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Atmospheric carbon depletion as a tracer of water oceans and biomass on temperate terrestrial exoplanets

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The conventional observables to identify a habitable or inhabited environment in exoplanets, such as an ocean glint or abundant atmospheric O_2, will be challenging to detect with present or upcoming observatories. Here we suggest a new signature. A low carbon abundance in the atmosphere of a temperate rocky planet, relative to other planets of the same system, traces the presence of a substantial amount of liquid water, plate tectonics and/or biomass. Here we show that JWST can already perform such a search in some selected systems such as TRAPPIST-1 via the CO_2 band at 4.3 µm, which falls in a spectral sweet spot where the overall noise budget and the effect of cloud and/or hazes are optimal. We propose a three-step strategy for transiting exoplanets: detection of an atmosphere around temperate terrestrial planets in about 10 transits for the most favourable systems; assessment of atmospheric carbon depletion in about 40 transits; and measurements of O_3 abundance to disentangle between a water- versus biomass-supported carbon depletion in about 100 transits. The concept of carbon depletion as a signature for habitability is also applicable for next-generation direct-imaging telescopes.

In 2022, humanity entered a new era of space exploration when the first data products from JWST were revealed[1]. JWST is the first of a new generation of great observatories to come online this decade and scientific accomplishments such as probing the atmospheres of terrestrial exoplanets and three-dimensional mapping of giant exoplanets are now within reach (Box 1).

The greatest potential for exoplanetary science lies in the detailed atmospheric characterization of a diverse range of planets to enable comparative studies informing formation, evolution and atmospheric processes, as well as investigating and contextualizing habitats[2]. Thus, our community must find and then reliably study planets suited for such quests. Over 30 years, over 5,200 exoplanets have been identified.

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BOX 1

Remote sensing of exoplanet atmospheres

Observational methods developed and refined over the past two decades now allow astronomers to collect a vast host of information about an exoplanet's atmosphere without having to leave the Solar System[91]:

- constraints on the vertical temperature, pressure and compositional profile of atmospheric limbs[72,92]
- information about the materials used during planetary assembly and their subsequent orbital evolution[71]
- the current thermodynamic state of the planet[93]
- distinguish molecules with different isotopes[94,95]
- measure wind velocities[96]
- probe evaporating exospheres[97,98]
- create crude topological and atmospheric maps for exoplanets[99,100]

Widely applied to hot close-in gas giants[101,102], these methods are now increasingly in development and will soon be applied to terrestrial planets[78,103], initiating the exploration of how diverse the atmospheric and climatic properties of exoplanets are[104] and, importantly, how those compare with the properties of planets within our Solar System.

The field of exoplanetary science is now transitioning from detection to characterization (Box 1).

Several teams have modelled terrestrial planet atmospheres[3–5], while others have assessed their observability[6–10]. These studies have found that the atmospheres of transiting temperate (defined as receiving a flux between 4× and 0.25× that of the Earth) terrestrial planets orbiting nearby ultracool dwarfs such as TRAPPIST-1[11] can be detected with JWST and their dominant atmospheric absorbers (for example, carbon dioxide (CO_2) and water (H_2O)) revealed after collecting of the order of 10 transits[7,12]. In addition, they show that the conventional biosignature gas molecular oxygen (O_2)[13,14] remains out of reach with JWST due to the narrowness of the O_2 lines combined with a low signal-to-noise ratio below 1 μm, even for ideal terrestrial planet targets (that is, those orbiting late M dwarfs, because of the much reduced size of their host star and the shortness of their temperate orbits[15,16]). Even the anti-biosignature O_2–X collisionally induced absorption band at 6.4 μm (X being here the collisioner), which is more readily accessible, remains mostly out of reach[9]. Indeed, detecting O_2 would require on the order of 1,000 planetary transits for the most favourable targets, which corresponds to the allowable observation time over an entire JWST cycle. It would take a few decades to collect data for planets that have orbital periods of 5 to 10 days, such as those within the habitable zone of TRAPPIST-1. In other words, with this new generation of great observatories and programmes gathering up to a few hundred planetary transits of terrestrial worlds, it will be possible to reveal atmospheric constituents that are strong absorbers and later derive preliminary constraints on abundances and temperature–pressure profiles, but these observations are not expected to assess the presence of life via O_2 detection. The detection of O_2 using the Extremely Large Telescope (ELT) appears much more promising by co-adding the individually resolved lines of its visible and near-infrared bands (for example, the 760 nm A-band), which takes advantage of high-resolution spectrographs[17]. The detection of O_2 (ref. 18) will be attempted using transit spectroscopy (which might be difficult[19]), and also reflected light spectroscopy (using the high-resolution high-contrast technique[20]), which is available for a couple of nearby non-transiting exoplanets (for example, Proxima b)[21]. Another biosignature of interest is ozone (O_3), which is produced when a large reservoir of O_2 irradiated with ultraviolet light[13,14]. O_3 bands in the ultraviolet and optical are usually sought after for Earth twins orbiting solar twins, but for late-M-dwarf hosts, which are faint in the optical and ultraviolet, the 4.8 μm band of O_3 is the most prominent feature, and of interest to this paper.

Similarly, the assessment of a planet's habitability (defined as a planet's capacity to retain large reservoirs of surface liquid water[22]) is difficult. A planet's habitability can be affected by a large range of factors, including its orbital properties, its bulk properties, the presence or lack of plate tectonics and magnetic fields, its atmospheric properties, and, finally, stellar activity[23], presenting a complex and thus far mostly theoretical assessment. Empirical measurements affected by the presence of surface liquid water would be handy; however, very few such observables of habitability ('habsignatures', defined in a similar way to 'biosignature' but applied to signatures of surface liquid water) exist. Examples include detecting an ocean glint[24], as has been done for Titan[25], but which is expected to be extremely challenging for exoplanets[26]. The presence of surface liquid-water oceans could also produce a substantial hydrogen exosphere, detectable in Lyman α[27]. However, this is a challenging habsignature too as it would not directly point to water as the related hydrogen-bearing molecule, nor whether water is present in its liquid phase[28] and is a method limited to the very nearest planetary systems due to interstellar absorption. Because of the relation between the carbon cycle on Earth and its tectonic activity, we note that a 'habsignature' might also indicate the presence of plate tectonics on exoplanets.

In this context, we propose that observations of CO_2 absorption in exoplanetary spectra can be used as a signature for habitability (as CO_2 can be removed from the atmosphere by dissolving into surface liquid water before being stored within the crust by tectonic activity) and also potentially as a biosignature (as biology traps carbon, for instance, as sediments and hydrocarbon deposits). The use of CO_2 depletion ('dCO_2') as a habsignature provides a rapid empirical diagnostic about which terrestrial exoplanets are likely to be habitable (that is, host surface liquid water). This approach also happens to identify planets that are most similar to the current Earth. The main concepts of this paper are represented schematically in Fig. 1.

