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1 **Ensuring planetary survival: Balancing the multifunctional nature of soils**

2

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34

35 **Abstract**

36 Not only do soils provide 98.7% of the calories consumed by humans, they also provide  
37 numerous other functions upon which planetary survivability closely depends. However, our  
38 continuously-increasing focus on soils for biomass provision (food, fiber, and energy) through  
39 intensive agriculture is rapidly degrading soils and diminishing their capacity to deliver other  
40 vital functions, including climate regulation, nutrient cycling, biodiversity protection, and  
41 water cycling. These trade-offs in soil functionality – the increased provision of one function  
42 at the expense of other critical planetary functions – are the focus of this review. We examine  
43 how land-use change for biomass provision in the spiral of ever increasing economic growth  
44 has decreased the ability of soils to provide regulating services including global climate,  
45 biodiversity, the cycling of water and nutrients, which sustain plant growth and ecosystem  
46 health, and protection of the Earth’s freshwater supplies. Given the existential threats facing  
47 humanity and their economies, it is imperative that we increase our focus on the multiple  
48 functions that soils provide for long-term human welfare and survival of the planet rather than  
49 focusing almost blindly on the short-term provision of biomass for economic profit. For this,  
50 there is an urgent need for predictive, multiscale models that quantify soil functional  
51 complexity and its link to economic models that can be used to guide policy and decision-  
52 making processes.

53

54 *Keywords:*

55

56 **1 Introduction**

57 Seven global existential cornerstones for the sustainable development of human societies are  
58 threatened, namely: Food Security, Water Security, Energy Security, Health, and Climate,  
59 Biodiversity, and Ecosystem Service Delivery. Although threats to these seven existential  
60 cornerstones are all global, complex, inter-related, and difficult to resolve, soil is related to all  
61 of them – soil is the single most important common variable in sustaining life on our planet  
62 (Kopittke et al. 2021; McBratney et al. 2014).

63

64 Soils are diverse and multifunctional –they contribute to provisioning functions that are as  
65 basis of human life and economies easily tangible such as the provision of food, fiber, and  
66 energy. Moreover, they also provide less tangible regulating and support functions with  
67 longer-term benefits such as regulation of climate, and biogeochemical cycles, and  
68 biodiversity protection supporting human health and the quality of life on our planet. Because  
69 of their critical importance, soils contribute to at least 12 of the sustainable development goals  
70 (SDGs) of the United Nations (Figure 2). Despite the multiple benefits of soils, society has  
71 historically focused almost exclusively on one single function – the provision of biomass  
72 (food, fiber and energy). The reason is that societal development is intimately linked to  
73 agricultural production, which is the basis of economic growth (Dethier and Effenberger,  
74 2012; Davis, 2017). However, by prioritizing biomass production, the capacity for soils to  
75 deliver the remaining functions has been compromised. Whilst agricultural production is  
76 clearly essential, society’s narrow recognition of the soils’ production function at the expense  
77 of its other functions, is limiting our understanding of how soil can be best managed to secure  
78 and capitalize on its multifunctionality. This is however imperative to address the global  
79 challenges, threatening the hospitability and survivability of our planet by worsening the  
80 existential challenges.

81

82 Here, we address the multifunctionality of soil and consider trade-offs in these functions,  
83 focusing on how the constant, global demand for productive agriculture is profoundly  
84 decreasing the ability of soil to provide other functions critical for planetary health (Vazquez  
85 et al. 2021; Zwetsloot et al. 2021). Indeed, it is increasingly clear globally that soil  
86 management to increase delivery of one function (especially food and fibre production) has  
87 substantially reduced the soils' capacity to deliver other functions (such as nutrient cycling,  
88 biodiversity protection, and climate regulation), as shown in Europe by Zwetsloot et al.  
89 (2021). To better inform policy and guide decision-making processes, there is an urgent need  
90 to develop predictive, multiscale models that quantify soil functional complexity and their  
91 contribution to ecosystem services (Lehmann et al. 2020) in view of their importance for  
92 progress towards stable economies, planetary health and sustainable development goals.  
93 Currently, this information is lacking, and the multifunctionality of soils is largely excluded  
94 from broader assessments of ecosystem services despite their role as a planetary master  
95 variable.

