N-related greenhouse gases in North America: Innovations for a sustainable future

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ABSTRACT

Agriculture contributes about 70-75% of Canadian and US anthropogenic emissions of nitrous oxide (N₂O). Although progress has been made in recent decades to improve nitrogen use efficiency (NUE) in North America, including a decrease in N₂O emissions per kilogram of harvested grain, significant technological, economic, and social impediments remain for further progress. A consensus has emerged for the need to foster partnerships to promote NUE research, extension, implementation, and performance indicators that encompass technical, social, and economic drivers of nutrient management. Recent innovative approaches include market trading, supply chain incentives, and consumer awareness. North America is a test bed for achieving greenhouse gas reduction and sustainability targets through voluntary private and public sector partnerships among growers, retailers, industry, scientists, regulators, and NGOs.

INTRODUCTION

Of all the major elements, human alteration of the nitrogen (N) cycle has been the most profound when natural vs. anthropogenic rates of mobilization are compared. For example, annual anthropogenic emissions of carbon dioxide (CO₂) are <10% of natural global fluxes of CO₂ through photosynthesis and respiration, whereas humans have about doubled the annual rate of fixation of atmospheric dinitrogen (N₂) gas into reactive N forms [1, 2]. Because of intensive agricultural and industrial development, the alteration of the US N cycle is greater than the global average [3], increasing N inputs to land by more than a factor of five over background rates [4,5]. On the other hand, while N fertilizer use is growing in emerging-market regions such as Asia, it has nearly leveled off in the USA and is growing only modestly in Canada [6,7]. Future trends will depend upon population growth, dietary choices, international trade, agricultural technology development and adoption, and economic, agronomic, and environmental policies.

Because of the phenomenon referred to as the nitrogen cascade [8], each atom of N present in reactive N species (defined as any N compound other than N₂) can be transformed to numerous other reactive N species, each of which can have its own unique impact on the environment until the reactive N is eventually converted back to unreactive N₂. Nitrous oxide (N₂O) is a form of

reactive N that has a mean residence time in the atmosphere on the order of 120 years [9], which means that several generations of humans will be impacted by current emissions. Although only a small fraction of reactive N is converted to N₂O, this species has a large environmental impact because it is both a potent greenhouse gas (GHG) and a reactant in destruction of stratospheric ozone [10]. This difference between quantity and impact makes mitigation of N₂O particularly challenging. While fertilizer costs may be as much as one-third of a farmer's operating costs, the small fraction that is lost as N₂O is economically trivial to the farmer. On the other hand, the impacts to society in terms of climate and stratospheric ozone stabilization are substantial.

Globally, about two-thirds of gross anthropogenic emissions of N₂O are from agriculture [10]. For North America, agriculture's contribution is slightly higher, at 70-75% (Figure 1). Fossil fuel combustion is the second largest source for North America (12-23%), again equal or slightly higher than the global average. In contrast, biomass burning is a less important source than in regions with tropical savannas.

US emissions of N₂O have been relatively constant over the period 1990 to 2005, with modest declines in emissions from industrial, transportation, and energy sectors offset by modest increases from agriculture (Figure 1). In contrast, agricultural emissions from Canada increased from 1990 to 2005 [7]. Future trends are uncertain. The US Environmental Protection Agency report (EPA:

<http://www.epa.gov/climatechange/EPAactivities/economics/nonco2projections.html>) used for projections in Figure 1 indicates that agricultural emissions in both the USA and Canada will grow about 50% from 2005 to 2030. However, the projected growth shown for 2010 did not occur in the USA, according to annual inventories since then (EPA: <http://www.epa.gov/climatechange/ghgemissions/usinventoryreport.html>).

Nitric oxide and nitrogen dioxide (NO and NO₂, respectively, and collectively known as NO_x) are also N-related GHGs because of their role in the formation of tropospheric O₃ (along with sunlight and volatile organic carbon compounds). In contrast to N₂O, however, agriculture contributes less than 10% of NO_x emissions [11,12] (US EPA: <http://www.epa.gov/ttnchie1/trends/>). Fortunately, NO_x emissions have declined from energy and transportation sectors in recent decades in North America, so that overall NO_x emissions are declining [3].