Reframing the search for liquid water and signs of life

Conventionally, the search for liquid water and for signs of biology rely on the detection of added observables to the planetary signal. Ocean glints[24] and hydrogen exospheres[27] are both added signals to the planet's. For life, observables are limited to atmospheric compounds viewed as 'life products' that otherwise would not be thermodynamically stable within the atmosphere of a lifeless planet. Examples shown in Fig. 2 include the presence of a high concentration of O_2, which itself can yield O_3 (refs. 13,14) and ionospheric O^+ (ref. 29), the presence of methane (CH_4) within a CO_2-dominated atmosphere[30], and the presence of other hydrocarbons (for example, ethane[31], chlorofluorocarbons[10] and so on) or other molecules (for example, nitrogen compounds[32]). Here we propose to reframe this search by detecting the depletion of an observable rather than the addition of one. By doing so, we provide a new framework to consider the search for signs of liquid water and/or life that will result in new pathways for these quests, complementary to those presented previously in the literature, thereby improving the prospects of identifying habitable/inhabited worlds. We present one such new pathway below.

One of the most striking differences between present-day Earth and its neighbouring planets relates to its low atmospheric carbon mixing ratio. As shown in Fig. 2, Earth's atmosphere has a remarkably low level of CO_2 among the Solar System terrestrial planets. While the atmospheres of Venus and Mars are composed of >95% CO_2, Earth's atmosphere contains only about 0.04% CO_2 (ref. 33). Most of the

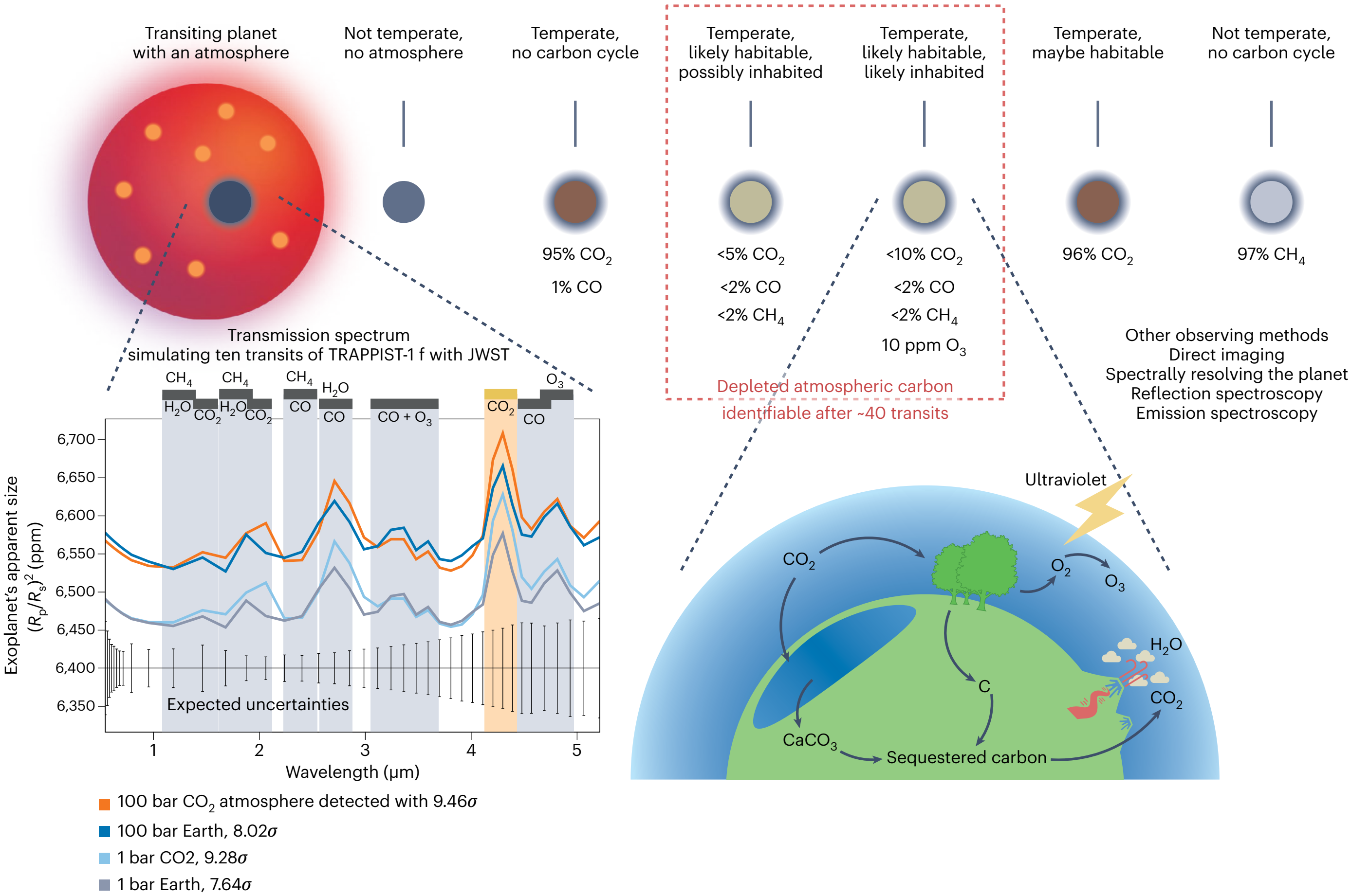

Fig. 1 | Illustration of our strategy to detect habitable exoplanetary environment via CO_2 depletion. Each planet to the right-hand side of the star describes a different scenario discussed in the text (along with illustrative atmospheric concentrations). The bottom-left panel depicts a simulation of the transmission spectrum of the temperate terrestrial planet TRAPPIST-1 f. We explore the detectability of an atmosphere with about ten JWST/NIRSpec Prism transit observations—the minimum needed to produce a reliable diagnostic. Note that the deviation from a flat signal (no atmosphere) is primarily supported by the strong absorption features of CO_2, notably at 4.3 μm (highlighted). Exo-atmospheric models from ref. 83 were used to make this panel. On the bottom right, we illustrate a simplified view of a carbon cycle involving surface liquid water and a biology sequestering cycle, producing a depletion in atmospheric carbon. Atmospheric concentrations given near the planets are illustrative. $(R_p/R_s)^2$, planet-to-star area ratio.

