts of atmospheric deposition and linkages to the administrative units (Williams & Young, 1999; Tozer & Lays, 2013). This study uses the replacement cost approach, which evaluates the cost of replacing an ecosystem service with a perfect man-made substitute. The replacement cost method is best used in cases such as this, where it is employed to establish the economic value of a single, rather than multiple, ecosystem services (Sundberg, 2004). The objective of this study was to assess and rank the contribution of atmospheric calcium (Ca^{2+}) deposition to soil provisioning ecosystem services within the contiguous United States (U.S.) by state and region. A monetary valuation of total (wet plus dry) atmospheric calcium (Ca^{2+}) deposition was calculated based on an average U.S. price of \$10.42 in the year 2014 per U.S. ton of limestone ($CaCO_3$) and an average U.S. price of \$33.00 in the year 2014 per U.S. ton of gypsum ($CaSO_4 \bullet 2H_2O$) (USGS, 2016; USGS, 2017).

2. Materials and methods

2.1 Total atmospheric Ca^{2+} deposition

Maps of annual atmospheric total deposition of Ca^{2+} (kg ha^{-1}) for the years 2000 through 2015 were downloaded from the National Atmospheric Deposition Program website (NADP, 2018) in Grid format (Table 1). Details on sample collection, laboratory methods, quality

Table 1. Data sources and descriptions (adapted from Goddard et al., 2009)

Data layer	Description	Source
Ca^{2+} deposition	Inverse Distance Weightingmaps in ArcGIS® Grid format – 2500 m resolution	http://nadp.slh.wisc.edu/NTN/annualmapsByYear.aspx
Loess	Gridded 0.1° × 0.1° from maps from the U.S. Geologic Survey	Lineback et al., 1983; Miller et al., 1988; Holbrook, et al., 1990; Gray et al., 1991; Hallberg et al., 1991; Denne et al., 1993; Whitfield et al., 1993; Swinehart et al., 1994

control, and calculations for annual atmospheric total deposition of Ca^{2+} at field sites can be found in several open-source publications using the NADP website (NADP, 2018). A detailed explanation of the NADP mapping methodology can be found in Schwede and Lear (2014). Briefly, estimates of annual atmospheric total deposition of Ca^{2+} at field sites are spatially interpolated to a continuous raster (gridded) map layer using Inverse Distance Weighting.

2.2 Loess distribution

Loess distribution was mapped using 0.1 × 0.1° gridded map layers derived from U.S. Geological Survey (USGS) maps (Lineback et al., 1983; Miller et al., 1988; Holbrook et al., 1990; Gray et al., 1991; Hallberg et al., 1991; Denne et al., 1993; Whitfield et al., 1993; Swinehart et al., 1994) by Kohfeld & Harrison (2001). This map layer depicts the approximate boundaries of loess deposition (Table 1).

2.3 Data analyses

A map of the annual mean total atmospheric deposition of Ca^{2+} (kg ha^{-1}) over the study period was computed using the Cell Statistics script in ArcGIS® 10.4 (ESRI, 2016). Summary statistics of this map were computed for each of the contiguous United States using the Zonal Statistics script in ArcGIS® 10.4 (ESRI, 2016). The annual mean atmospheric total deposition of Ca^{2+} (kg ha^{-1}) over the study period for each state wasthen converted to U.S. dollars per area (i.e., hectare) and U.S. dollars in Microsoft Excel using the following equations:

$$\$/ha = (Ca^{2+}deposition, kg/ha) \times \frac{100.09g\ CaCO_3}{40.08\ g\ Ca^{2+}} \times \frac{1lb_m}{453.59g} \times \frac{1U.S.ton}{2000\,lb_m} \times \frac{\$\,price}{U.S.ton\ CaCO_3} \quad (1)$$

$$\$/ha = (Ca^{2+}deposition, kg/ha) \times \frac{172.17g\ CaCO_4{\cdot}2H_2O}{40.08\ g\ Ca^{2+}} \times \frac{1lb_m}{453.59g} \times \frac{1U.S.ton}{2000\,lb_m} \times \frac{\$\,price}{U.S.ton\ CaCO_4{\cdot}2H_2O} \quad (2)$$

$$\$/ha = (price\ per\ area\ from\ eqn.1\ or\ 2) \times (area\ in\ ha) \quad (3)$$

