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Disruption of a Planetary Nitrogen Cycle as Evidence of Extraterrestrial Agriculture

Jacob Haqq-Misra[1], Thomas J. Fauchez[2,3,4], Edward W. Schwieterman[1,5], and Ravi Kopparapu[2,4]
[1] Blue Marble Space Institute of Science, Seattle, WA, USA; jacob@bmsis.org
[2] NASA Goddard Space Flight Center, Greenbelt, MD, USA
[3] American University, Washington, DC, USA
[4] Sellers Exoplanet Environment Collaboration (SEEC), NASA Goddard Space Flight Center, Greenbelt, MD, USA
[5] Department of Earth and Planetary Sciences, University of California, Riverside, CA, USA
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Abstract

Agriculture is one of the oldest forms of technology on Earth. The cultivation of plants requires a terrestrial planet with active hydrological and carbon cycles and depends on the availability of nitrogen in soil. The technological innovation of agriculture is the active management of this nitrogen cycle by applying fertilizer to soil, at first through the production of manure excesses but later by the Haber–Bosch industrial process. The use of such fertilizers has increased the atmospheric abundance of nitrogen-containing species such as NH_3 and N_2O as agricultural productivity intensifies in many parts of the world. Both NH_3 and N_2O are effective greenhouse gases, and the combined presence of these gases in the atmosphere of a habitable planet could serve as a remotely detectable spectral signature of technology. Here we use a synthetic spectral generator to assess the detectability of NH_3 and N_2O that would arise from present-day and future global-scale agriculture. We show that present-day Earth abundances of NH_3 and N_2O would be difficult to detect, but hypothetical scenarios involving a planet with 30–100 billion people could show a change in transmittance of about 50%–70% compared to preagricultural Earth. These calculations suggest the possibility of considering the simultaneous detection of NH_3 and N_2O in an atmosphere that also contains H_2O, O_2, and CO_2 as a technosignature for extraterrestrial agriculture. The technology of agriculture is one that could be sustainable across geologic timescales, so the spectral signature of such an "ExoFarm" is worth considering in the search for technosignatures.

Unified Astronomy Thesaurus concepts: Technosignatures (2128); Astrobiology (74); Biosignatures (2018); Habitable planets (695); Spectroscopy (1558)

1. Introduction

The search for biosignatures seeks to discover evidence of extraterrestrial life through the detection and spectral characterization of exoplanetary atmospheres. Many possibilities for detectable biosignatures have been suggested, which includes various combinations of CH_4, CO_2, O_2, O_3, and H_2O based on Earth's history. Specifically, the concept for searching for a combination of O_2 and CH_4 gases was first suggested by Lovelock (1975) as an example of disequilibrium present in Earth's atmosphere that results from the presence of life. Lovelock (1975) observed that the chemical composition of Earth's present-day atmosphere remained in a state of thermodynamic disequilibrium, whereas the atmospheric constituents of Venus, Mars, and Jupiter were much closer to an equilibrium state. The combined detection of O_2 and CH_4 would indicate that a planet has a substantial surface flux of both because CH_4 is readily oxidized by O_2, and on Earth the major sources of both of these gases are biological. But by themselves, neither O_2 nor CH_4 would be considered a compelling biosignature (Schwieterman et al. 2018). Although this example focuses on biosignatures of present-day Earth, similar principles can be applied to ancient Earth (e.g., Arney et al. 2016, 2017, 2018). Additional disequilibria biosignatures that have been suggested include N_2–O_2 and CO_2–CH_4 pairs (Krissansen-Totton et al. 2016, 2018). In general, the chemical fluxes and abundances observed in a planet's atmosphere should be evaluated in the context of stellar and planetary characteristics, to assess the potential of a habitable planet to host life.

The search for technosignatures is a continuation of the search for biosignatures, which includes the idea of looking for spectral evidence of technology in the atmospheres of exoplanets. The term "technosignature" refers generally to any "evidence of technology that modifies its environment in ways that are detectable" (Tarter 2007), which could include a broad class of astronomically observable phenomena. For an overview of modern prospects in the search for technosignatures, see the reviews by Wright (2021), Socas-Navarro et al. (2021), and Lingam & Loeb (2021). A handful of suggestions have been proposed for detectable atmospheric technosignatures, which focus on a single gaseous species as an indicator of extraterrestrial technology. Molecules such as chlorofluorocarbons (CFCs) and halofluorocarbons (HFCs) are examples of industrial products that can have long atmospheric residence times and could be detectable at mid-infrared wavelengths (Schneider et al. 2010; Lin et al. 2014; Haqq-Misra et al. 2022). Atmospheric pollution could also indicate planetary-scale technology, such as elevated abundances of NO_2 due to combustion that could be detectable in the 0.2–0.7 μm range (Kopparapu et al. 2021). CFCs and HFCs are almost entirely produced by industry on Earth, while the major sources of NO_2 are also industrial, so the detection of these atmospheric constituents in an exoplanetary atmosphere would provide compelling evidence of technology on another planet.