Here we focus here on innovations related to mitigating the relatively large agricultural emissions of N₂O in North America. We first consider technical innovations and socioeconomic impediments at the farm level. We then describe emerging market-driven innovations, such as including N₂O protocols in carbon trading markets and corporate efforts to improve the sustainability of their supply chains. Finally, we discuss a growing trend of consumer awareness of nitrogen issues. In contrast to regulatory approaches that have had some successes in Europe, the current political aversion in the USA and Canada to command-and-control regulation has created conditions for North American to become a test bed for the effectiveness of voluntary approaches for improved nutrient management led by the private sector.

INNOVATIONS IN NITROGEN AND N₂O MANAGEMENT ON THE FARM

Nitrogen use efficiency (NUE) has increased in US agriculture during the last three decades due to increasing crop yields while N application rates have mostly leveled off [3,6] (USDA: <http://www.ers.usda.gov/data-products/fertilizer-use-and-price.aspx#26718>). The increase in NUE has been particularly pronounced where improved irrigation and planting of hybrid seed have permitted crop yields to increase without substantially increasing N inputs. Additional innovations contributing to improved NUE include genetically modified, stacked-trait crops, precision agriculture technologies, conservation tillage practices, and decision support tools for farmers and crop advisors. Associated with this increase in NUE has been a decrease in N₂O emission intensity, from 0.62 mg N₂O per kilogram of harvested corn grain in the 1990s to 0.47 mg N₂O kg⁻¹ of harvested corn grain in the late 2000s [6]. Similar gains in GHG intensity have also been reported for other crops in the US (Field to Green, 2010). There remains considerable potential for further N₂O emission reduction, such as estimates of about 6 million tCO₂e per year mitigation from N rate reduction projects in corn in the North Central Region of the U.S. alone [13].

North American companies are actively contributing to the global fertilizer industry's efforts to develop and support the 4R Nutrient Stewardship initiative (International Fertilizer Industry Association: <http://www.fertilizer.org/HomePage/LIBRARY/Publication-database.html/The-Global-4R-Nutrient-Stewardship-Framework-for-Developing-and-Delivering-Fertilizer-Best-Management-Practices.html2>), which is based on the principles of using the *right* nutrient source, at the *right* rate, *right* time, and in the *right* place to achieve further increases in NUE and to minimize unintended losses of nutrients to the environment. Many of these recent innovations are reviewed by [14], including enhanced efficiency nitrogen fertilizers, nitrification and urease inhibitors [15,16,17], N-sensor based technologies [18,19,20], and placing N-sensing capabilities in unmanned aerial vehicles (UAVs). On-line support tools, such as Adapt-N (<http://www.adapt-n.com/in-action/faqs/>) have been targeted toward specific farmers' needs for nitrogen management. Initiatives such as the Adapt Network (www.adaptnetwork.org) and On Farm Network (www.isafarmnet.com) have created networks of farmers, their advisors, grower organizations, and NGOs to partner in the collection, analysis, and interpretation of field data to enable growers to make more efficient, site-specific management decisions.

Not all NUE improvements will necessarily reduce N₂O emissions [21]. No-till and reduced tillage effects on N₂O emissions have been mixed [14,22,23,24,24]. Similarly, while winter cover crops can retain residual inorganic N, cover crops have been shown to increase springtime N₂O emissions in some fields, possibly because of the release of labile carbon and N from cover crop residues [26,27,28]. The issue of potential pollution swapping (e.g., nitrate leaching versus NH₃ and N₂O emissions), is difficult to assess [29], especially since leached nitrate and volatilized NH₃ may result in N₂O emissions downstream and downwind [8,21].

Although technological advances are needed, it is becoming increasingly recognized that economic and social impediments remain obstacles to adoption of some of these technologies and best management practices. Stuart et al. [30] demonstrated that most farmers in Michigan consider private sector seed and fertilizer retailers and crop advisors as their most important and trusted sources of information about nutrient management. Traditional university-based or government-based agricultural extension services ranked much lower, suggesting that

partnerships between extension and private sector advisors and retailers are needed to get updated information out to farmers. Lack of trust of government and university extension is an important social barrier to implementation of research innovations. While university-based and government-based extension will remain important sources of up-to-date information and innovation, there is a trend for these extension services to inform certified crop advisors and retailers, who then effectively disseminate this information as a service to their farmer-clients. Success of this model depends on both trust between the crop advisor and farmer and the need for the advisors to be well informed by public sector extension services.