96

97 We build on previous reviews, such as that of McBratney et al. (2014) who developed a  
98 framework for 'soil security', that of Amundson et al. (2015) who examined the  
99 interconnection between soil, climate and food security, and that of Kopittke et al. (2019) who  
100 examined how agricultural intensification is degrading soils. First, we examine the multiple  
101 functions of soils, considering their importance for the health of both humans and the planet.  
102 Next, we examine how land-use changes, driven by the need for increased agricultural  
103 production, are causing trade-offs in the ability of soils to deliver its other key functions. We  
104 also consider how the decreasing ability of soil to provide these other functions, such as  
105 climate regulation, can be halted and reversed. We make the case for soil organic carbon  
106 (SOC; for simplicity and brevity, we use the term 'SOC' to also include soil organic matter,  
107 SOM) as the integral component of the soil matrix that links and underpins critical soil

108 functions, and argue for a better understanding of carbon (C) fluxes and persistence. Finally,  
109 we contend that it is imperative to develop a better understanding of the trade-offs in soil  
110 multifunctionality, including approaches to quantify and model these broad trade-offs and  
111 their implication to enable more efficient and effective soil management practices that  
112 promote sustainable agricultural production to support economies and planetary health to  
113 ensure the prosperity and survival of human societies of our planet.

114

## 115 **2 Functions of soils**

116 It is first prudent to delineate between soil ‘functions’ and broader ‘ecosystem services’ – soil  
117 functions provide a soil-related contribution to ecosystem services, with these ecosystem  
118 services requiring an inter- and transdisciplinary approach given that soils do not act  
119 independently (Bouma 2014). Soil functions can be categorized in multiple ways, including  
120 provisioning functions, support functions, regulating functions, and cultural functions.  
121 Provisioning functions provide humans with biomass (food, energy, and fiber), raw materials,  
122 and a physical environment, with humanity generally focusing on those functions that provide  
123 tangible benefits such as food, fibre and energy production to sustain economic growth.  
124 Support functions are roles of soils that underpin other functions, and include nutrient cycling,  
125 water cycling, and biodiversity. Although support functions are generally not economically  
126 evaluated due to double-counting (Jónsson and Davíðsdóttir 2016), we include information in  
127 the present review to highlight the importance of soils in this regard. Regulating functions  
128 include climate regulation, biological control of pests and diseases, and the recycling of  
129 wastes and detoxification, with these being directly economically valued (Jónsson and  
130 Davíðsdóttir 2016). Finally, the cultural functions of soil include heritage and recreational  
131 functions (Jónsson and Davíðsdóttir 2016).

132

133 Here, we focus on (i) biomass production (food, fiber, and energy), (ii) climate regulation,  
134 (iii) biodiversity protection and habitat provision, (iv) nutrient cycling, and (v) water cycling  
135 as five of the key soil dimensions describing soil multifunctionality (Figure 3) linked to  
136 planetary survivability of human societies (Kopittke et al. 2019; Steffen et al. 2015; Vazquez  
137 et al. 2021; Vogel et al. 2019; Zwetsloot et al. 2021).

138

### 139 *2.1 Production of biomass (food, fiber, and energy) through land-use change*

140 Humans rely almost entirely on soils to provide their biomass: food, fiber, and energy. Indeed,  
141 an estimated 98.7% of the daily calories consumed by humans have their origins in soils  
142 (2,895 kcal per capita), with only 1.3% from aquatic systems (38 kcal per capita) (FAO 2021).  
143 Although soils have sustained humans by providing biomass for millennia through social  
144 practices such as hunting and gathering, the establishment of agriculture and the rapidly  
145 increasing population growth over the last centuries has led to land-use change and the  
146 adoption of intensive production systems to satisfy the increasing demand. To produce their  
147 food and other commodities, humans currently use 1,600 million ha (12% of the ice-free land)  
148 of productive land for cropland, with a further 3,200 million ha (25%) dedicated to permanent  
149 grassland and pasture (FAO 2021). It is often this profound global land-use change, largely  
150 for agriculture, that is decreasing the ability of soils to provide the other functions described  
151 in later sections.

152

153 Of key importance is that the demand for food (plus fiber and energy) has grown markedly  
154 over the last one-and-half centuries, and is correlated with an increase in land-use change  
155 (Figure 1). For example, the human population increased from 2.5 billion in 1950 to 7.8  
156 billion in 2020, with a concomitant increase in cereal production from 0.74 Gt in 1961 to 2.9  
157 Gt in 2016. The human population will continue to increase even further, reaching a projected  
158 9.8 billion by 2050. Accordingly, demand for food will also continue to increase coupled with



159 changes in diets, with food production required to increase by 70% between 2005 and 2050  
160 (ELD 2015).