One of the criticisms of these suggestions is that long-lived technological civilizations may be unlikely to accumulate significant amounts of atmospheric pollution. Industrially produced constituents such as CFCs and HFCs would only be observable if there were a regular flux into the atmosphere. One possible scenario could involve the use of industrially produced greenhouse gases in order to terraform a planet like Mars to make it more habitable (Marinova et al. 2005; Dicaire et al. 2013), but the abundance of such emissions is restricted on Earth today due to a need to prevent undesirable greenhouse warming by these molecules. Detecting NO_2 at elevated abundances would be consistent with a planet engaged in widespread combustion, but combustion itself may not be a sustainable practice over long timescales due to the negative impacts of pollution and finite fuel sources. There may be a large number of atmospheric technosignatures that are unique to industry or cities, but any molecules that are only produced for a short time in the history of a planet—and that do not persist for geologic timescales—will be unlikely to be observed.

An ideal technosignature would be sustainable for a long time, as such long-lived evidence would be the most likely to actually be detected (Kipping et al. 2020; Balbi & Ćirković 2021). The two Laser Geodynamics Satellites, known as LAGEOS, are highly reflective satellites used for geodynamics, with no moving parts, that will remain in stable medium-Earth orbits for more than 8 million years (Spencer 1977). The LAGEOS satellites are thus an example of a long-duration technosignature, although the detectability of LAGEOS itself around Earth may be challenging at exoplanetary distances. Another possible long-duration technosignature is the use of low-albedo energy collectors, which could be detectable by infrared surface imaging (Berdyugina & Kuhn 2019) or spectral signatures in reflected light (Lingam & Loeb 2017). Such technosignatures may not be detectable on Earth today, but they represent plausible trajectories for technosignatures in Earth's future.

An even more ideal technosignature would consist of multiple chemical species. This Letter suggests that global-scale agriculture provides such a technosignature. This is not the first time agriculture has been suggested as a technosignature: Sagan & Lederberg (1976) noted that the possibility of agriculture on Mars could be ruled out based on the lack of checkerboard-like patterns from Mariner 9 imagery. In principle, changes in albedo associated with the timing of crop planting and harvesting could also be detectable by conducting observations over multiple epochs that correspond to different planetary seasons (Schwieterman et al. 2018; Schwieterman 2018), as such changes associated with agriculture can be observed on Earth today (Seneviratne et al. 2018). In this Letter, we show that the accumulation of NH_3 and N_2O from large-scale agriculture is an example of a multispecies and long-lived atmospheric technosignature.

2. Agriculture and Nitrogen

Agriculture is one of the oldest technologies in history. The Agricultural Revolution ∼10,000–20,000 yr ago began with the end of the last ice age and marked the beginning of permanent human settlements based on agriculture. From a geochemical perspective, agriculture requires a terrestrial planet with an active hydrological cycle as well as a carbon cycle in order to drive photosynthesis. Large-scale photosynthesis could be detectable as an infrared reflectance spectrum that could serve as a biosignature (e.g., Kiang et al. 2007), but crop cover alone would be insufficient to serve as a technosignature. Instead, the technological innovation of agriculture is the active management of the nitrogen cycle. The byproducts of this disrupted nitrogen cycle—specifically NH_3 and N_2O—could serve as atmospheric indicators of agriculture.

