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Detection of pre-industrial societies on exoplanets

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Abstract

Approximately 22% of sun-like stars have Earth-like exoplanets. Advanced civilizations may exist on these, and significant effort has been expended on the theoretical analysis of planetary systems, and accompanying practical detection instruments.

The longevity of technological civilizations is unknown, as is the probability of less advanced societies becoming technological. Accordingly, searching for pre-industrial extra-terrestrial societies may be more productive.

Using the earth as a model, a consideration of possible detectible proxies suggests that observation of seasonal agriculture may be possible in the near future – particularly in ideal circumstances, for which quantitative analysis is provided. More speculatively, other detectible processes may include: species introduction; climate change; large urban fires and land-use or aquatic changes.

Primitive societies may be both aware that their activities may be observed from other planets, and may deliberately adjust these activities to aid or conceal detection.

Introduction

Prevalence of non-technological societies

Taking the Earth as a model planet, we find that technological (radio-capable) civilization has existed for of the order of a century (Circkovic, 2007; Penny, 2011), whilst agrarian societies have existed for around 10 000 years (Johnson and Earle, 2000). While the industrial era is typically characterised by the adoption of heat engines, facilitating mechanised mass manufacture and transport, astronomers may regard radio-capable civilization as being the temporal marker of industrialization, due to its importance for interstellar communication.

Humankind has been altering the environment for a period many times longer (Gillespie, 2008), such as by hunting megafauna to extinction, and burning scrub.

When compared to a search for technological societies as short-lived as our own, regarding Earth's scenario as typical would suggest that capable detection technologies would offer up to 100× more opportunities to investigate agrarian societies than their technological counterparts. Furthermore, there would be additional opportunities to investigate primitive societies – although the lack of a clear start date for environmentally modifying primitive societies means it is difficult to offer a comparable factor. Nevertheless, an additional order of magnitude is a feasible estimate – potentially giving timescales around 1000× longer than for our radio-capable civilization, if detection of the most primitive societies were possible.

If technological civilizations are typically long-lasting – or cyclical (Roberts, 1968) – the suggested 100 × figure will be too high. Conversely, this figure will be too low if more primitive societies are frequently:

(1) destroyed before industrialisation (e.g. by war, disease or natural disasters);
(2) unable to industrialise (due to e.g. lack of metal ores or fire-compatible environments; cognitive restrictions or cultural constraints).

Identification of proxies

Detection of pre-industrial societies on exoplanets can be considered by using Earth as a model – with due consideration of the risk of overlooking alien life of unfamiliar forms. Regarding earth processes as typical may result in a concerted search for only a very small subset of detectable extra-terrestrial societies. However, detailed consideration of Earth's history and prehistory offers an opportunity to explore a broad range of proven proxies for intelligent life. By contrast, extending this process to radically different imagined life-forms – e.g. eusocial, liquid-methane dwelling octopodes with a millennial lifecycle; sentient and sophisticated mycorrhizal networks; or ultra-fast, ultra-dense life forms living on neutron stars (as imagined by Forward, 1980) – would be highly speculative, and would not readily produce a workable list of target proxies. Nevertheless, we note particularly that intelligence may evolve in:

1. aquatic environments unsuitable for industrial society (cephalopods and cetaceans offering examples of such animal intelligence, on earth);
2. cold, organic biospheres – such as postulated for Titan – where life chemistry may be very different from earth's, and biological activity (and resulting movement) very much slower.

Application of appropriate detection methods to planets that differ significantly from Earth is possible – as they may still be able to develop earth-like societies. For example, planets may have much smaller oceans, orbit different types of stars, be tidally locked or differ substantially in size from the Earth (Orosz *et al.*, 2012). Such techniques could additionally aid discovery of societies on exomoons. Nevertheless, this paper specifically considers only societies that might be regarded as broadly Earth-like – i.e. with terrestrial aliens, on planets with atmospheres and a hydrological cycle. For clarity, the term 'anthropogenic' is used in this document to include intelligent extra-terrestrials.