161

162 As the demand for food increases, there is likely to be a concomitant increase in demand for  
163 fiber and energy (biofuels) production from soils. For example, ethanol production, which  
164 was 20 GL per year in 2000, is projected to increase to ca. 130 GL per year in 2030  
165 (OECD/FAO 2021), with biofuel production estimated to account for 32 million ha of land  
166 globally in 2013 (Langeveld et al. 2013).

167

168 Thus, the challenge is how best to increase biomass production whilst maintaining soil  
169 resources. To a large extent, this is expected to be achieved by improving production  
170 efficiency and yield rather than by increasing the area of land under agriculture (Tillman et  
171 al., 2011). Indeed, over the decade to 2030, 87% of the projected increase in global crop  
172 production is expected to come from yield improvements, 7% from increased cropping  
173 intensity, and only 6% from an expansion of cropland (OECD/FAO 2021). Similarly,  
174 increased production in livestock will likely result from intensification, although herd  
175 enlargement will contribute significantly to emerging and low-income countries (OECD/FAO  
176 2021). Globally, changing climates already require the adaptation of current farming practices  
177 and areas used for agricultural production. There are also other approaches that can be used  
178 for increasing food security, such as decreasing food wastage or changing dietary habits, but  
179 these and other approaches are beyond the scope of this review.

180

## 181 2.2 *Climate regulation*

### 182 2.2.1 *Role of soil in climate regulation*

183 Soils play a critical role in climate regulation, primarily through their importance in the global  
184 C cycle. Indeed, soils store more organic C (ca. 2344 Pg of organic C within the surface 3 m,

185 and ca. 1500 Pg C in the surface 1 m) (Scharlemann et al. 2014), than in the atmosphere (875  
186 Pg C in 2019) and vegetation (600 Pg C) combined. Not only is the total SOC stock large, but  
187 SOC is highly dynamic – each year, ca. 61 Pg of C enter soils from vegetation with similar  
188 amounts being lost from soils to the atmosphere due to mineralization (Lehmann and Kleber  
189 2015). Thus, ca. 7 % of the atmospheric C pool is cycled through soils every year. As such,  
190 any human-induced decrease in the quantity of C either entering soils (inputs) or increases in  
191 the quantity lost from soils (outputs) can result in marked increases in atmospheric CO<sub>2</sub>  
192 concentrations. Furthermore, most productive (and hence C-rich) ecosystems are founded in  
193 soils, and thus the loss of soils also results in the loss of the associated biomass C. It has been  
194 estimated that the economic value of soil climate regulation is up to US\$268 per hectare per  
195 year (Jónsson and Davíðsdóttir 2016); on a global scale this roughly equates to US\$3.5  
196 trillion per year for the global ice-free land area (13,000 million ha).

197

### 198 2.2.2 *Effects of anthropogenic land use change on soil climate regulation*

199 Although SOC stocks are large, it has long been recognized that, for the most part, the use of  
200 soils for agricultural production has resulted in a marked loss of this SOC. In global meta-  
201 analyses, following conversion of forest to cropping, SOC stocks have reportedly decreased  
202 an average of ca. 42% (Guo and Gifford 2002; Kopittke et al. 2017). Associated with the loss  
203 of SOC, the release of CO<sub>2</sub> from soils following land-use change is estimated to have resulted  
204 in the release of ca. 133 Pg of C, primarily in the last 200 y (Sanderman et al. 2017). This  
205 represents ca. 25% of total cumulative global anthropogenic emissions of CO<sub>2</sub> since ? and  
206 some 16% of the total increase in radiative forcing due to greenhouse gases (Kopittke et al.  
207 2021).