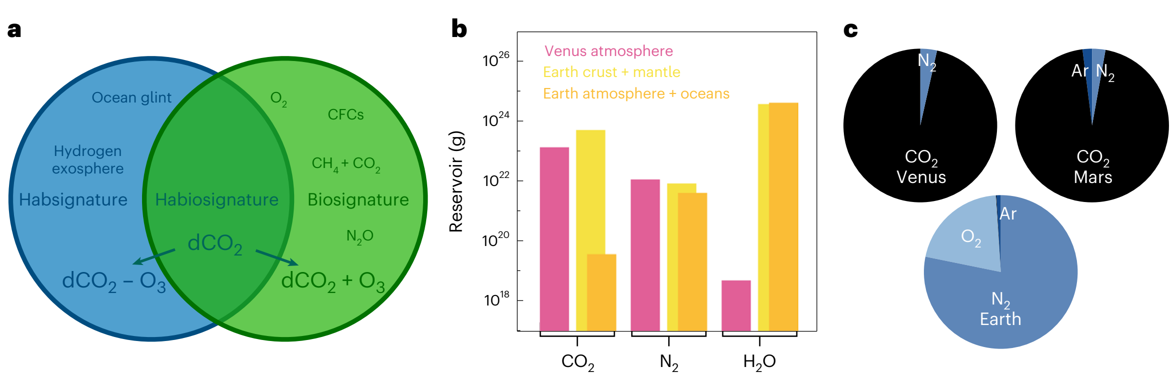

Fig. 2 | CO_2 depletion as a signature of liquid water and/or life. a, Schematic representation of observables associated with the presence of surface liquid water ('habsignature'), of a biomass ('biosignature') or both ('habiosignature'). CFCs, chlorofluorocarbons. **b**, Comparison between present-day Venus's and Earth's interior and atmospheric volatile inventories (data from ref. 33). **c**, Relative atmospheric abundances for Venus, Earth and Mars.

atmospheric CO_2 that was present on early Earth is now sequestered in its rocks[34,35]. Within an order of magnitude, there is a similar mass of carbon nowadays within Venus's atmosphere as there is locked as minerals within Earth's crust[36]. Earth's atmospheric carbon has been depleted by its hydrosphere and its biosphere. This is why atmospheric carbon depletion (dCO_2) in a temperate rocky planet is a tracer of water oceans (a habsignature), biomass (a biosignature) or both at once, which we refer to as a 'habiosignature' (see Fig. 2 and Box 2 for more definitions). Transition periods such as the Archaean, during which Earth was both habitable and inhabited, might be harder to diagnose with dCO_2. However, we note that Earth's atmosphere, while possessing a much larger carbon content than the present day, already had a depleted CO_2 level (ranging from ~10% at 4 Gyr to ~2% at 2.5 Gyr), with nitrogen (N_2) already being the dominant compound[37].

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BOX 2

A few definitions

In this paper, we make use of the terms biosignature, habsignature and habiosignature. We define them as follows.

- A biosignature is defined as an observable associated with the presence of life. It is most often a chemical signature but it need not be.
- We define a habsignature as any process providing evidence of a hydrosphere.
- A habiosignature indicates the presence of a hydrosphere and/or of a biosphere, both planet-shaping processes of interest to astronomers.

Atmospheric carbon depletion as a biosignature

Biology—as we know it—does not just produce chemicals, it also consumes them. Thus, biology cycles elements and removes some molecules from its environment, such as sulfur, nitrogen and carbon-bearing molecules, to make other products[38]. In this paper, we focus on carbon cycling and more specifically, on the removal of atmospheric CO_2, which is expected to be the primary carbon-bearing molecule in the atmosphere of terrestrial planets[39]. The two main processes for biological CO_2 depletion on Earth are (1) oxygenic photosynthesis, where carbon is sequestered in soils and hydrocarbon deposits, and (2) the creation of shells, made from calcite and aragonite ($CaCO_3$), which are stored as sediments in rivers and oceans[40,41]. Accordingly, life on Earth has a substantial role in the carbon cycle[42] with about 20% of modern global carbon sequestration being biologically driven[43]. Biology's ability to extract carbon from the atmosphere might have initiated one of the snowball Earth events[44]. This being written, in most cases it is expected that biology has a minor role in the sequestration of carbon, as its ability to fix carbon is ultimately capped by the water cycle within which it operates[43]. Therefore, other signatures, such as O_3, need to be considered to fully ascertain the presence of biological activity when a substantial depletion of atmospheric carbon is detected (see 'Observations of the 4.3 µm CO_2 band').

Depletion as a biosignature has been proposed to interpret a depletion of sulfur dioxide (SO_2)[45] in the clouds of Venus, low concentrations of hydrogen compounds on Titan[46] and depleted carbon monoxide (CO) within CH_4-rich atmospheres[47,48]. Although controversial, a related example of a depletion as a signature in the exoplanet literature is the concept of anti-biosignatures (for example, a large concentration of CO (ref. 49) or H_2 (ref. 14)), where in that particular context the absence of a depletion is proposed as the signal.

Atmospheric carbon depletion as a habsignature

Liquid water readily dissolves atmospheric CO_2 (refs. 50,51), which can facilitate the formation of carbonates[52], creating a detectable habsignature. CO_2 is expected to dominate the speciation of outgassing products of rocky planets with a bulk composition and redox state similar to Earth's, followed by CO, H_2O and N_2 (ref. 39). When Earth cooled to temperatures that allowed liquid water, much of the atmospheric CO_2/CO dissolved into the new global ocean. Komatiite, a mafic to ultramafic igneous rock that paved the seafloor on early Earth, was exposed to this CO_2-enriched seawater and, as a result, underwent extensive mineral carbonation that caused an initial decrease in the CO_2 concentration of seawater and the atmosphere[35]. Evidence of mineral carbonation is not limited to Earth. Carbonate alteration of the Martian meteorites Lafayette and ALH84001 indicates that mineral carbonation probably occurred during the Noachian and Amazonian periods when liquid water was available on Mars's surface[53]. There are also signs of mineral carbonation on Ceres[54]. Therefore, similar processes can be expected to operate on habitable rocky exoplanets[55].

The speciation of gases during magmatic degassing is strongly influenced by atmospheric pressure[39]. For planets with similar bulk composition to Earth, while water may dominate the mix for pressures under ~3 bar, above that threshold, CO_2 is expected to dominate. Current models therefore suggest that temperate terrestrial planets are able to produce a large (up to ~100 bar) CO_2 atmosphere via outgassing[39] and, if their surface temperature allows for water condensation, to sequester a large faction of it in their hydrosphere. If terrestrial exoplanets that underwent igneous differentiation expose magnesium- and iron-rich (mafic or ultramafic) lithologies to CO_2-rich fluids at temperatures lower than 300 °C (ref. 56), carbonate minerals can form at the expense of primary igneous minerals, such as olivine, which is the most abundant mineral in our Solar System. This process, referred to as mineral carbonation, is rapid on geological timescales[57].

It is possible that Venus was more similar to Earth during most of its history than it is at present. Current observations are compatible with Venus being both tectonically active and hosting habitable conditions on its surface as recently as 1 Gyr to 0.7 Gyr ago[58,59]. If this was the case, increasing temperatures could have lead its surface liquid-water bodies to evaporate and its hydrogen to escape to space, as evidenced by its D/H ratio[60]. As outgassed CO_2 dominates Venus's atmosphere, there would not have been an efficient carbonation process in place since. Observations are also compatible with Venus being never able to condense its water vapour into oceans[59,61]. In either scenario, a relatively low carbon abundance in the atmosphere of a temperate rocky exoplanet, compared with other planets within the same system, appears to be a reliable habsignature of recent and extensive amounts of liquid water at its surface.