At a 2013 conference dedicated to understanding the economic and social impediments to adoption of improved NUE practices, which was attended by scientists, farmers, crop advisors, and other stakeholders (<http://nitrogennorthamerica.org/NUE-KansasCity2013.html>), farmers reported that N fertilizer costs are large enough for them to want to improve NUE, but they also pointed out that the economic risk of applying too little N is very high. In short, N application provides an important economic margin of safety, like relatively inexpensive insurance. This economic barrier to improving NUE may require policies that distribute costs and risks to society, so that the farmer does not bear them alone. The conference reached the following general consensus recommendations:

- Develop partnerships and networks at local and regional levels between industry, universities, governments, NGOs, crop advisors, and farmers to demonstrate the most current, economically feasible, best management practices. Regulations, incentives, and outreach, have been most effective when tailored to local conditions, administered and enforced by local entities, and where local “buy-in” has been obtained.
- Provide improved, continuing education to private sector retailers and crop advisors on the most up to date nutrient management practices through professional certification programs. Providing farmers with science-based recommendations through trusted sources of information will help address the perceived need to apply additional nitrogen to reduce risk.
- Tie nutrient management to performance-based indicators, including clearly defined NUE indicators on the farm, with strong incentives for participation and reporting of data. Well-defined environmental quality indicators downwind and downstream are also needed and should be tied to monetary values where appropriate and feasible.
- Restore investments in research, education, and extension by federal and state governments that are essential for advancing the knowledge and skills needed for cropping system innovations. This research and development must integrate agronomic, ecological, economic, and social science knowledge of food production and related environmental, economic, and social costs to society.

NEW MARKET INNOVATIONS

An environmental market makes it possible to buy and sell credits for environmental activities. One example that has operated in North America for decades is U.S. Environmental Protection

Agency's Clean Air Market for nitrogen and sulfur oxides (<http://www.epa.gov/airmarkets/trading/factsheet.html>). More recently, interest has been focused on carbon markets for the buying and selling of emissions credits that have been either generated by GHG emission reduction projects (voluntary), or distributed by a regulatory body (compliance), respectively [31]. Emissions reductions are traded as carbon credits (offsets); one credit representing a GHG reduction equal to one metric ton (tonne) of carbon dioxide equivalent (tCO₂e). Six GHGs are typically included in these markets; three are relevant to agriculture, including N₂O. A carbon (or other GHG) protocol – effectively a set of instructions on how to carry out a carbon offset project – contains information to aid project development and deployment, including GHG calculation methods. Of the five Nitrous Oxide Reduction Protocols (NERPs) that focus on N₂O mitigation in croplands, four are associated with the voluntary carbon market in the U.S. and are housed with and overseen by three carbon standard organizations (CSOs):

- Verified Carbon Standard. <http://www.v-c-s.org/>
- American Carbon Registry. <http://americancarbonregistry.org/>
- Climate Action Reserve. <http://www.climateactionreserve.org/>

Projects (essentially a contract to reduce GHG emissions) that use these protocols can be submitted by individuals and organizations from the private and public sector for third party validation and verification.

Three of the four US NERPs are underpinned with empirical data from field experiments conducted in commercial corn rotations in Michigan [32,33]. Specifically, they quantify direct N₂O emissions reductions based on response curves for N₂O flux as a function of N fertilization rate, an IPCC Tier II methodology [34]. These response curves are nonlinear, following evidence that N₂O fluxes increase disproportionately as fertilization rates exceed the crop's capacity to utilize added nitrogen [35]. A recent global meta-analysis showed this nonlinear response to be robust [36], although there is also evidence for regional variation [37]. Indirect emissions are calculated using IPCC Tier I equations. These protocols are straightforward – a reduction in N fertilizer rate, achievable through multiple management options, including improved timing, placement and formulation of N fertilizer, primarily determines the offset volumes awarded. All three of these NERPs are derived from an identical dataset, however there are practical differences, brought about through the protocol validation process, that are important for project implementation [38].