208

209 The need to increase SOC concentrations is recognized through programs such as the ‘4 per  
210 mille’ initiative which intends to encourage the introduction of sustainable practices with an

211 aspirational goal to increase global SOC stocks by 0.4% (4 per 1000) per year (Rumpel et al.,  
212 2020). There are adjustments to conventional cropping systems that can be used to potentially  
213 increase SOC stocks, though highly dependent on environment. For example, the use of  
214 conservation agriculture can, in some circumstances, result in a modest increase in SOC  
215 stocks, as can the addition of organic materials to the soil. In the meta-analysis of Kopittke et  
216 al. (2017), the use of no-till resulted in an average 8% increase in SOC stocks, whilst the  
217 addition of organic amendments to the soil resulted in a 25% increase. Whilst such increases  
218 in SOC stocks by alternate management practices are critical, the gains in C stocks obtained  
219 by improved management remain smaller than the original decrease in C stocks caused by  
220 land-use change. Thus, it is clear that consideration could also be given to the conversion of  
221 soil used for agricultural production to a system with a higher density of vegetation such as  
222 ‘carbon farms’. For example, Guo and Gifford (2002) calculated that the conversion of  
223 cropland to secondary forest increased C stocks by 53% whilst conversion to pasture  
224 increased C stocks by 19%. For this to occur, there need to be a clear approach for quantifying  
225 benefits in terms of increasing climate regulation along with trade-offs in form of greenhouse  
226 gas emissions and the value of lost agricultural production.

227

228 Brief mention should also be given to the contribution of the soil N cycle in agricultural  
229 systems to climate regulation. Globally, 109 Tg of N fertilizers are applied, with the  
230 application of these fertilizers to soils contributing to the release of greenhouse gases due to  
231 the production of nitrous oxide (N<sub>2</sub>O). Indeed, soils account for 60% of total N<sub>2</sub>O emissions  
232 (Tian et al. 2019), being a total of 3.7% of the global increase in radiative forcing due to  
233 anthropogenic greenhouse gas emissions (Kopittke et al. 2021). In this regard, it is imperative  
234 to increase the efficiency of N fertilizer usage which has decreased from 68% in 1961 to 47%  
235 in 2010 (Lassaletta et al. 2014). This could be achieved through the development of more

236 efficient fertilizers, utilization of other management approaches to increase uptake of N by  
237 plants, or increased incorporation of N-fixing legumes in cropping systems.

238

### 239 2.2.3 *Quantifying the contribution of soils in climate regulation*

240 For any given soil, the actual (current) contribution to climate regulation can be quantified by  
241 measuring the SOC stocks and their change, with SOC being a direct measurement of the  
242 primary indicator of this function. For managed systems (such as in soils used for cropping),  
243 it is necessary to compare this actual state to its potential value in a restored system or in any  
244 other system with alternative management practices. These potential values can be estimated  
245 through pedotransfer functions that rely upon various other parameters, including soil texture,  
246 bulk density, and climate (Vogel et al. 2019). Hence, for managed systems, the difference  
247 between the potential and the actual contribution represents the magnitude of climate  
248 regulation which has been lost due to human use of soils, such as clearing land for agricultural  
249 production.

250

## 251 2.3 *Nutrient cycling*

### 252 2.3.1 *Role of soil in nutrient cycling*

253 The importance of the role that soils play in storing and cycling of nutrients cannot be  
254 overstated – without nutrient storage and (re-)cycling in soils, plant growth in both natural  
255 ecosystems and agricultural systems would cease almost entirely. For example, global soils  
256 contain huge amounts of nitrogen (N) and phosphorus (P), 200 Pg N and 50 Pg P, with this  
257 being equivalent to 50% of N in plants and 10% of P (Smil 2000; Stevenson and Cole 1999).  
258 To provide context, these soil N stocks (200 Pg N) are ca. 1800-times larger than annual  
259 production of reactive N through the Haber-Bosch process for fertilizers (109 Tg N) (FAO  
260 2021), with the annual production of N fertilizers accounting for ca. 1.5% of global energy  
261 use. Although soils contain huge reserves of nutrients, only a small fraction is immediately

262 available to plants. In this regard, SOC plays a central role in nutrient storage and cycling in  
263 soils – the gradual mobilization of nutrients by mineralization or solubilization, which is  
264 critical for nutrient cycling between plants and soil, is mainly mediated by soil  
265 microorganisms (Marschner 2012). Accordingly, it has been estimated that the value of this  
266 nutrient cycling through soil, using replacement cost, is up to US\$180 per hectare per year  
267 (Jónsson and Davíðsdóttir 2016), which equates to a value of up to US\$2.3 trillion per year  
268 for the global, ice-free land.