Nitrogen is an essential nutrient for life, but the vast reservoir of nitrogen in Earth's atmosphere is unavailable to most organisms because the N_2 triple bond is difficult to break. The process of converting N_2 into a soluble form is known as nitrogen fixation. Abiotic nitrogen fixation occurs from lightning through the reaction

$$N_2 + 2CO_2 \rightarrow 2NO + 2CO, \quad (1)$$

which was the only form of nitrogen fixation on prebiotic Earth and represents about 2% of total nitrogen fixation today. Biological nitrogen fixation is an anaerobic process that evolved early in the history of life on Earth, which allowed organisms to harvest N_2 from the atmosphere. In the oxic environment of Earth today, biological nitrogen fixation is performed by a range of microorganisms using variations on the enzyme nitrogenase in order to break the N_2 triple bond, which can be summarized as the reaction

$$2N_2 + 6H_2O \rightarrow 4NH_3 + 3O_2. \quad (2)$$

In an aqueous environment, the resulting NH_3 is converted further into the ammonium ion, NH_4^+. These products can be directly taken up by other organisms, or else they can be oxidized into nitrates by nitrifying microorganisms through the reactions

$$2NH_4^+ + 3O_2 \rightarrow 2NO_2^- + 2H_2O + 4H^+, \quad (3)$$

$$2NO_2^- + O_2 \rightarrow 2NO_3^-. \quad (4)$$

The NH_4^+ and NO_3^- ions provide a form of nitrogen that can be used by other microorganisms, as well as plants, for constructing amino acids. Nitrogen returns to the atmosphere through denitrification, which is an anaerobic process that mostly occurs in low-oxygen regions of the deep ocean and can be summarized by the reaction

$$5CH_2O + 4NO_3^- + 4H^+ \rightarrow 5CO_2 + 2N_2 + 7H_2O. \quad (5)$$

Molecular nitrogen can also return to the atmosphere thorugh the anaerobic anammox pathway$NH_4^+ + NO_2^- \rightarrow N_2 + 2H_2O$).The reactions above describe the nitrogen cycle as it operates on Earth today, and similar processes have been occurring as early as the rise of oxygen ∼2.3–2.4 Gyr ago (e.g., Stüeken et al., 2015). For further discussion of Earth's nitrogen cycle, see Sullivan & Baross (2007) and Catling & Kasting (2017).

Early forms of agriculture relied on manure as the primary source of nitrogen fertilizer, which was applied directly to fields where the nitrogen would be converted by microorganisms into NH_3 or NH_4^+ through the process of ammonification. Such practices increased the demand for animal husbandry and other sources of manure as populations grew. Crop rotation was later discovered as a way to replenish soil nitrogen in farmlands by planting nitrogen-fixing crops in alternate years. But the greatest innovation in agriculture, and arguably the most significant discovery of the twentieth century, is the use of the

Haber–Bosch process to synthesize ammonia for producing fertilizer. The Haber–Bosch process is a high-temperature industrial process for fixing N_2 from the atmosphere that follows the reaction

$$N_2 + 3H_2 \rightarrow 2NH_3, \quad (6)$$

which uses a metal catalyst (Cherkasov et al. 2015). The main source of H_2 today is natural gas, but other sources of H_2 such as biomass or water electrolysis also suffice. The ability to manufacture fertilizer using the atmosphere's supply of N_2 has allowed farmers to enrich their soils with compounds such as ammonium nitrate (NH_4NO_3) as a supplement or replacement to urea and manure. These fertilizers release ammonium (NH_4^+) and/or nitrate (NO_3^-) ions when dissolved in water, which is then applied to saturate the soil where it can provide a source of nitrogen to plants. Excess fertilizer that is not utilized by plant roots contributes to an increase in nitrogen gas emissions, discussed further below. The Haber–Bosch process revolutionized global agriculture and enabled the production of food surpluses to support a planet populated by billions of people. The expansion of global agriculture has led to an increase in the production of synthetic fertilizers as well as the demand for animal domestication, which leads to an increase in the release of atmospheric nitrogen gases. Indeed, the total anthropogenic fixed nitrogen flux is now equivalent to or greater than nonanthropogenic sources of fixed nitrogen (Battye et al. 2017).

The most notable nitrogen-based atmospheric constituent due to anthropogenic activity is ammonia (NH_3). About 81% of the $\sim$58 Tg yr^{-1} of nitrogen in total ammonia emissions is anthropogenic, with about 65% from agriculture, 11% from biomass burning, and 5% from other industrial processes (Seinfeld & Pandis 2016). Only 19% of NH_3 sources are nonanthropogenic, primarily from the volatilization of NH_3 from seawater or undisturbed soil as well as from wild animals. The NH_3 from agriculture enters the atmosphere from the volatilization of ammonia in soil as well as from domestic animals, all of which originates from fertilizer production (Jenkinson 2001). Atmospheric NH_3 due to agriculture and animal husbandry has been observed by the Atmospheric Infrared Sounder (AIRS) on the NASA Aqua satellite over a 14 yr duration and shows rates of emission that have increased by about 2% per year, which correlates with increased fertilizer use in some parts of the world (Warner et al. 2016, 2017). The residence time of NH_3 in the atmosphere is only hours to days, as most NH_3 falls back to the surface through wet or dry deposition. If sufficient NH_3 remains in the atmosphere, then it can combine with N_2O or SO_2 to form aerosol particles. The accumulation of detectable and increasing quantities of NH_3 on Earth indicates the intensification of agricultural and industrial activities.