Instrumentation methodologies

Various methodologies have been suggested to investigate exoplanets, and to narrow down the search for potentially life-supporting planets (Segura *et al.*, 2003, 2005; Beichman *et al.*, 2004; Herbst & Leger, 2007). Typically, this does not involve the direct spatial optical resolution of exoplanets, as a planet in a resolvable orbit would ordinarily be too far from its star to sustain Earth-like life (Biller, 2013). Other techniques used or proposed include: transit spectroscopy (Charbonneau *et al.*, 2002; Kreidberg, 2018), to detect absorption bands in planetary atmospheres; spectropolarimetry (Mohler *et al.*, 2010; Sterzik *et al.*, 2012; Fossati *et al.*, 2019), and similar scattering-based techniques (Lattanzi *et al.*, 2005), to detect aerosols (such as smoke particles or clouds); reflected light monitoring (glint) (Bailey, 2007; Belu *et al.*, 2010, Batalha *et al.*, 2019); or direct light observation (Konopacky *et al.*, 2015; Birkby, 2018), to view planets (albeit with the problematic confounder of starlight). Combinations of methods, together with increases in resolution and improvements in the frequency of observations, will improve observational capabilities in the coming decades (Fujii *et al.*, 2018).

Time-series interpolation

Some astronomical or planetary processes can best be understood by aggregating the data from various specimens, each at different stages of an overall life cycle. These disparate examples can then be interpolated into a model life cycle. This technique may be used for reconstructing everything from the origin and fate of stars (Henderson and Stassun, 2012), to the developmental stages of extinct fossil animals. Assuming that observation of a substantial number of extra-terrestrial civilizations on exoplanets is possible, it may be possible to detect common patterns of development – thus potentially permitting reconstruction of typical civilization life cycles, despite these involving entirely separate alien life forms. Many of the detectable phenomena discussed below may only become statistically meaningful when observed over a large number of planets, or for extended periods of time. This technique would only work if similarly-developing extra-terrestrial societies are common throughout the galaxy.

Detectable phenomena

Urban fires

Detection of light produced directly from urban lighting has been proposed (Loeb and Turner, 2012). In pre-industrial societies, widespread street lighting would likely be combustion-based (although chemoluminescence is possible), and would therefore be of sufficiently low intensity that interplanetary detection would be implausible. However, the Great Fire of London shows that large urban fires are possible. The light output from such fires would be many orders of magnitude brighter than that from combustion-based street lighting, of similar area Fig. 1.

Large fires are necessarily easier to detect than small fires. However, pre-industrial cities were generally small in size, limited by their agricultural hinterlands and resultant transport networks. Furthermore, urban fires may be instantaneously limited in size, even as they spread through the urban environment. Any very large pre-industrial city would likely require a waterborne transport network (Chant & Goodman, 2005), which would itself reduce the likelihood that fires would become extensive (both by providing firebreaks and offering a ready supply of water for extinguishing fires).

It is postulated that (particularly in the event of military action, terrorism or similar) a widespread or multi-seat urban fire could exist on such a scale as to be directly observed at interplanetary distances, given a very large city (or network of cities).

Proving a fire to be urban, as opposed to a wildfire, is problematic. Indeed, it is likely that wildfires are ordinarily far larger than urban fires (Williams, 1982). Nevertheless, it is possible that an urban fire may occur on a planet that is either rainy or has fire-resistant vegetation – thus allowing the isolation of any urban fires as atypical for that planet. However, this leaves the difficulty of distinguishing urban fires from infrequent wildfires. This type of detection would require long observation periods, or the simultaneous observation of large numbers of target planets; colossal urban fires are presumed to be generally rare (decadal to centurial, and longer on sparsely-populated or primitive planets with few cities).