Atmospheric carbon depletion as an habiosignature

A planet's concentration of CO_2 has long been known to be important to maintain its habitability. Research so far has focused on determining CO_2 concentrations that allow water to remain in a liquid phase at the surface[2,55,62–64], in particular under the assumption of an Earth-like carbon cycle. For example, refs. 62,64 proposed empirical tests of the concept of the habitable zone, by making the hypothesis of having a terrestrial planet population large enough to be able to statistically study how the CO_2 mixing ratio evolves with a planet's insolations. Refs. 55,63 proposed additional empirical tests by statistically studying how the CO_2 mixing ratio evolves between planets in and out of the habitable zone. Here we take a complementary approach by considering that habitable planets will often have non-habitable neighbours. We argue that a terrestrial planet with an atmospheric carbon abundance measurably lower than others within the same system implies the presence of a hydrosphere and/or of a biosphere. Moreover, the water and carbon cycles are intertwined in a biological and geological context. Therefore, the concept of 'habiosignature' might go further than semantics as Gaian cycles, a complex interplay of geological and biological processes[65–67], are probably responsible for the relative long-term climate stability of our planet[66,68,69], of which atmospheric carbon depletion is a tracer.

While we argue in this paper that a depletion in atmospheric carbon is a habiosignature, we focus more specifically on CO_2 (and thus a depletion in CO_2 (dCO_2)) primarily because of the ease of measuring its spectral features in the mid-infrared, and its applicability to rocky planets with compositions similar to Earth's.

Practical applications of detecting dCO_2

Systems with multiple terrestrial planets (with atmospheres) are needed before attempting to use dCO_2 as a habsignature and habiosignature. As little as one additional terrestrial planet within the system might be sufficient. Here we stress that the more planets in a given system, and the closer they are to the planet being investigated, the better the calibration and thus the stronger the reliability of a depleted feature such as dCO_2.

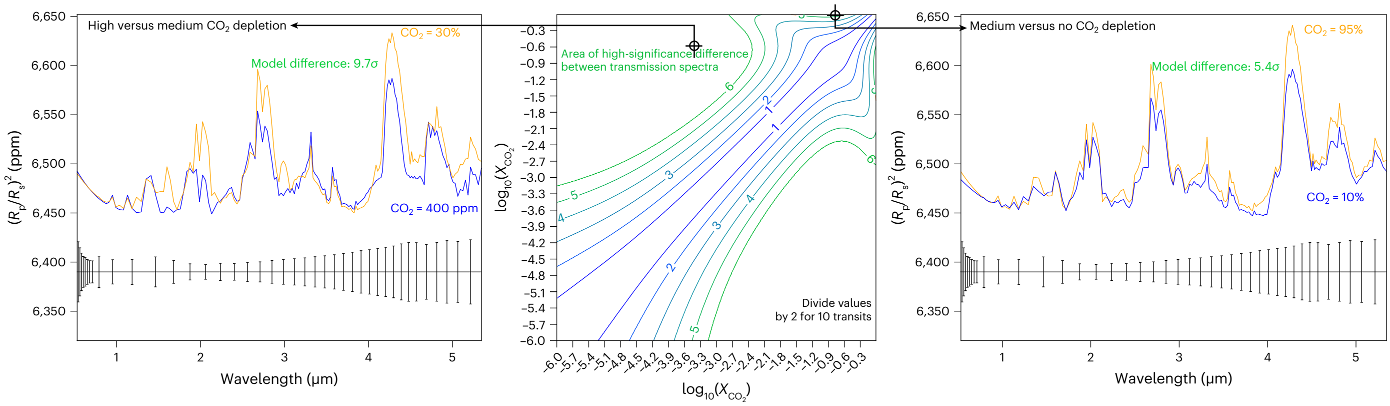

Fig. 3 | Detectability of CO_2 depletion as an habiosignature with JWST. Middle: significance map of CO_2-level effects on the spectrum of TRAPPIST-1 f with 40 JWST/NIRSpec Prism transits. Values reported represent the deviation between two transmission spectra with different concentrations of CO_2 (X_{CO_2}) from 1σ (blue) to 6σ (green). The region around the 1:1 line surrounded by the 1σ contour is at low significance. The width of that region represents the confidence interval with which a given X_{CO_2} can be retrieved (typically ~0.5 dex $\log_{10}(X_{CO_2}=-3.0)$). Left: comparison between the spectra of TRAPPIST-1 f with a high CO_2 depletion ($X_{CO_2}=400$ ppm) and a medium CO_2 depletion ($X_{CO_2}=30\%$). The spectra and their associated 1σ error bar (black) are shown for a resolving power of $R\approx30$. Right: comparison between the spectra of TRAPPIST-1 f with a medium CO_2 depletion ($X_{CO_2}=10\%$) and without any CO_2 depletion ($X_{CO_2}=95\%$).

The physical properties of exoplanetary systems have low entropies, meaning that planetary systems are expected and found in 'peas in a pod' architectures[70]. Similarities between neighbouring planets helps to calibrate depletions for a given planet. Proximity to the snow line could affect a planet's C/O ratio[71]; however, this transition is not expected to lead to orders-of-magnitude differences in the initial carbon inventory, and C/O can be estimated from the atmospheric composition[72].

Observations using direct imaging (for example, using METIS with the ELT[73]) would be the most convenient. Compared with the transit method (Box 1), it is more likely to identify all planets of a system, including those that might have a different redox state (having formed further from their star). Direct imaging is also a practical route to avoid a number of false positives and false negatives that we outline in 'Observations of the 4.3 μm CO_2 band'. Unfortunately, the study of temperate rocky worlds via directing imaging remains out of reach to this day, whereas such planets are now accessible via transmission spectroscopy.

Detectability of the dCO_2 habiosignature with JWST

Currently, JWST can search for dCO_2 for terrestrial planets transiting late M dwarfs, which are expected to be abundant[74]. Figure 3 shows that detecting the presence of an atmospheric carbon depletion in the atmosphere of a temperate terrestrial planet with JWST is within reach. Specifically, it shows that for a planet such as TRAPPIST-1 f, the mixing ratio of CO_2 can be constrained to within ~0.5 dex within 40 transits (Fig. 3, middle). This results holds for planets TRAPPIST-1 e, g and h, as they are expected to have a similar signal-to-noise ratio to planet f, while the three innermost planets would require less than half that number of transits[7,11]. While elemental composition varies between different stellar systems (and between rocky planets from different star systems[75]), within the same system, the planetary elemental compositions are expected to be roughly similar[71,76]. This results in a capability to distinguish between high- and medium-depletion levels (carbon-dioxide mixing ratios of $X_{CO_2}=400$ ppm and $X_{CO_2}=30\%$, respectively) at the ~10σ level. It also allows to distinguish between medium- and negligible-depletion levels ($X_{CO_2}=10\%$ and $X_{CO_2}=95\%$, respectively) at the ~5σ level.