Another significant atmospheric constituent that arises from anthropogenic activity is nitrous oxide (N_2O). Of the $\sim$16 Tg yr^{-1} of nitrogen in total N_2O emissions, about 40% to 50% is from agriculture and industry, with the most significant nonanthropogenic sources being the oceans and wet tropical soils (Reay et al. 2012; Tian et al. 2020). Most emissions of N_2O are the result of denitrification by microorganisms, which in agriculture is enhanced by nitrates added to soil as fertilizer. Other anthropogenic sources of N_2O include irrigation, water degassing, and animal production—much of which is still ultimately connected to the use of fertilizer—as well as biomass burning. The atmospheric residence time of N_2O is about 120 yr, with the major sink occurring due to photodissociation in the stratosphere and a smaller but significant sink from reactions with O(^{1}D) radicals. Within the troposphere, N_2O is relatively uniformly distributed and also acts as an effective greenhouse gas. The presence of N_2O on Earth is generally connected with soil microbiology, but anthropogenic activities that are largely connected with agriculture have enhanced such N_2O emissions from soil (Tian et al. 2015).

Other trace gases are also emitted as the result of agriculture and animal domestication. Agriculture contributes NO and NO_2 to the atmosphere from biomass burning and soil denitrification, which accounts for about 25% of total NO_x emissions (Seinfeld & Pandis 2016)—although there are large uncertainties with these estimates (Jenkinson 2001). Nevertheless, a much larger fraction of about 65% of present-day NO_x emissions is due to fossil fuel combustion; this certainly could serve as a technosignature (Kopparapu et al. 2021), but NO_x generated from combustion is a separate source from agricultural emissions of NO_x that derive from the application of fertilizer. Methane (CH_4) is also emitted from agriculture—notably rice agriculture and ruminant ranching—as well as from biomass burning, landfills, and energy use. About 70% of total CH_4 emissions are anthropogenic, with the rate of these emissions continuing to increase (Seinfeld & Pandis 2016).

Human civilization continues to expand its use of agriculture, and thereby intensify its use of industrial nitrogen fixation to make fertilizer. But there is no particular reason that agriculture itself depends on growth, and as long as sustainable sources of energy are used, then global-scale agriculture could in principle sustain itself across long timescales based on the use of industrial nitrogen fixation (e.g., Soloveichik 2019; Smith et al. 2020; Wang et al. 2021; Rouwenhorst et al. 2021). Whereas processes like combustion may be short-lived due to a finite supply of fossil fuel, the use of industrial nitrogen fixation only requires a planet with a predominantly N_2 atmosphere, a supply of H_2, and a sustainable source of energy. Thus, the spectral signature of agriculture is well suited as a candidate for a technosignature that could persist for millennial, and perhaps even geological, timescales. There is little imagination required to speculate that extraterrestrial civilizations, if they exist, would find great value in industrial nitrogen fixation (notably, this is one of the technologies that enables our own civilization to thrive and contemplate our own spectral detectability).

What, then, is the expected spectral signature of an "ExoFarm"? The planetary requirements for agriculture as we know it are a hydrological, carbon, and nitrogen cycle, with an atmospheric reservoir of N_2 and abundant O_2 for photosynthesis. These requirements themselves are aligned with the disequilibrium biosignature of the combined detection of O_2 and CH_4. In the event that such a planet is discovered, then evidence of elevated levels of NH_3 combined with N_2O would provide evidence of global-scale agriculture. Because of its extremely short lifetime, the observation of NH_3 would imply a continuous large-scale source of emissions, which could be sustained for long periods of time through industrial nitrogen fixation. Although some microorganisms also fix nitrogen, they do not represent significant sources of atmospheric NH_3 on Earth. Likewise, the associated detection of N_2O and other nitrogen-containing species would provide confidence that the

Table 1
Agricultural Scenarios with Estimated Atmospheric Abundances of Nitrogen-containing Species

Scenario	NH_3 (ppb)	N_2O (ppb)	CH_4 (ppb)
Preagricultural Earth	2	170	570
Present-day Earth	10	335	1900
Future Earth 30B	30	590	4300
Future Earth 100B	100	1900	14000

production of NH_3 is associated with industrial disruption of a planetary nitrogen cycle.