Conceivably, the combustion products of large urban fires may differ from those of natural fires:

(1) Combustion gas spectroscopic characteristics, or aerosol spectropolarimetric properties may differ from those of natural fires – potentially due to drier combustion material, or the different temperature and oxygen levels in urban fires (Fields *et al.*, 1989).
(2) Some specific artificial (but pre-industrial) substances may have combustion products that may be detectable through transit spectroscopy (e.g. from burned paints, leathers etc.) (DeHaven, 1958).

However, these differences would naturally be minimised in pre-industrial societies – in which the predominant sources of flammable materials would presumably be plant- or animal-based. These would consequently mimic the signatures of natural burning – save for their dry state, which may result in detectibly different combustion products (Brode and Small, 1986) – albeit likely in small quantities. However, these combustion signatures are not necessarily distinguishable from dry materials in desiccated natural environments. The accurate distinction of urban fires from natural ones would therefore ideally require a number of large urban fires to occur on a single planet. This would require

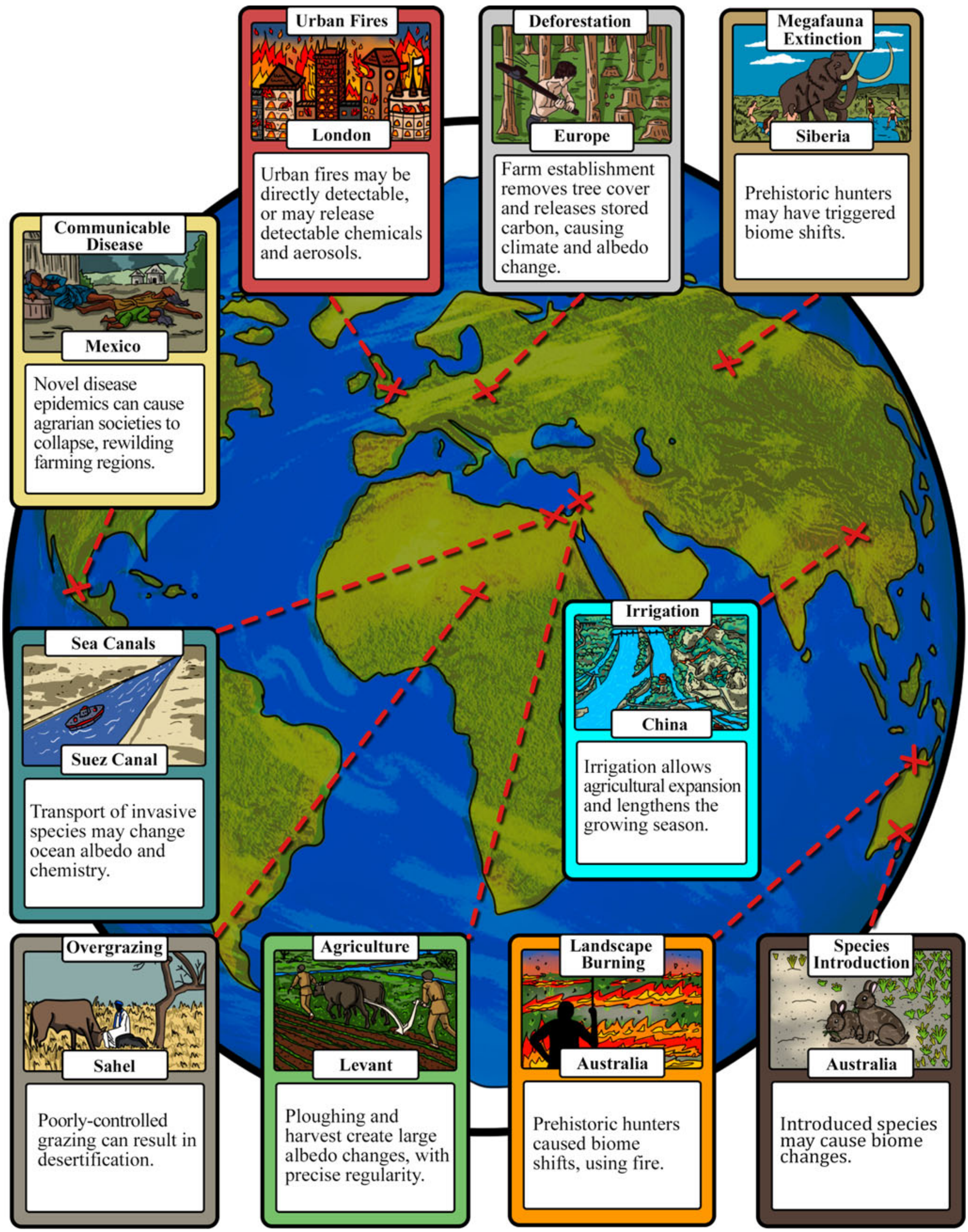

Fig. 1. Illustration of a series of terrestrial events, potentially detectable at interstellar distances with future technologies.

long observation periods or the chance observation of a period of severe conflict.

Land use change

The dawn of farming is associated with land surface changes resulting from the rise of agriculture and pastoralism (Marshall, 2020) – i.e. substituting grasslands and forests with croplands and pastures (Lambin *et al.*, 2001), species introduction (Reidsma *et al.*, 2006), or fire-clearance (although this pre-dates formal agriculture). These are all processes that can be observed with the use of remote sensing methods, through the changes in surface albedo they produce (Boisier *et al.*, 2013; Wang *et al.*, 2017). Fires may be detected by other methods, as previously described.