Note that the price values calculated in U.S. dollars and dollars per ha represent the money that would be required simply to purchase agricultural limestone ($CaCO_3$) or gypsum ($CaSO_4{\bullet}2H_2O$) based on an average price of $10.42 per U.S. ton of $CaCO_3$ in U.S. (2014) and a 2014 U.S. average price of $33.00 per U.S. ton of uncalcined gypsum (USGS, 2016; USGS, 2017). The values reported would not cover other important costs, such as the equipment, fuel, and labor that would be required to incorporate the calcium amendments into the soil, nor any external costs associated with mining the limestone, gypsum, etc. (Groshans et al., 2018b). The reported values also assume that all calcium being deposited onto the soils by deposition remains in the soil and is not subject to losses due to runoff, erosion, groundwater recharge, etc. Lastly, it is important to take note that the original sources of calcium in the deposition is not accounted for in our analyses; because calcium in rainfall and dust is thought to originate primarily from terrestrial sources (e.g., wind erosion of soils), there likely is some amount of calcium recycling and redistribution that occurs both spatially and temporally across the U.S. (Schlesinger, 1997; Goddard et al., 2009).

3. Results and discussion

Atmospheric Ca^{2+} deposition provides a substantial monetary value to the U.S. and it was evaluated by state and region using an accounting framework adapted from Groshans et al. (2018b). Atmospheric Ca^{2+} deposition provides goods (e.g., Ca^{2+}, etc.) and services (e.g., provisioning, etc.) for agricultural benefit (e.g., liming, etc.) and therefore can be evaluated using commodity prices for agricultural limestone ($CaCO_3$) and gypsum ($CaSO_4 \bullet 2H_2O$) (Table 2). The total provisioning ecosystem value of atmospheric calcium deposition was \$65M (i.e., 65 million U.S. dollars) based on an average 2014 price of \$10.42 per U.S. ton of $CaCO_3$ or nearly \$355M based on an average 2014 price of \$33.00 per U.S. ton of gypsum ($CaSO_4 \bullet 2H_2O$). The value of average annual Ca^{2+} deposition varies at the country scale by state and region.

3.1 The value of average annual total Ca^{2+} deposition at the country scale by state and region (2000-2015)

The highest ranked states for value of total Ca^{2+} deposition were: 1) Texas (\$9.30M, \$50.7M), 2) Kansas (\$3.67M, \$20.0M), and 3) New Mexico (\$3.53M, \$19.3M), where the first and second values shown in parentheses for each state are based on the price of limestone or gypsum, respectively. The top three states with the highest area-normalized total mean annual values were:1) Kansas (\$0.17 ha^{-1}, \$0.94 ha^{-1}), 2) Iowa (\$0.16ha^{-1}, \$0.86 ha^{-1}), and 3) Illinois (\$0.14 ha^{-1}, \$0.76 ha^{-1}) (Fig. 2).The highest ranked regions for value of total Ca^{2+} deposition were: 1) Northern Plains (\$14.7M, \$80.2M), 2) Midwest (\$14.0M, \$76.5M), and 3) South Central (\$13.7M, \$74.5M), while the highest ranked regions based on area-normalized total Ca^{2+} deposition values were: 1) South Central (\$0.12 ha^{-1}, \$0.67 ha^{-1}), 2) Midwest (\$0.12 ha^{-1}, \$0.64 ha^{-1}), and 3) Northern Plains (\$0.09 ha^{-1}, \$0.47 ha^{-1}) where again the two values in parentheses are based on limestone and gypsum, respectively.

Table 2. Conceptual overview of the annual atmospheric Ca^{2+} deposition accounting framework used in this study (adapted from Groshans et al., 2018b)

Biophysical Accounts (science-based)	**Administrative Accounts (boundary-based)**	**Monetary Accounts**	**Benefits**	**Value**
Soil extent:	Administrative extent:	Ecosystem good(s) and service(s):	Agriculture:	Commodity:
- Soil order	- Country - State - Region	Goods: - Ca^{2+}, $CaCO_3$, $CaSO_4 \bullet 2H_2O$ Services: - Provisioning (e.g., food) - Commodity	- Liming equivalent - pH buffering	- Price of lime - Price of gypsum