It is worth emphasizing that NH_3 or N_2O alone would not necessarily be technosignatures, as either of these species could be false positives for life (e.g., Harman & Domagal-Goldman 2018) or could arise from nontechnological life (e.g., Roberson et al. 2011; Seager et al. 2013a, 2013b; Sneed 2020; Phillips et al. 2021; Huang et al. 2022; Ranjan et al. 2022). Rather, it is the combination of NH_3 and N_2O that would indicate disruption of a planetary nitrogen cycle from an ExoFarm, which may also show elevated abundances of NO_x gases as well as CH_4. The short lifetime of NH_3 in an oxic atmosphere implies that a detectable abundance of NH_3 would suggest a continuous production source. Although NH_3 could be produced abiotically by combining N_2 and H_2, an atmosphere rich in H_2 would be unstable to the O_2 abundance required to sustain photosynthesis. The technosignature of an ExoFarm would therefore require the simultaneous detection of both NH_3 and N_2O in the atmosphere of an exoplanet along with O_2, H_2O, and CO_2.

3. Detectability Constraints

Large-scale agriculture based on Haber–Bosch nitrogen fixation could be detectable through the infrared spectral absorption features of NH_3 and N_2O as well as CH_4. A robust assessment of the detectability of such spectral features in an Earth-like atmosphere would ideally use a three-dimensional coupled climate–chemistry model to calculate the steady-state abundances of each of these nitrogen-containing species a function of biological and technological surface fluxes. But as an initial assessment, we consider a scaling argument to examine the spectral features that could be detectable for present-day and future Earth agriculture.

We define four scenarios for considering agriculture on an Earth-like planet, with the corresponding atmospheric abundances of nitrogen-containing species listed in Table 1. The present-day Earth scenario is based on recent measurements of NH_3, N_2O, and CH_4 abundances (Seinfeld & Pandis 2016; IPCC 2021). The choice of 10 ppb for NH_3 is toward the higher end for Earth today and corresponds to regions of intense agricultural production.

The preagricultural Earth scenario serves as a control, where the agricultural and technological contributions of NH_3, N_2O, and CH_4 have been removed. Note that this approach assumes that eliminating the technological contributions to the atmospheric flux of these nitrogen-containing species will reduce the steady-state atmospheric abundance by a similar percentage; this approach is admittedly simplified, but the results can still be instructive for identifying the possibility of detectable spectral features.

The third and fourth scenarios project possible abundances of NH_3, N_2O, and CH_4 for futures with 30 and 100 billion people, respectively. Earth holds about 7.9 billion people today, and population projections differ on whether or not Earth's population will stabilize in the coming century (Gerland et al. 2014; Warren 2015; Vollset et al. 2020). These two population values were selected because they correspond approximately to the maximum total allowable population using all current arable land (∼30 billion) and all possible agricultural land (∼100 billion) (Mullan & Haqq-Misra 2019). Most published estimates of Earth's carrying capacity range from about 8 to 100 billion, although some estimates are less than 1 billion while others are more than 1 trillion (Cohen 1995). Theoretically, an extraterrestrial population with the energy requirements of up to 100 billion calorie-consuming humans could sustain Haber–Bosch synthesis over long timescales, as long as sustainable energy sources are used (e.g., Soloveichik 2019; Smith et al. 2020; Wang et al. 2021; Rouwenhorst et al. 2021). These scenarios also follow a scaling argument by assuming that the per-person contributions of these three nitrogen-containing species will remain constant as population grows. This again is a simplifying assumption that is intended as an initial approach to understanding the detectability of such scenarios.