Observational perks of the 4.3 μm CO_2 band

In addition to possibly yielding the detection of an habiosignature, the spectral range surrounding the strong 4.3 μm absorption band of CO_2 (ref. 77) in the near-infrared offers observational benefits that support two other characterization steps: (1) the detection of atmospheres for terrestrial exoplanets, and (2) the distinction between a biological and geological atmospheric carbon depletion.

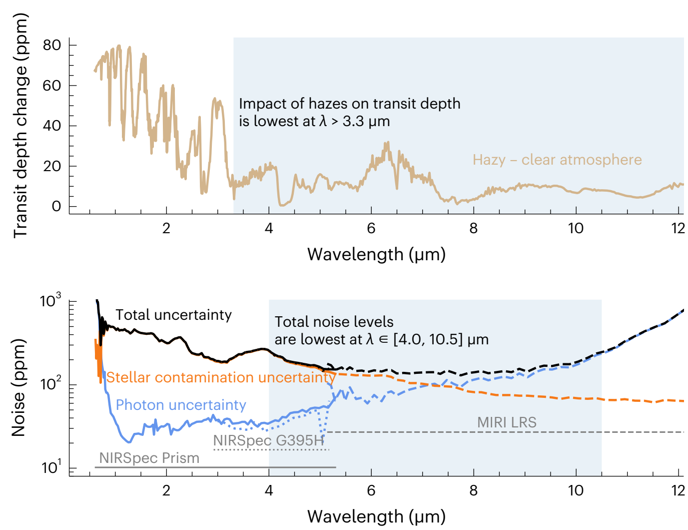

Fig. 4 | Optimum wavelength range for transmission spectroscopy considering the effects of hazes and stellar contamination. Top: the difference between 'hazy' and 'clear' atmosphere transmission spectra for TRAPPIST-1 e[12]. The impact of haze on the transit depth is smallest at wavelengths greater than 3.3 μm. Bottom: photon-limited uncertainties increase at the shortest and longest wavelengths, where the photon flux from the star is limited. Different JWST observational setups and their respective wavelength ranges are shown via grey horizontal lines (NIRSpec Prism, NIRSpec G395H, and MIRI LRS). Systematic uncertainty due to stellar contamination increases towards shorter wavelengths, where contrasts between spots and faculae with respect to the photosphere are greatest. The combined uncertainty from these noise sources reaches a minimum between 4 μm and 10.5 μm. See details in Methods.

Detecting the atmosphere of a temperate terrestrial exoplanet

Until now, it was only possible to search for hydrogen-dominated atmospheres using the Hubble Space Telescope[78]. JWST and the upcoming ELTs now offer the possibility to search for the presence of atmospheres for favourable terrestrial targets, such as the TRAPPIST-1 planets, in as little as five to ten transits[7,12]. More transits, however, may be needed due to (1) stellar contamination of the planets' transmission spectra[79] and/or (2) the presence of clouds and/or hazes[12,80,81].

We show in Fig. 4 that there exists a sweet spot where the combination of both effects and the photon noise is optimal. The effect of stellar contamination decreases while photon noise increases beyond

BOX 3

A study of isotopic fractionation

Isotopic fractionation can be remotely detected[94,105], owing to the fact that a change in a molecule's mass distribution results in shifts in its absorption lines. For CO_2, the main difference in the 4.3 μm band between the dominant isotopes ($^{12}C^{16}O_2$ and $^{13}C^{16}O_2$) is a substantial shift of the bandhead by ~0.2 μm (Fig. 5, left).

Isotopic fractionation is notably driven by atmospheric escape, biological activity and water–rock interactions. In general, biological activity preferentially incorporates the light isotopes (for example, ^{12}C and ^{1}H) into organic compounds; the removal of those organic compounds then drives the residual carbon toward heavier values. Plants and algae have approximate $\delta^{13}C$ values between -10×10^{-3} and -40×10^{-3} (ref. 106) and a 2H-to-1H ratio (δ^2H) between -90×10^{-3} and -180×10^{-3} (ref. 107).

Despite the presence of a global biology on Earth that contributes to about 20% of global carbon sequestration[43], Earth's atmospheric carbon isotopic fractionation is consistent with other objects in the Solar System[108]. Similarly, Earth's rock record shows no substantial changes in $^{13}C/^{12}C$ over the past 3.5 Gyr (refs. 109,110), challenging our current understanding of isotope fractionation in extant metabolic pathways[111].

The picture further complexifies when one accounts for other sources of isotope fractionation that also favour the removal of light isotopes, such as atmospheric escape[112]. In addition to interpretation challenges, the detection of carbon fractionation in the atmosphere of a terrestrial planet will probably be out of reach with upcoming observatories. Figure 5 shows the expected contribution of $^{13}CO_2$ to be around the 5 ppm level for an isotopic fraction similar to Earth's atmosphere, and around the 15 ppm level for 100× Earth's $^{13}CO_2$ isotopic fractionation. These values are smaller than the ~20 ppm precision expected on such a spectral bin with ~100 transit observations (Fig. 5, right). Therefore, carbon isotopologues are unlikely to be informative biosignatures for the JWST era[113].

BOX 4

Insights from oxygen abundance

While the sequestration of atmospheric CO_2 by a planet's hydrosphere allows for the removal of both carbon and oxygen[50–52], the sequestration of atmospheric CO_2 by a planet's biosphere leads primarily to the removal of just the carbon, leaving oxygen as a by-product[13,24]. For redox states similar to Earth's, CO_2 is expected to be the dominant molecule in the secondary atmospheres of terrestrial planets by orders of magnitude[39]. If CO_2 is depleted in a substantial manner by a photosynthetic biosphere, a large fraction of O_2 will consequently be returned to the atmosphere.

While O_2 is challenging to detect directly for known transiting exoplanets with upcoming observatories[9,114], its presence can be inferred by detecting its photochemical by-product O_3 (refs. 13,115). Indeed, O_3 offers a series of strong absorption bands, similar to CO_2, including one at 4.8 μm (ref. 77) in the vicinity of the 4.3 μm band of CO_2. An Earth-equivalent level of O_3 can readily be detected at the ~5σ level with ~100 transits of TRAPPIST-1f observed with JWST/NIRSpec (Fig. 5, right). This means that O_3 concentrations down to the 10 ppm level will be detectable for temperate terrestrial exoplanets with the JWST[116]. We note that Earth's ozone level (10–15 ppm) may serve as a lower limit considering the higher level of stellar ultraviolet irradiation that temperate terrestrial exoplanets orbiting late M dwarfs will face, as they are the only terrestrial exoplanets amenable for atmospheric characterization with JWST[16].