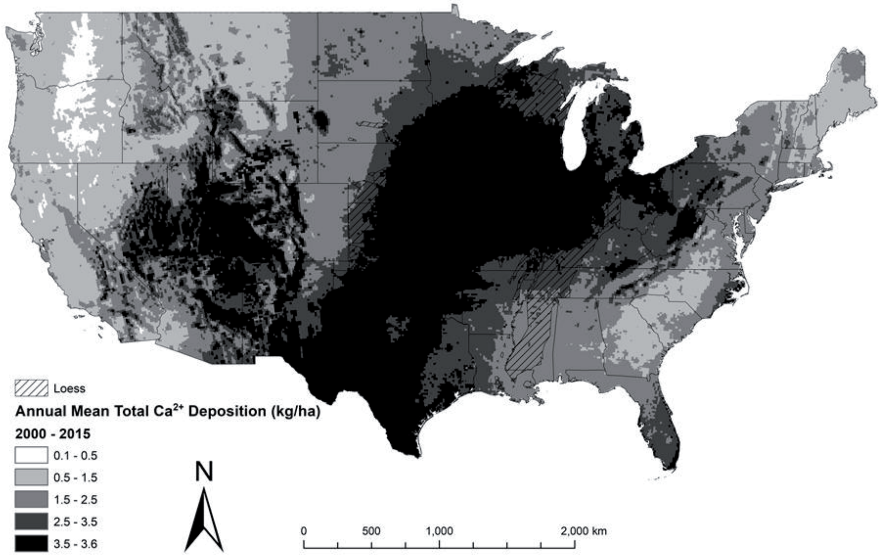

Fig. 2. Average annual total Ca^{2+} deposition (kg/ha) for the years 2000 to 2015 in the contiguous United States

3.2 Economic and management implications

The atmosphere is traditionally viewed as a "public good" outside of market evaluation, but it can be a source of nutrients deposited into the soils within privately-owned lands in different geographic regions. This deposition can be quantified, valuated, and linked to the property rights and markets for more efficient use and management. Coase (1960) argued that introduction of property rights for the goods and services allows for "these goods and services to be traded and their provision regulated by the market and by the legal system." Why is atmospheric calcium deposition economically important? Atmospheric calcium deposition is important for crop productivity and soil nutrient management. Knowledge of atmospheric calcium deposition and its market value can lead to more efficient use of liming and fertilizer materials therefore benefiting farmers, consumers, and society in general.

Calcium from atmospheric deposition improves the quality (nutrient content) and quantity (yield) of crops (USDA/NRCS, 1999), leading to a net gain in the welfare of society as a whole. The monetary benefits of atmospheric deposition of Ca^{2+} ions for food consumers, producers, and overall society can be estimated based on its values calculated in this paper. The welfare changes, when atmospheric deposition of Ca^{2+} ions is and is not present, are illustrated with the following example.

When calcium is present in atmospheric deposition, the supply curve of agricultural commodity A is S_1 and the demand curve of it is D_1 (Fig. 3). The corresponding market equilibrium price and quantity of A are p and q_1, respectively. The consumer surplus, which measures the consumer's monetary gain by purchasing the commodity A, is the area bpa; the producer surplus, which measures the producer's monetary gain by selling the commodity A, is the area pca. The total social welfare, which is the summation of consumer and producer surpluses, is the area bca.

Now let's consider a situation where calcium is not available in atmospheric deposition. For producers, they would have to purchase the same amount of calcium (normally from fertilizers) in order to grow commodity A. This would mean that their input costs would be higher. For consumers, their demand for commodity A would go down, because its quality (i.e., its nutrient content) decreases the less calcium there is in it. The new supply and demand curves are S_2 and D_2, respectively. The market equilibrium quantity decreases from q_1 to q_2 . The equilibrium market price may remain the same, go up, or go down, dependent on the other market conditions of commodity A. Assuming for simplicity that the new price remains the same (though the following analysis would be the same if the new price goes up or down), the consumer and producer surpluses are the area epd and pfd, respectively. The total social welfare is the area efd. When calcium is not present in atmospheric deposition, the consumer's and producer's monetary gains (consumer and producer surplus) reduce by the areas of beda and fcad, respectively.

In the market of commodity A, the total social welfare reduces by the area beda plus fcad. The monetary values of loss in consumer, producer, and social welfare depend on the shapes of the supply and demand curves in the market, and more importantly, on the value of calcium in atmospheric deposition. The values calculated in this study allow one to quantify welfare gains (losses) in different crop markets at different locations when calcium in atmospheric deposition is present (absent). Moreover, the aggregate welfare changes can also be estimated by adding up all welfare changes from individual markets.