We consider the detectability of all four of these scenarios using the Planetary Spectrum Generator (PSG; Villanueva et al. 2018, 2022). PSG is an online radiative transfer tool for calculating synthetic planetary spectra and assessing the limits of detectability for spectral features that can range from ultraviolet to radio wavelengths. The ultraviolet features of NH_3, N_2O, and CH_4 are strongly overlapping and only show weak absorption, but mid-infrared features of all these species could be more pronounced. The mid-infrared spectral features of NH_3, N_2O, and CH_4 calculated with PSG for preagricultural, present-day, and future Earth scenarios are plotted in Figure 1, which shows the relative intensity (top) and transmittance spectra (bottom) for observations of an Earth-like exoplanet orbiting a Sun-like star.

The spectra shown in Figure 1 show the strongest absorption features due to NH_3 from 10 to 12 μm, while N_2O shows absorption features from 3 to 5 μm, 7 to 9 μm, and 16 to 18 μm. Absorption features due to CH_4 overlap some of the N_2O features from 3 to 5 μm and 7 to 9 μm. The change in peak transmittance between 10 and 12 μm (bottom panel of Figure 1) for NH_3 compared to the preagricultural control case is about 50% for the future Earth scenario with 100 billion people and about 25% for the scenario with 30 billion people. For N_2O, the change in peak transmittance between 16 and 18 μm compared to the preagricultural control case is about 70% for 100 billion people and 50% for 30 billion people. The change in relative intensity (top panel of Figure 1) for the 100 billion people scenario is up to about 10% compared to the preagricultural control case between 7 and 9 μm and 10 and 12 μm. Present-day Earth agriculture would exert a weakly detectable signal that might be difficult to discern from the preagricultural control case, but future scenarios with enhanced global agriculture could produce absorption features that are easier to detect.

The spectral features of NH_3, N_2O, and CH_4 could be detectable in emitted light or as transmission features for transiting planets. Specifically, the N_2O line at 17.0 μm shows a strong dependency with the N_2O volume mixing ratio and to a second order the NH_3 line at 10.7 μm. For the future 100 billion case, both display strong enough absorption to be