O_3 could also be produced via the photodissociation of CO_2 into CO and O_2. However, only a small fraction of CO_2 is expected to be dissociated in such a way, as seen for Venus and Mars (see False positives and false negatives) leaving an even smaller fraction of the resulting O_2 turned into O_3. Thus, while the atmospheric depletion of CO_2 is an habiosignature preventing from distinguishing between the presence of a hydrosphere and a biosphere, and O_3 is an ambiguous biosignature just like O_2, together they form a reliable and readily accessible biomaker for the JWST era.

~1 μm for stars such as TRAPPIST-1. Therefore, a local minimum exists, dependent on the number of transits needed (photon noise). Figure 4 presents the uncertainty associated with the transmission spectrum of a TRAPPIST-1 planet gathered over ten transits—the nominal amount for the reconnaissance of atmospheres around temperate terrestrial planets. To allow for an easy comparison, we report the uncertainty at a uniform spectral resolving power of $R \approx 30$. The local minimum for such an exploration programme is found between 4 μm and 10.5 μm. This wavelength range overlaps with the wavelength range over which hazes have a marginal impact on a planet's transmission spectrum, namely, wavelengths above ~3.3 μm (ref. 12), although the exact threshold depends on the aerosol size distribution.

The precision sweet spot for the reconnaissance of terrestrial planets with JWST via transmission spectroscopy thus lies between 4 μm and 10.5 μm. In this spectral window, one absorption feature dominates across all models of secondary atmospheres contemplated in the literature: the CO_2 4.3 μm band[12,80]. In fact, as shown in Fig. 1, this band's absorption typically dominates absorption by molecules at shorter wavelengths as well.

CO_2 absorption bands are of particular interest for atmospheric reconnaissance (that is, a low signal-to-noise ratio spectrum) as they are both strong and sharp. The bands are strong because CO_2 is an excellent absorber in the infrared[77], even at a low atmospheric concentration (like in Earth's atmosphere). In fact, this molecular feature is the first reported by JWST in the atmosphere of an exoplanet[1]. The bands of CO_2 are sharp and dense in opposition to, for example, the broad and 'sparse' absorption bands of H_2O and CH_4 (ref. 77). These two qualities of the CO_2 bands allow them to be more prominent in low-resolution spectra and thus not drowned out by correlated noise. As a result, the 4.3 μm CO_2 band appears to be an optimal signature to detect the presence of secondary atmospheres around terrestrial planets, while being accessible to the JWST and has been proposed for JWST observations already as a diagnostic test of the presence of a terrestrial planet atmospheres[82].

Habitable or inhabited?

Once an atmosphere has been detected around a temperate terrestrial exoplanet, we can reasonably expect that an extensive observing campaign will be dedicated to studying its atmospheric properties more in detail. For context, the atmospheric reconnaissance of the TRAPPIST-1 system initiated during JWST's Cycle 1 has already been supported by 8 different observing programmes, totalling over 200 hours. The scale of such a large characterization programme will be capped to ~100 planetary transits, limited by the availability of windows of opportunity

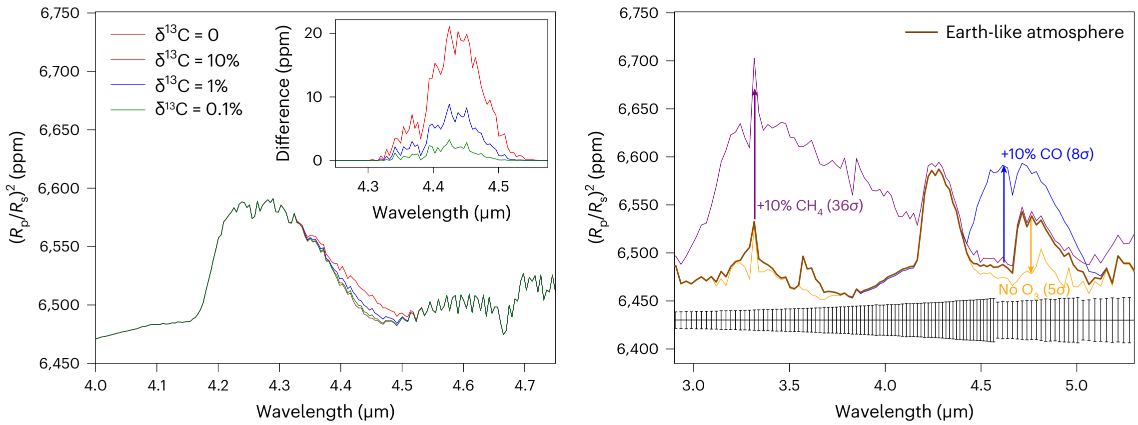

Fig. 5 | Disentangling between the water- or life-based origin of a CO_2 depletion habiosignature. Left: effect of different ^{13}C-to-^{12}C ratios ($\delta^{13}C$) on TRAPPIST-1 transmission spectrum. Effects seen are limited to up to 15 ppm (differences between models shown in the inset), implying that detection of the isotopic fractionation of carbon in the atmosphere of a temperate terrestrial planet with JWST is out of reach (requires >300 transits). Right: effect of O_3 depletion and CH_4 and CO 10% enrichment on TRAPPIST-1 f transmission spectrum. The spectra and their associated 1σ error bar (black) are shown for a resolving power of $R \approx 130$. Detecting O_3 in the atmosphere of a temperate terrestrial planet would support the biological origin of a CO_2 habiosignature and is within reach with ~100 JWST transit observations.

and by the telescope's lifetime. We use the TIERRA code[83] to model planetary spectra and show that ~40 transits would be sufficient to yield constraints on the abundances of the dominant atmospheric absorbers. Figure 3 shows that the abundance of strong absorbers such as CO_2 can be constrained to within 0.5 dex, down to the 10 ppm level (Earth's CO_2 concentration, for comparison, is 400 ppm), thereby allowing to assess the presence of a habiosignature around planets such as TRAPPIST-1's.

Assuming a habiosignature is revealed in the atmosphere of a temperate terrestrial planet, the next natural step will be to disentangle between a geological and biological origin, that is, a habitable and inhabited environment. In Box 3, we review isotopic fractionation of CO_2 and find it unlikely, and in Box 4, we investigate the abundance of O_3 and find it a likely avenue to distinguish habitable from inhabited (Fig. 5).

False positives and false negatives

Any signature has false positives and false negatives that can seriously impact the interpretation of a detected feature[13,14], or, in the present case, the identification of a depleted feature. However, we find that dCO_2 as a habiosignature has few such issues.