The spread of human societies into new areas has often been accompanied by land-use change, predominantly for agricultural use, or to optimise hunting lands. This involves a variety of processes: forest clearance (Clark, 1947; Clement and Horn, 2001); irrigation (Clark, 1947; Doolittle, 2014); scrub burning (Ryan *et al.*, 2013), marsh drainage (Menotti, 2012) etc., whilst such changes are significant at a local scale, they would have to be continental in scale to have a realistic chance of being detected at interplanetary distances. Fortunately, the historical and prehistorical record on earth offers examples – e.g. the European colonization of the New World, and the much earlier arrival of humans in Australia. The migration of settlers from Western Europe triggered rapid changes in the land-use of the Americas. Firstly, introduced diseases contributed to the collapse of existing civilizations (King, 2015), which resulted in the rewilding of farmlands. Then, as more settlers arrived and spread, the land was manipulated by controlled grazing and cultivation – resulting in a very different pattern of land-use than was previously the case. Similarly, in Australia, the landscape was shaped by fire (Bowman, *et al.*, 2004) and by hunting of megafauna (Johnson, 2005). These changes may have occurred around 10× as long ago as the rise of agriculture – and, conceivably, could have been practised to a detectable extent by archaic hominins.

Both expansion and contraction of societies may affect land-use. Pandemics (Little, 2007), migration (Conn *et al.*, 2002), war (Van *et al.*, 2015), genocide (Robinson *et al.*, 2000), continental discovery (Sandor *et al.*, 2002) etc., have all driven land-use change in human history and pre-history. In modern times, there have been more subtle changes, due to increasing concentrations of CO_2 in the atmosphere (Zhu *et al.*, 2016). Use of artificial fertilizers has resulted in a widespread greening (Johansson *et al.*, 2008). There has also been an accompanying increase in eutrophication (Jørgensen and Richardson, 1996), and an extension of ocean dead zones (Gupta, 2015), which provide alternative proxies. Some of these changes, such as the mining of near-surface coal seams (Dodson *et al.*, 2014) and the utilisation of phosphate fertilizers (Rutherford *et al.*, 1994), can conceivably be conducted at scale by pre-industrial societies.