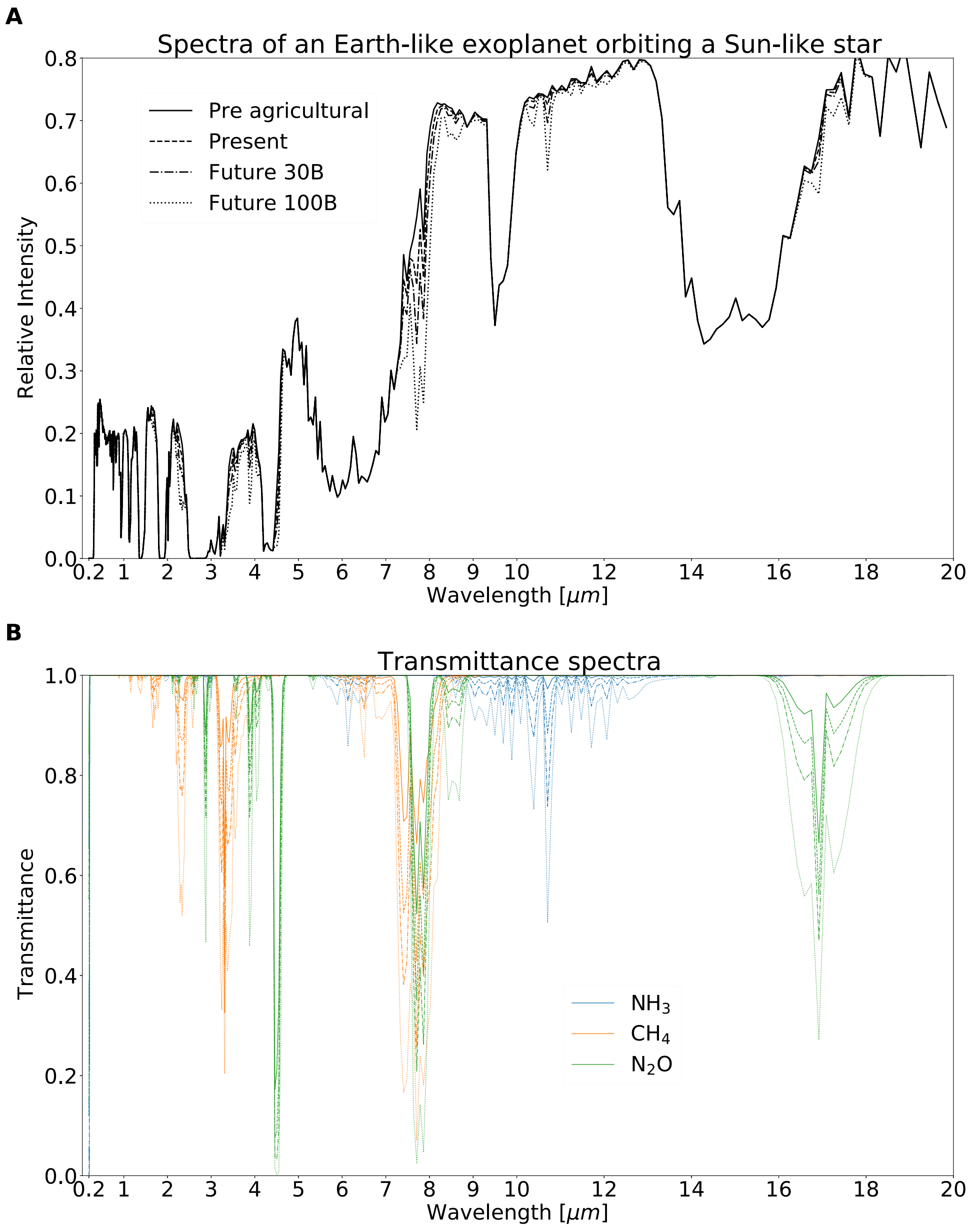

Figure 1. Infrared spectral features of NH_3, N_2O, and CH_4 for preagricultural, present-day, and future Earth scenarios, with relative intensity shown in the top panel and transmittance shown in the bottom panel. Calculations are performed with the Planetary Spectrum Generator.

detectable by the Large Interferometer for Exoplanets (LIFE; Quanz et al. 2021; LIFE collaboration et al. 2021), Origins (Meixner et al. 2019) and Mid-InfraRed Exo-planet CLimate Explorer (MIRECLE; Staguhn et al. 2019) infrared mission concepts. The James Webb Space Telescope (JWST) Near Infrared Spectrograph (NIRSpec) could potentially detect CH_4 within the 0.6–5.3 μm range for transiting exoplanets (Krissansen-Totton et al. 2018). However, the detection of CH_4 alone would provide no basis for distinguishing between technological, biological, or photochemical production. The detectability of these spectral features do not necessarily directly correspond to the peak transmittance, and a full accounting of the detectability of each band would need to account for the observing mode and instrument parameters. It is beyond the scope of this present paper to present detectability calculations for specific missions, as any missions capable of searching for mid-infrared technosignatures are in an early design phase, at best. One of the goals of this Letter is to highlight the importance of examining mid-infrared spectral features of exoplanets, as many potential technosignatures could be most detectable at such wavelengths. Also, it demonstrates the duality of the search for biosignatures and technosignatures. The search for passive, atmospheric technosignatures does not require the development of a dedicated instrument but can leverage the capability of instruments dedicated to the search for biosignatures.

Another, more technically challenging possibility for detecting industrial N-fixation would be constraining the ^{15}N to ^{14}N isotopic ratios of N-bearing atmospheric gases, including NH_3 and N_2O. The Haber–Bosch process introduces a well-known depletion in δ^{15} N, the "^{15}N Haber–Bosch effect" (Yang & Gruber 2016). Future work would be required to assess the spectral detectability of industrial $^{15}N/^{14}N$ impacts, but would certainly require high-resolution spectroscopy.

We note that other studies have considered the role of NH_3 as a biosignature and its possible detectability. Huang et al. (2022) examined the accumulation of NH_3 in an optimal environment of a hydrogen-rich planet orbiting an M-dwarf star and concluded that JWST could detect such spectral features at NH_3 abundances of about 5 ppm. This is more than an order of magnitude greater than the NH_3 abundance in our future Earth scenario with 100 billion people. Even so, such speculation by others suggests a need for broader thinking with regard to the possible biosignatures and technosignatures that could be detectable.

4. Next Steps

The calculations presented in this Letter indicate the possibility of detecting a technosignature from planetary-scale agriculture from the combined the spectral features of NH_3 and N_2O, as well as CH_4. The signature of such an ExoFarm could only occur on a planet that already supports photosynthesis, so such a planet will necessarily already show spectral features due to H_2O, O_2, and CO_2. The search for technosignatures from extraterrestrial agriculture would therefore be a goal that supports the search for biosignatures of Earth-like planets, as the best targets to search for signs of nitrogen cycle disruption would be planets already thought to be good candidates for photosynthetic life.