From their very first detections, exoplanets' orbital and physical properties have defied expectations[84–86]. We have tried to explore many false-positive signatures, but unknown and efficient CO_2 removal processes could well operate on an exoplanet. In this event, the detection of an atmospheric carbon depletion would not be attributed to the presence of a hydrosphere or a biosphere, but it would reveal an unexpected sequestration mechanism efficient on a planetary scale. This depleted feature would thus still be of very high scientific interest and could possibly spark novel industrial exploration of processes capable of balancing anthropogenic emissions of CO_2, and address climate change on Earth. More research is needed to understand how atmospheric carbon reacts with different solvents, at different temperatures and pressures, and how photochemistry in terrestrial planet atmospheres around M dwarfs works while considering different bulk compositions, as well as to study the possible nature and availability of such solvent alternatives.

We explore a series of false-positive and false-negative scenarios in Boxes 5 and 6, respectively.

Summary and future prospects

Life on Earth is obvious. It shapes most aspects of our environment, including the composition of the atmosphere above us, and of the ocean and rocks below us[65,68]. Life on Earth has a truly global effect. In other words, life on Earth is planet-shaping. Planet-shaping life is really what astronomers are after[67].

An atmosphere such as Earth's becomes depleted in carbon owing to the action of extensive amounts of surface liquid water, and/or by intense biological processes. Plate tectonics buries carbon away from the atmosphere, causing atmospheric depletion of CO_2 over geological timescales[87].

In much of the scientific literature, observables are appreciated as a signal, an addition to something otherwise presumed pristine. However, planet-shaping life does not just produce but also consumes[38], and Earth's systems that sustain it (for example, liquid water) also actively remove chemical species from the atmosphere[50–52]. We believe it is just as important to consider depleted signals as habsignatures and biosignatures. In the context of atmospheric carbon depletion, a depleted CO_2 feature compared with other planets within the same system is a good habiosignature, as it traces both habitable and inhabited environments. We explored the likelihood of false-positive signals (Box 5) and found all those we could imagine were unlikely to exist. We also investigated false-negative signals (Box 6) and proposed means of addressing them. This is why we assess that CO_2 depletion is a robust habiosignature applicable to most temperate rocky exoplanets, particularly those most similar to Earth.

Measuring the CO_2 absorption feature comes with multiple benefits. Even at low concentrations, CO_2 absorption is the most detectable of all atmospheric features for a transiting temperate terrestrial exoplanet. Furthermore, CO_2 is located at wavelengths where contamination from clouds and hazes is minimal, and where stellar contamination decreases below the typical photon noise.

These facts lead us to propose an observational strategy: to target the CO_2 feature, to first assess the presence of an atmosphere and to obtain an initial estimate of CO_2 concentration on several planets of the same system. Should these reconnaissance observations reveal depleted CO_2 features, a more extensive observing campaign should accurately measure their CO_2 abundances to detect any depletion, while also measuring CH_4, CO and O_3.

Methods

The JWST photon uncertainties in Fig. 4 are calculated using PandExo[88]. Systematic uncertainties due to stellar contamination are calculated via a Monte Carlo approach using the temperatures and covering fractions of the two dominant photospheric components inferred from Hubble Space Telescope observations. We allow the covering

BOX 5

False-positive scenarios

A false positive of dCO_2 as a habiosignature would imply the detection of an atmosphere depleted in CO_2 without the contribution of a hydrosphere or a biosphere. We consider five such possible scenarios in the following.

- **Dry sequestration.** Some rocks have a demonstrated ability to react with atmospheric CO_2 and sequester it, such as brucite, peridotite or serpentinite[57], which are considered for engineered carbon capture and sequestration to combat climate change. However, mineral carbonation of rocks is relatively inefficient when CO_2 is dry[117] or if temperatures are low (≪100 °C)[57]. Reactions leading to carbon sequestration usually need access to water and the kinetics of all known carbon mineralization reactions currently occurring on Earth are greatly enhanced by water[118]. For instance, brucite is one of most reactive minerals in the presence of CO_2 as long as water is available; brucite remains unreactive under a dry CO_2 atmosphere[119]. The deep carbon cycle between the exosphere and the planet interior is critical in controlling atmospheric levels of CO_2 and the solid Earth operates on timescales >10^5 years[52]. However, the removal of CO_2 from the atmosphere is closely linked to the presence of water, either directly through the uptake of CO_2 in the surface ocean or indirectly via the dissolution of silicate minerals and precipitation of carbonate minerals. Using the Solar System as an example, even at high CO_2 fugacities, such as on Venus, and high surface temperatures, CO_2 is stable in the atmosphere and indicates that dry carbonation of rocks has a likely minimal impact on carbon removal and is an unlikely false positive under dry conditions (Venus has lost most of its water[22]).
- **Nightside cold trap.** In a scenario of atmospheric collapse, most of the atmospheric CO_2 freezes on the nightside of a planet (tidally locked or not)[120], leaving low atmospheric CO_2 partial pressures in some cases[121]. Atmospheric collapse becomes increasingly likely for planets farther from their star. A collapse can be identified in some cases by measuring an exoplanet's atmospheric temperature using transmission spectra. In addition, planets with measured atmospheric compositions compatible with this situation will need detailed and dedicated three-dimensional numerical climate simulations to contextualize their CO_2 concentrations before any statement is made regarding their habitability. All the TRAPPIST-1 planets are expected to be tidally locked[11]. For planets such as TRAPPIST-1f, which we used in our simulations, atmospheric collapse is not expected for pressures typically >0.7 bar (ref. 121).
- **Photodissociation of** CO_2. In this scenario, CO_2 is photodissociated or chemically transformed into other compounds. Our premise, however, is about atmospheric carbon abundance and not just about CO_2 abundance. The most likely carbon-bearing product from an atmospheric reaction involving CO_2 is CO (ref. 122), which is also observable in the same 4–5 μm band (Fig. 5) on which we encourage efforts to focus. As such, it is possible to measure the overall atmospheric carbon abundance with the same data. In any case, it is expected that at most 10% of CO_2 would transform into CO and O_2 (ref. 122) for an atmosphere initially containing 1 bar of CO_2, which would be detectable with JWST (Fig. 5). Atmospheres with higher partial pressures in initial CO_2 produce fractionally less CO (ref. 123) as seen, for instance, on Venus. Furthermore, we advocate measuring and comparing several planets of the same system together as photodissociative effects are expected to decrease with orbital separation. Photodissociation is expected to decrease quadratically with distance from the star, in a monotonic function. As such we do not expect order-of-magnitude differences between a series of adjacent planets, allowing a means to diagnose this process from others. The cases of Venus and Mars highlight that this is not a scenario of particular concern[122].
- **Photodissociation of other species.** Another aspect to consider relates to the production of O_3 as a product of the photodissociation of stratospheric water. Refs. 124,125 have shown that slow-rotating terrestrial planets orbiting M dwarfs can have moist greenhouse conditions with important levels of water vapour in their stratospheres. Late M dwarfs such as TRAPPIST-1 are active longer into their life cycles and have stronger far-ultraviolet and weaker near-ultraviolet emissions, leading to exotic photochemistry[8,49,125,126]. This suggests that stratospheric water may produce a false-positive detection of the biosignature dCO_2+O_3.
- **Reduced interior.** A planet's atmospheric composition depends on whether its interior is oxidized or reduced[127,128]. In the latter case, instead of CO_2, CO and CH_4 are expected to be the main carbon carriers. Neither CO nor CH_4 dissolve well in liquid water, preventing carbon depletion via the hydrosphere. Planetary bulk compositions are expected to be increasingly reduced with orbital distance from their host star[129], something that is also seen in the Solar System. Planets with different bulk compositions are also expected to outgas a different atmospheric chemistry[39]. The detection of CO_2 in large concentrations for an outer planet indicates an oxidized world and would calibrate the inner system and allow the detection of depleted feature on those planets. Disk-driven migration is known to move planets from their birth place, and planetary objects similar to Titan, Triton and Pluto, assembled in hydrogen-rich parts of the disk, might be brought to the habitable zone[71,130]. These objects have different bulk densities and will be identified from their position in a mass–radius diagram[131]. In addition, should a temperate rocky planet be in a reduced state, this can be easily diagnosed from their atmospheric composition[131,132]. CO would show a prominent feature in the same 4–5 μm range with CO_2 absent (Fig. 5, right). CH_4 has an absorption band at 3.3 μm, likely to be observed with the same instrumental set-up. Both the CO and the CH_4 features present a higher level of significance than those of CO_2. For reduced sets of planets, different sets of biosignature and habsignature would need to be found.
- **Other surface solvent.** In this scenario, an abundant liquid solvent other than liquid water is able to dissolve and sequester carbon efficiently at room temperature. CO_2 is soluble in other liquids such as ethanol (alcohols) or polyethylene glycol[133,134] but, to our knowledge, such compounds do not form abiotically in substantial amounts on a planetary scale. Liquid is a fairly efficient solvent for CO_2 (ref. 135) that can form in large amounts on a planetary scale, for instance, Titan's lakes. However, liquid CH_4 is only stable at extremely low temperatures (~120 K) that are not habitable for life as we know it. Water remains one of the most abundant molecules in the Universe, and the most abundant solvent expected to be outgassed and condensed for a temperate terrestrial planet[39].