Resulting continental-scale changes in reflected or absorbed spectra, and observed aerosol proxies, would likely emerge on centurial or millennial timescales – requiring extended or parallel observation. Such signals would be difficult to distinguish from natural ecosystem changes. Aggregate analysis of a number of planets may be required to extract an amount of data sufficient to justify any robust conclusions. Notably, changes in levels of greenhouse gases may result from pre-industrial land-use change (e.g. deforestation) (Pielke *et al.*, 2002) – and these are potentially capable of detection at interstellar distances (see section 'Climate change and fossil fuel use').

More speculatively, the deliberate creation of huge geoglyph monuments cannot be ruled out. Much as the Nazca lines are visible from the air, greatly amplified versions of this phenomenon could conceivably be detectable at interstellar distances. Such monuments could be created by modifying the landscape surface, or the distribution of dyes. In deserts, such modifications may be persistent. This concept stretches both the capacity for creation and detection to its limit. Notably, such monuments may be created incidentally, or with the deliberate intention of communication; speculative consideration of extra-terrestrial life pre-dates industrialisation by centuries (Scharf, 2019); this discussion continued as astronomy and science developed at around the time of the industrial revolution (Crowe, 1986). Similarly, a reverse process is possible – where civilization may take care to reduce or disguise detectable signs of their society's existence or activities.

Introduced species and extinctions

The effect on natural biota as a result of the introduction of invasive species is comparable to anthropogenic land-use change. Modifying species, such as beavers (Anderson *et al.*, 2006); predators, such as rats (Abdelkrim *et al.*, 2005); or the pathogens and vectors responsible for plant diseases like Dutch Elm Disease (Castello *et al.*, 1995), have often resulted in rapid ecosystem changes. Conceivably, a change may have a very broad impact on a biome scale – e.g. instigating a transition from deciduous to coniferous woodland. In that example, winter loss of leaves may be detectable, by looking for seasonal changes in leaf cover. This can be achieved by observing the particular optical signature of chlorophyll, or other light-harvesting molecules; or alternatively by looking for the winter signature of bare ground, or snow.

Whilst these changes are conducted by natural processes, they are triggered by an anthropogenic event. Conclusions in the section on 'Land use change' therefore also apply to the effects of introduced species. Such signals would be particularly useful in conjunction with other indicators of expanding civilization.

Such effects may also apply to bodies of open water, as well as the land surface. An extra-terrestrial world could be imagined, in which oceans were separated and radically different. For example, a planet may have two large oceans, only one of which has surface photosynthetic life (e.g. azolla). Any anthropogenic activity that transferred photosynthetic species from one ocean to the other would trigger potentially-detectable changes over a number of timescales, as the introduced species spread: annual blooms (Platt *et al.*, 2009), a decadal increase of extent, and longer-term planetary biogeochemical change (Asner and Vitousek, 2005). Notably, spectropolarimetry may be particularly useful for monitoring the presence or characteristics of oceans of exoplanets – due to the polarisation of light reflected from the ocean surface. Additionally, ocean processes (aerosols and gas release) influence cloud formation – giving another route to detect ocean changes.

The opposite of species introduction is extinction. Whilst the introduction of pathogens (as briefly discussed above) is one possible cause, there are many other reasons for extinction. The loss of megafauna species to hunting has been strongly associated with human expansion – particularly in prehistoric times (Duncan *et al.*, 2002). More modern analogues exist in the near-extinction of the American bison (Taylor, 2011) – which is a component of the New World changes discussed. In all such cases, it is at least conceivable that ecosystem changes from comparable events could be detectable at interplanetary distances – provided that these were both pronounced, and continental in scale. To give a specific example: the loss of large grazing animals may result in the conversion of grassland to the forest (Gibson and Brown, 1991). As described above, such a transition may be detectable by leaf colour, seasonal fall, or the presence of monoterpene hazes (Kerr and Ostrovsky, 2003).