A better constraint on the detectability of the spectral features of an ExoFarm would require the use of an atmospheric photochemistry model. This Letter assumed simple scaling arguments for the abundances of nitrogen-containing species, but the steady-state abundance of nitrogen-containing atmospheric species will depend on a complex network of chemical reactions and the photochemical impact of the host star's UV spectrum. In such future work, the increases of NH_3 and N_2O, and CH_4 from agriculture would be parameterized via surface fluxes instead of arbitrary fixed and vertically constant mixing ratios. A network of photochemical reactions would then determine the vertical distribution of those species in the atmosphere. A photochemical model could also capture the processes of wet and dry deposition of NH_3, which is the major sink in Earth's present atmosphere, as well as aerosol formation from NH_3 and SO_2/N_2O that can occur in regions of high agricultural production. Past studies have predicted more favorable build-up of biosignature gases on oxygen-rich Earth-like planets orbiting later spectral type (K- or M-type) stars due to orders of magnitude less efficient production of OH, $O(^1D)$, and other radicals that attack trace gases like CH_4 (Segura et al. 2005; Arney 2019). The photochemical lifetime of N_2O and therefore its steady-state mixing ratio will be enhanced by less efficient production of $O(^1D)$ radicals that destroy it. However, because deposition is the major sink of NH_3, it is not clear whether a different stellar environment would alter the atmospheric lifetime of NH_3, and if so, to what extent. The application of an appropriate photochemical model could answer this unknown.

Examining the four scenarios in this study with such a photochemical model would require additional development work to extend the capabilities of existing models to oxygen-rich atmospheres. Past photochemical modeling studies that have included NH_3 considered anoxic early Earth scenarios where the focus was determining the plausible greenhouse impact of NH_3 to revolve the faint young Sun paradox (Kasting 1982; Pavlov et al. 2001). More recent studies have considered NH_3 biosignatures in H_2-dominated super-Earth atmospheres, which would greatly favor the spectral detectability of the gas relative to high molecular weight O_2-rich atmospheres (Seager et al. 2013a, 2013b; Sneed 2020; Phillips et al. 2021). On H_2 planets with surfaces saturated with NH_3, deposition is inefficient, and sufficient biological fluxes can overwhelm photochemical sinks and can allow large NH_3 mixing ratios to be maintained (Huang et al. 2022; Ranjan et al. 2022). These "Cold Haber Worlds" are far different from the O_2–N_2 atmosphere we consider here, where surfaces saturated in NH_3 are implausible and photochemical lifetimes are shorter. Ideally, future calculations would use a three-dimensional model with coupled climate and photochemical processes suitable for an O_2–N_2 atmosphere to more completely constrain the steady-state abundances, and time variation, in nitrogen-containing species for planets with intensive agriculture.

Future investigation should also consider false-positive scenarios for NH_3 and N_2O as a technosignature. One possibility is that a species engages in global-scale agriculture using manure only; such a planet could conceivably accumulate detectable quantities of NH_3 and N_2O without the use of the Haber–Bosch process. The distinction between these two scenarios might be difficult to resolve, but both forms of agriculture nevertheless represent a technological innovation. Whether or not similar quantities of NH_3 and N_2O could accumulate on a planet by animal-like life without active management is a possible area for future work. External factors such as stellar proton events associated with flares could also produce high abundances of nitrogen-containing species in an atmosphere rich in NH_3 (e.g., Airapetian et al. 2017), so additional false-positive scenarios should be considered for planets in systems with high stellar activity.

This Letter is intended to present the idea that the spectral signature of extraterrestrial agriculture would be a compelling technosignature. This does not necessarily imply that extraterrestrial agriculture must exist or be commonplace, but the idea of searching for spectral features of an ExoFarm remains a plausible technosignature based on future projections of Earth today. Such a technosignature could also be long-lived, perhaps on geologic timescales, and would indicate the presence of a technological species that has managed to coexist with technology while avoiding extinction. Long-lived technosignatures are the most likely to be discovered by astronomical means, so scientists engaged in the search for technosignatures should continue to think critically about technological processes that could be managed across geologic timescales.

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ORCID iDs

Jacob Haqq-Misra https://orcid.org/0000-0003-4346-2611
Thomas J. Fauchez https://orcid.org/0000-0002-5967-9631

Edward W. Schwieterman https://orcid.org/0000-0002-2949-2163
Ravi Kopparapu https://orcid.org/0000-0002-5893-2471

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