BOX 6

False-negative scenarios

A false negative is a planet that possesses large amounts of liquid water and/or a biosphere, but its atmosphere is not depleted in CO_2. We consider three such possible scenarios in the following.

- **Subsurface biosphere.** An atmosphereless planet can be habitable in its interior if habitability is defined to also include subsurface liquid water. Such a situation is similar to Europa and Enceladus[136,137]. In this particular case, this is an issue of definition. An atmospheric signature is only valid where there is a detectable atmosphere. Other planets might present low atmospheric pressures that are hard to detect, similar to the case of Mars. Those cases will be noticed easily. From their already known radius and/or the mass, it is possible to deduce a past atmospheric escape.
- **Saturated oceans.** Depleted CO_2 as a habsignature only functions if carbon continuously dissolves into the ocean. Plate tectonics moves the crust about and, in doing so, moves carbonates outside of oceans onto land, which we can see nowadays as limestone deposits. Tectonics also mostly buries carbonates out of reach of the atmosphere into the crust and back into the mantle[35,43,87]. A false negative could emerge for rocky exoplanets without plate tectonics, and/or where the oceans become saturated and can no longer absorb any more CO_2 (refs. 138,139). Without other known efficient sinks, CO_2 would therefore remain in the atmosphere. Should this scenario happen, other widely used biosignatures can still be employed, and used in exactly the same way as they are being considered nowadays. However, while the onset of plate tectonics is still a highly debated topic[140,141], it is generally accepted that liquid water is required to weaken the protoplates' yield stress[142], and that liquid water and carbonates lubricate the plates' motion. This means that tectonics might be an inevitability of a habitable and inhabited world[22,65,66]. For packed, close-in systems of exoplanets, such as the TRAPPIST-1 system[11], plate tectonics might also be initiated tidally[143] or via impacts[144].
- **Transient CO2concentration.** In this scenario, an extensive liquid-water ocean is present but has not had time yet to remove enough atmospheric carbon for a detection. The Archaean Earth represents such a transition period. Yet, as discussed in 'Reframing the search for liquid water and signs of life', dCO_2 was detectable as a habsignature during most of the eon (Fig. 3). However as biomarker, it would probably be inconclusive as Earth was dominated at the time by methanogens[30,37], as we consider oxic biospheres (such as the modern Earth) in this study. Earth's oceans contain about 2 bars of CO_2 currently[34,36]. If released in the atmosphere, the oceans would absorb those 2 bars of CO_2 in ~0.2 Gyr, at current absorption rates[37,43,52]. Indeed, it is thought that most of Earth's primordial atmospheric CO_2 was dissolved by the time biological processes emerged on Earth about 0.5 Gyr after formation[35,37]. This makes this false-negative scenario likely to be observed in less than 1 in 50 habitable rocky planets. We note here that this scenario might be a faux-false negative, as a sudden release of bars of CO_2 (that could equally be produced by other events such as asteroid/comet impacts or extensive volcanic episodes) would trigger a substantial temperature increase due to greenhouse effects[62,63], thus reducing the habitability and inhabited nature of the planet temporarily.
- **Habitability near the outer edge.** A planet near the outer edge of the habitable zone requires a high CO_2 partial pressure to maintain habitable conditions at the surface[2,22,62–64]. For instance, moving Earth to the orbit of Mars requires about 2 bars of CO_2 to keep water in a liquid state. Our simulations (Fig. 3) show that such a scenario is difficult to distinguish. After collecting 40 transits with JWST, any concentrations >50% CO_2 do not produce spectra that are significantly different ($<3\sigma$) to those from atmospheres with 100% CO_2. Other habsignatures will need to be deployed for those cases.

fraction of the lesser component to vary uniformly from 0% to double the reported covering fraction, calculate the corresponding stellar contamination signal following ref. 79 and report the standard deviation of the contamination signal for 10,000 such realizations as the systematic uncertainty. We draw the component spectra from the DRIFT-PHOENIX grid[89] using speclib (https://github.com/brackham/speclib). The total uncertainties are the quadrature sums of the photon and systematic uncertainties. The synthetic transmission spectra were generated using TIERRA (https://github.com/disruptiveplanets/tierra), a publicly available one-dimensional transmission model written in Python originally introduced in ref. 83. Measurement uncertainties reported for the spectra in Figs. 1, 3 and 5 are calculated using texttt-PandExo (https://github.com/natashabatalha/PandExo) introduced in ref. 90.

Code availability

The PandExo and TIERRA codes, used for this paper, are publicly available.

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The authors declare no competing interests.

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