Seasonal agricultural changes

Large-scale agricultural monocultures have specific optical signatures. Ploughing, growing, flowering, ripening and harvesting are all potentially detectable – and highly temporally reliable. The more extensive a monoculture, the larger the signal would be. A planet with a wheat monoculture would transition from a near-white ripened crop to near-black bare earth (Lobell *et al*., 2003), accompanying the harvesting and ploughing season. As discussed above, a sudden loss of chlorophyll-containing surface vegetation would potentially be observable. By contrast, natural ecosystem processes rarely expose extensive bare soil in a sudden change, nor would they result in a sudden loss of surface chlorophyll (fires and snow excepted). However, careful parameterisation of leaf fall changes would be required, to demonstrate clear and detectable differences from ploughing events. Comparably, a canola crop would have vivid yellow flowers in season (Rabe, 2003). On a planet with extensive continents and pervasive monocultures, the agricultural cycle would offer a potentially strong signal, which is robustly periodic over annual timescales. However, other planets may lack strong annual seasonality, so such periodicity is not guaranteed.

Albedo changes due to harvesting would only be a function of the fraction of the planet covered in the land (L_{FRAC}), the fraction of land covered by the crop (L_{CROP}) and the changes in albedo before and after harvest (dA). Assuming a change in albedo as high as 0.2 (Davin *et al*., 2014; Seneviratne *et al*., 2018) and the conditions of a single supercontinent covering 50% of the planet completely covered in the same crop, this yields a potentially measurable change in the albedo of around 10%. This figure depends on the precise position of the continent, and the geometry of the planet's position relative to its sun and the human observer.

With the European Space Agency-Switzerland optical photometric space mission CHaracterizing ExOPlanet Satellite (CHEOPS) (Cessa *et al*., 2017), Serrano *et al*. (2018) reported that it would be possible to detect the albedo of a planet depending on the ratio of its radius compared to that of its star. In particular, they report that an albedo similar to that of the Earth is detectable when this ratio exceeds 0.04, but the noise level remains too high to determine a 10% change in albedo for a radius up to 0.07. This ratio for the Earth is <0.0092. Currently, the largest candidate to have been found with a density similar to the Earth has been Kepler 10c, with a radius 2.32 times bigger than the Earth (Rajpaul *et al*., 2017); current satellite capabilities would not be capable of resolving such a change, given a star like our Sun. Smaller stars, however, such as M-Dwarf stars (Red Dwarf), could present a chance at detection. This kind of star, which accounts for 85% of all stars in the Milky Way, would tend to have tidally locked orbiting planets (Kasting *et al*., 1993) – meaning that any seasonality would not arise from comparable mechanisms to that found on earth. While this could make the emergence of plant-like life harder than around Sun-like stars, recent results have shown that atmospheric collapse in the presence of tidal locking may not happen (Merlis and Schneider, 2010); more complex life might indeed be possible (Tarter *et al*., 2007), and detectable seasons would still occur if the orbit of the planet is not circular. In this case, considering that the size of M-dwarf stars lies between 0.1 and 0.6 Sun radii, detection might be possible with current capabilities for Earth-sized planets if the star lies at the lower end of the spectrum. Dragomir *et al*. (2019) detected an Earth-sized planet orbiting such a star, but its closeness to the star makes it unsuitable for life. Future planned missions (such as the PLAnetary Transits and Oscillations of stars PLATO – Catala, 2008) might lower the detectability threshold further.

While white dwarfs would also be good candidates for this kind of detection – given their small size and dimness – the red giant phase of their evolution tends to destroy close-orbiting planets (Villaver and Livio, 2009). It is therefore unlikely that anything but cold and distant planets will remain in their orbit (Vanderburg *et al*.,2000), although the possibility of smaller planets remaining cannot be completely excluded (Barnes and Heller, 2013).