The fourth NERP (<http://americancarbonregistry.org/carbon-accounting/acr-fertilizer-management-v2.0>) uses an IPCC Tier III methodology, with multiple site-specific and other sourced data in the moderately complex biogeochemical model DNDC to quantify direct and indirect N₂O emissions reductions resulting from changes in N fertilizer use and application. Parameter sensitivity analyses and 'ground-truthing' with measured N₂O emissions data are essential for project integrity.

The fifth NERP is overseen by the Alberta provincial government and is part of a Canadian compliance market, although participation in offset generation is voluntary, as with all current NERPs. The Alberta protocol is practice- and intensity-based. Offsets are awarded based on the adoption of particular N management practices and modified according to project yield.

(<http://environment.gov.ab.ca/info/library/8294.pdf>). Implementation of specific suites of N best management practices (BMPs) are defined, based on rate, source, timing and placement, rather than measured N₂O emissions reductions. These management ‘packages’ are classified as basic, intermediate, and advanced, requiring successively more ‘sophisticated’ management for qualification.

Future carbon market crediting tools for N₂O mitigation may include USDA’s GHG quantification tool (Q-tool; [39]) and the COMET-Farm™ accounting system (<http://cometfarm.nrel.colostate.edu/>). In the former, the N₂O estimator for the effect of N-fertilizer additions is based on nonlinear response curves found in Michigan [33], with baseline rates provided by the Daycent dynamic model [40], and scalars for N management and other practices provided by meta-analyses. The latter, also reliant on DayCent, is being used in the development of a NERP for crops in Iowa and Illinois.

Participation in NERP projects can provide economic and environmental benefits, including increased NUE, reduced N fertilizer costs, and increased revenue from offset credits. A pilot project in Michigan developed by Michigan State University (MSU) and the Electric Power Research Institute (EPRI) that reduces N input to corn, generated the world’s first carbon offsets from a NERP in spring 2014 (<http://cornandsoybeandigest.com/fertilizer/new-nitrogen-reduction-trading-program>). Efforts are underway to expand on this initiative (e.g., <http://www.deltanitrogen.org/>). However, large-scale adoption of NERPs may be challenging due to real and perceived issues that include:

- Lack of information and transparency (e.g., limited awareness of opportunities, lack of technical assistance, protocol complexity);
- Data access and sharing (e.g., data held by service providers not producers, low trust levels for organizations involved in offset generation);
- High cost (e.g., documentation and administrative time, third party validator and verifier fees);
- Insufficient financial reward (current tCO₂e price ~ \$5-10; equivalent to only 25-50 kg of corn (1-2 bushels);
- Uncertainty in calculation methods (i.e., are offsets generated ‘real’).

Some concerns can be alleviated by: 1) having agricultural organizations such as farmers unions operate as aggregators, (e.g., the North Dakota Farmers Union (<http://carboncredit.ndfu.org>) role with the former Chicago Climate Exchange (CCX), to help defray producer costs and provide greater trust in the process); 2) developing straightforward, standardized protocols based on long-term empirical field data from commercial farms and agricultural research sites; 3) stacking N₂O offsets with water quality or other mitigation credits (e.g., the Ohio River Basin Trading Project; <http://wqt.epri.com>) to add further incentive for practice adoption or change; and; 4) adopting a hybrid policy approach, by for example combining complementary policies with a cap-and-trade program (e.g., Regional Greenhouse Gas Initiative [RGGI]; <http://www.rggi.org>).

Another innovative effort is resulting from California’s Assembly Bill 32 (AB 32; <http://www.arb.ca.gov/cc/ab32/ab32.htm>), which requires California’s Air Resources Board (ARB) to reduce California GHG emissions to 1990 levels by 2020. AB 32 provided the ARB

with broad authority to develop market-based compliance mechanisms. A GHG cap-and-trade program and many complementary policies have been adopted. Sectors under the cap can use offsets from non-capped sectors to comply with up to 8% of their compliance obligation. This translates to a maximum allowed offset volume of ~218 million tCO₂e from 2013-2020, with an estimated offset supply of 66 to 140 million tCO₂e using currently approved protocols over the same period [41]. As with other compliance markets in North America, there are no approved cropland N management (i.e., N₂O mitigation) protocols at this time. This may be expected to change in the future – ARB has co-funded a number of projects to improve understanding of N₂O emissions associated with fertilizer use and other applications in California (<http://www.arb.ca.gov/ag/fertilizer/fertilizer.htm>). Given the projected shortfall in offset volume, N₂O mitigation projects in crop agriculture may have a large role to play.