Besides providing necessary information for welfare analysis, this study has other important economic implications. First, the values calculated in this article are helpful in raising public awareness of the impacts of atmospheric depositions on agriculture by putting a "price tag" on atmospheric deposition of Ca^{2+} ions. Second, policymaking to regulate open access resources (like atmospheric deposition in this case) is, in general, a slow and costly procedure, as the spatial heterogeneity of those resources has to be

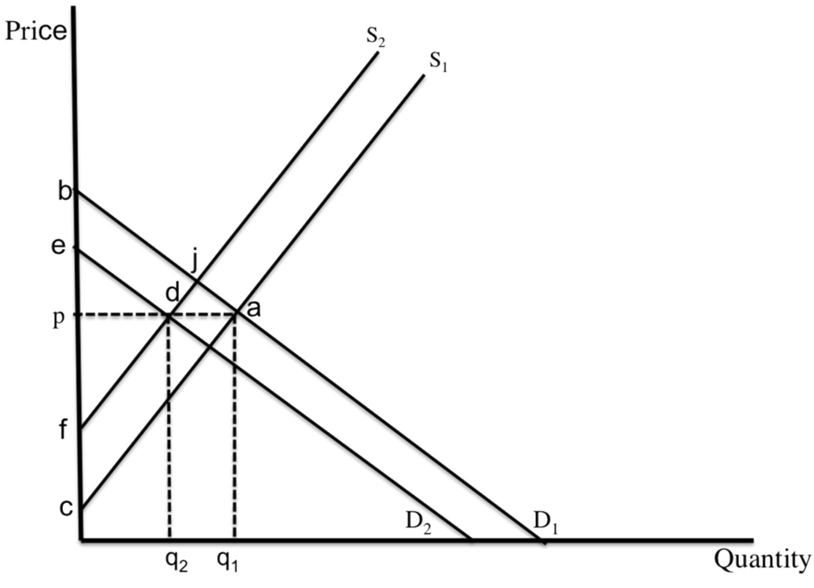

Fig. 3. The consumer surplus, producer surplus, and total social welfare when atmospheric deposition of Ca^{2+} ions is and is not present

addressed (Carlsson & Sandström, 2008). The evaluation procedure in the study, with its focus on regional differences, provides important and valuable information for future policymaking. Third, while the current literature is rich in cost-benefit analyses of environmental interventions (for example, studies of the Greenhouse effect), the value of the atmospheric deposition of Ca^{2+} ions and its effects on welfare have not been taken into account in most analyses. Without recognizing the market value of the atmospheric deposition Ca^{2+} ions, past findings related to this topic might be biased or even outright misleading.

Atmospheric calcium deposition can be a significant source of a life-supporting nutrient, which is important in achieving one of the 17 United Nations (UN) Sustainable Development Goals: "2. End hunger, achieve food security, and improve nutrition and promote sustainable agriculture." Given a global population of 7.5 billion people (2017), and a recommended daily intake of 1 g per person per day of calcium (U.S. Department of Health and Human Services and U.S. Department of Agriculture, 2015-2020), it would require at least 7500 metric tons/day of calcium to ensure that every person is able to meet their daily calcium requirement.

4. Conclusions

Soil provisioning ecosystem services are impacted by the atmospheric input of calcium (Ca^{2+}) ions. Annual atmospheric deposition of Ca^{2+} ions furthers the liming of soil; however, deposition spatially varies in the United States. For example, the Midwest and Northern Plains regions have high Ca^{2+} deposition due to Ca-rich dust from loess-derived particles and relatively low rainfall (e.g., mean annual precipitation <120 cm yr^{-1}). Some fraction of the deposited Ca^{2+} will be available for plant uptake. This study ranked the provisioning value of soil ecosystem services of atmospheric Ca^{2+} deposition from 2000 to 2015 within the contiguous United States by state and region. The total provisioning ecosystem value of atmospheric calcium deposition was \$65M (i.e., 65 million U.S. dollars) based on an average 2014 price of \$10.42 per U.S. ton $CaCO_3$ or nearly \$355M based on an average 2014 price of \$33.00 per U.S. ton gypsum ($CaSO_4{\bullet}2H_2O$). Calculating global terrestrial soil nutrient pools and fluxes requires an understanding of the dynamic nature of atmospheric Ca^{2+} deposition. The atmosphere is traditionally viewed as a "public good" outside of market evaluation, but it can be a source of nutrients deposited to the soils within privately-owned lands in different geographic regions.

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