Beyond the direct optical detection of agricultural land manipulation, there is a possibility of detecting secondary outputs of agriculture. Stubble burning was extensive in the UK until outlawed (Clapp, 2014). If such burning was planetary in scale, atmospheric smoke loading may be observable (Smith *et al*., 2007), e.g. via spectropolarimetry. Again, combustion products could potentially be distinguished from those of natural fires – meaning that the type of smoke, and not merely its extent, could be used as a detection strategy. Methane produced by ruminants may also constitute a detectable agricultural proxy (see section 'Climate change and fossil fuel use').

Climate change and fossil fuel use

Climate change may be caused by the exploitation of carbon-rich fossil fuels, which were extracted before the industrial era (Low Tech, 2011; Pirani, 2018).

Climate change can also be caused by the expansion of the number of ruminant livestock (Ripple *et al*., 2013), and land-use change (Flannery, 2005). Climate change can potentially be detected at interstellar distances, e.g. by using the secondary eclipse method (Baskin *et al*., 2013), as well as the measurement of greenhouse gas concentrations, as previously discussed.

Whilst we associate climate change with the industrial era on earth, it is potentially possible that different geologies may facilitate sudden, large-scale exploitation of fossil fuel resources. For example, if settlement of the Americas was accompanied by discovery and exploitation of large and easily-accessible fossil fuels reserves, a scenario is conceivable where detectable climate change was a result – without assuming industrialisation.

Separately from climate change, direct signs of fossil fuels combustion may be detected. For example, the use of such fuels on earth is associated with mercury and sulphur pollution, as well as smoke. Pre-industrial fossil fuel use, particularly in colder climates, was predominantly for heating. This offers a potentially detectable seasonal cycle.

Conclusions

A number of pre-industrial anthropogenic processes are possible models for comparable processes on exoplanets. These processes may be detectable at interplanetary distances. The challenge is not only observation *per se*, but the disentanglement of signals of anthropogenic activity from those arising from natural processes.

This paper suggests the following anthropogenic phenomena – and the possible detectable proxy signals that may result – as possible candidates for detection:

(1) Urban fires: direct optical detection of flame; detection of smoke by spectropolarimetry; transit spectroscopy to detect non-natural combustion products. Fires are sporadic and unpredictable. Additionally, the signal is likely to be small, and hard to separate from natural events. Furthermore, continuous observation of target planets would be required to detect such a transient phenomenon.
(2) Land-use or aquatic change: spectroscopy of sunlight reflected from the planet surface under ecosystem change, caused by expansion/contraction of the cultivated area; spectropolarimetry or spectrophotometry of smoke from clearance fires etc. Equivalent aquatic changes are possible. Additionally, indirect effects – such as changes to cloud cover – may be observed. The principal limitation is the long time period needed for observation and the lack of repeatability on a single planet.
(3) Introduced species: our conclusions from land-use change apply generally to this potential observation target. We note that effects resulting from species introduction are likely to accompany other land-use changes; the observational challenges are similar, and the signals potentially difficult to distinguish. (N.B. Marine introductions are also possible.)
(4) Seasonal agricultural practices: spectroscopy of reflected sunlight in ploughing/harvesting; detection of smoke by spectropolarimetry. This combines potentially-large signals with potentially-regular repetition, and is hence the favoured candidate for systematic detection. However, considering the likely differences expected as a result of defined ploughing and/or burning activities, it may be difficult to distinguish from natural biological cycles – e.g. seasonal leaf fall. This paper offers quantitative evidence that idealised agriculture may be observable, were seasonal agriculture to exist on planets orbiting Red Dwarf stars.
(5) Climate change: spectroscopy of greenhouse gases, direct observation of temperature changes; direct observation of combustion products. In the case of pre-industrial societies, this would likely involve long observation periods (multiple decades, to centuries). Furthermore, the resulting signal is likely to be, on average, smaller than that of comparable industrial societies.

In summary, it is suggested that a thorough evaluation be made of the opportunities to detect seasonal agriculture on exoplanets and exomoons, whilst keeping an open mind on the search for the other, less promising proxies identified.

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