SUPPLY CHAIN INNOVATIONS

Establishing incentives for innovative management in agriculture with the goal to decrease N₂O emissions and other losses of N to the environment can occur at multiple levels in the food production process. One approach being taken is to leverage supply chain sustainability goals to spur large-scale adoption of conservation agriculture in commodity grain production by commercial entities. Due in part to current political aversion to command-and-control regulatory approaches, North America is currently serving as a test bed for voluntary collaborative stakeholder groups of producers, agribusinesses, food and retail companies, conservation and non-profit organizations, universities, and agency partners. These stakeholders are working together to define, measure, and develop a supply-chain system for agricultural sustainability. Greenhouse gas emissions are among the sustainability indicators adopted by multi-stakeholder groups such as Field to Market (Field to Market, 2012: <http://www.fieldtomarket.org/>).

Field to Market has developed an online “fieldprint calculator” for row crop farmers that indexes the effects of their agronomic practices, thereby helping growers evaluate their farming decisions and compare their sustainability performance relative to their own past performance and in anonymous peer-to-peer benchmarking. One of the objectives is to empower farmers with the knowledge and tools they need to implement conservation agriculture practices that preserve natural resources, reduce costs, and ultimately, increase crop yields and farm profitability in the long term. Field to Market reported six member-led pilot projects involving over 300 US farmers.

Walmart, one of the members of Field to Market, announced a new fertilizer initiative in September 2013, that requires companies who use commodity grains to develop fertilizer optimization plans across 14 million acres of farmland by 2020 (Walmart: <http://news.walmart.com/news-archive/2013/09/12/walmart-highlights-progress-on-the-sustainability-index>). Its goal is to eliminate 20 million metric tons of greenhouse gas emissions from its global supply chain by 2015 for the products that it sells. When Walmart analyzed the biggest hotspots for greenhouse gases for its top 100 products, it found that fertilizer was the number one hotspot for approximately half of those products. Thus far, 15 of Walmart’s major suppliers – who represent 30% of food and beverage sales in North America – have developed fertilizer optimization plans. These suppliers were given a plan template and guidance on the

different levels of performance possible, but were given the freedom to develop a plan that makes sense for their business and hopefully their supplier farmers. Walmart's demand signal is significant, but also has a long way to travel – first to its supplier companies (like Kellogg's), then typically to a grain aggregator/elevator/mill, and from there to the farmer. Depending on the transparency of the food company's supply chain, this flow of information can be relatively simple (i.e., when they have contracts directly with growers) or complex (i.e., when they buy grain on the spot market and get it off a rail car). Working through these complex supply chains requires innovative approaches to measurement and data sharing.

The Environmental Defense Fund (EDF), also a member of Field to Market, is helping Walmart develop a strategy to address fertilizer hotspots in its supply chain in a way that can benefit farmers. For example, they are streamlining the mechanisms and processes that major food companies and grain suppliers use to effectively connect to grain growers. Several “proving projects” are pursuing a common approach of engaging the food companies, the grain suppliers, and the grower community to develop and deploy a suite of effective options that grain growers can use to optimize their fertilizer use and improve soil health. Information about grower adoption of these options that result in improved water quality and reduced greenhouse gas emissions will be aggregated and tracked across broad sourcing areas to then facilitate supply-chain reporting. One example of these proving projects involves working with Smithfield/Murphy-Brown on sustainably-sourced feed grains. In 2014, this project focuses on the feed grains sourced directly in North Carolina, South Carolina and Virginia, where Murphy-Brown owns several grain mills. The project is then expected to expand in 2015 to the feed grains the company sources from the US Midwest.

At a time when companies in the agriculture supply chain are just beginning to think about how to respond to sustainable sourcing demands coming from major retailers like Walmart, it is critical to set out an approach that can work for all of the different links in that chain. EDF's proving projects are intended to establish replicable models that other companies will be able to follow. Persuading major food companies and agribusinesses to implement complementary approaches is necessary to bring the adoption of conservation agriculture to scale quickly and to achieve success in terms of both economic outcomes for growers and sustainability benefits for water quality, climate stability, and more.

CONSUMER-BASED INNOVATIONS

In addition to innovations on the farm and in the supply chain to decrease N₂O emissions, there is also the need for innovations at the consumer level. There are two areas that are particularly noteworthy—sensible protein consumption and decreased food waste [42]. These two areas are in the control of the consumer, and taken together they have the potential to significantly decrease the amount of N needed to grow food, because less food would need to be produced. To put it more directly, consumers should eat to dietary protein recommendations and not waste food.

An analysis of the potential impact of actions on these two areas in the UK showed that eating to the recommended protein consumption would decrease a consumer's total nitrogen footprint by

33%. Decreasing food waste at the distribution and consumer levels by 50% would further decrease the footprint by 7%. Combining these two activities would lead to a 39% reduction to a consumer's total nitrogen footprint [43]. If these two actions were taken in the US, the percentage decrease would be larger, because more food is wasted (19% in the UK vs 25% in the US; [44]) and more protein is consumed (5.0 kg N/cap/year in the UK vs 5.2 kg N/cap/year in the US; FAOSTAT: <http://faostat.fao.org/site/345/default.aspx>). If changes in consumer habits lead to less demand for per capita food production, especially per capita meat consumption, then less N will be required in the food production process, likely leading to reduced N₂O emissions to the environment from agriculture.

Changes to dietary patterns and food purchase habits will first require education. Awareness of the environmental impacts of dietary choices is being promoted through efforts such as Meatless Monday (Meatless Monday: <http://www.meatlessmonday.com/about-us/>). The Meatless Monday website reports that 38 secondary school districts, 74 secondary schools and 129 United States colleges and universities are currently participating in the program. Other programs that promote increased public awareness about the impacts of choices of resources on nitrogen losses to the environment are aimed at the consumer through nitrogen footprint tools (<http://www.n-print.org/>) for the consumer [42] and for institutions such as universities [45].

The implementation of these changes on a personal level requires personal choices. Motivations include a reduced environmental impact, improved personal health by reducing protein consumption to the recommended level, and saving money by reducing food waste. Institutions, such as secondary schools or universities, can also implement policies to reduce consumption and food waste. Examples include tray-less dining halls, participation in Meat Free Mondays, and composting any remaining food waste.

CONCLUSION

Nitrogen use efficiency has been improving in North American agriculture during the last four decades, including lower N₂O production per unit of grain produced. Nevertheless, agriculture remains that largest source of regional N₂O emissions, and much potential remains to improve efficiencies and reduce emissions further. Further progress is made difficult by several social and economic impediments to adopting best management practices. Innovative technical approaches and policy tools are being developed in North America, which may help overcome some of these impediments for improving nitrogen use efficiency in agriculture and thereby reduce N₂O emissions. Nitrous oxide Emission Reduction Protocols (NERPs) have been developed for carbon credits to be traded in carbon markets. The corporate sector is leading a new initiative to examine supply chains of food and other commodities for sustainability criteria, including establishing voluntary goals for reducing greenhouse gas emissions from farmland. Partnerships among retailers, suppliers, growers, and NGOs are emerging to assist farmers to meet these sustainability goals while maintaining profitability and food security. At the same time, efforts to make consumers more aware of the environmental impacts of their dietary choices are underway through personal nitrogen footprint analysis tools and programs to encourage reduced meat consumption at least one day per week. The effectiveness of these innovative market, supply chain, and consumer awareness efforts remains to be seen, as they are

just getting underway. Along with advances in research and extension, these innovations offer the possibility of a non-regulatory approach to reducing nitrous oxide emissions from the North American farming sector. Success will require effective partnerships among private and public sectors and multiple stakeholders.

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Figure 1: Historic and projected N₂O emissions for USA and Canada, 1990 - 2030 (US EPA: <http://www.epa.gov/climatechange/EPAactivities/economics/nonco2projections.html>). Historical estimates are reported for 1990, 1995, 2000, and 2005, and projections of emissions are provided for 2010, 2015, 2020, 2025, and 2030. Agricultural sources include soils and manure management and “other”. See text for discussion of 2010 US emissions, which did not grow, as projected here. The apparent temporary increase in Canadian agricultural emissions reported for 1995 are from the “other agricultural emissions” category, which jumped by about a factor of 10 according to the EPA report. We suspect that this is a clerical error of a misplaced decimal point, but have no means of confirming our suspicion, so we plot the data as reported.