269

### 270 *2.3.2 Effects of anthropogenic land use change on soil nutrient cycling*

271 Through its effect on plant biomass, plant diversity, and soil properties (including changes to  
272 microbial diversity), land-use change alters both total stocks of soil nutrients as well as their  
273 cycling. This is particularly important for nutrients closely associated with SOC (especially N,  
274 P, and S) given both the profound decrease in SOC stocks and concentrations with land-use  
275 change (see Section 2.2), as well as the critical role of SOC in soil fertility. For example, it  
276 has been reported in a global meta-analysis that upon conversion of forest to cropping land,  
277 the median decrease in soil N stocks was 42%, with corresponding decreases being 31% for P  
278 and 32% for S (Kopittke et al. 2017). Not only does land use change alter nutrient stocks in  
279 soils, but there is a concomitant influence on microbial abundance, diversity and activity (see  
280 later), and hence nutrient cycling. Indeed, land use change from natural to agricultural  
281 ecosystems can disrupt nutrient cycling by decreasing organic matter and nutrient return to the  
282 soil, accelerating SOC decomposition rates through tillage, and also increasing nutrient losses  
283 through runoff, erosion, volatilization and leaching (Magdoff et al. 1997). Further, conversion  
284 of naturally diverse ecosystems to agricultural use can have detrimental effects on nutrient  
285 cycling by reducing the diversity of organic materials entering the soil, which reduces food  
286 web diversity and thus nutrient cycling (Kostin et al. 2021; Tsiafouli et al. 2015). This loss of  
287 SOC from agricultural systems, together with the coupled decrease in nutrient cycling, has

288 flow-on effects for agricultural production and its economic returns due to a loss of soil  
289 fertility. For example, in a meta-analysis, it was found that increases in SOC concentrations  
290 would potentially increase yields of wheat by 10% and maize by 23% (Oldfield et al. 2019).  
291 The same study showed that lower amounts of N-fertiliser are needed to produce similar  
292 yields in SOC rich soils as compared to SOC poor ones.

293

294 The deleterious effect of land use change on nutrient stocks and the cycling of these nutrients  
295 can be reversed, at least in part, by a range of management strategies. This can be achieved,  
296 for example, by using higher plant diversity, such as rotations or mixed cropping, ensuring  
297 that the organic materials entering the soil have a wide range of properties which enhance  
298 diversity of soil biota and hence nutrient cycling (Kostin et al. 2021; Liu et al. 2020). Cover  
299 cropping can also enhance nutrient cycling by increasing microbial activity and mobilizing  
300 nutrients, such as N and P (Hallama et al. 2019). Permanent plant cover and the associated  
301 minimal soil disturbance also increase the amount of organic materials available for  
302 breakdown by soil biota and reduce soil erosion which improves nutrient cycling (Steven et  
303 al. 2021). Reduced tillage or no tillage practices can help to retain SOC and improve soil  
304 structure, reducing erosion and nutrient loss (Magdoff et al. 1997). Finally, the application of  
305 organic amendments can cause marked increases in nutrient cycling and fertility, with Sandhu  
306 et al. (2008) reporting that the economic value of nutrient cycling was US\$260 per hectare per  
307 year in organically managed fields compared to US\$142 per hectare per year in  
308 conventionally managed fields. At the expense of food production, cropped soils can also be  
309 returned to secondary forest, which may substantially increase SOC stocks (see Section  
310 2.2.2), concomitantly increasing the ability of soil to store and cycle nutrients.

311

312 If soil is considered solely from the perspective of the short-term goal of biomass production,  
313 a number of soil functions can be replaced with the application of readily available inorganic

314 nutrients and other agrochemicals. Indeed, this is the basis of many agricultural production  
315 systems that utilise relatively cheap synthetic inputs to mitigate the risk of low yielding crops.  
316 The ease and economic benefits of using synthetic fertilisers to optimise yield has also meant  
317 that modern plant varieties are typically selected under conditions that select against certain  
318 soil biota. This further diminishes the contribution of these species to soil biological fertility  
319 and also limits their adaptability to extreme climatic events, such as drought, which may lead  
320 to economic losses due to crop failures.

321

### 322 2.3.3 *Quantifying the contribution of soils in nutrient cycling*

323 Soil nutrient cycling and storage is determined by a range of mechanisms before their uptake  
324 by plants, including their fate as part of SOC and linked to soil cation exchange capacity  
325 (CEC, being especially important for storage of nutrients such as Ca, Mg, and K). Hence,  
326 quantification of the contribution of soil to nutrient cycling is complex, but generally includes  
327 an assessment of SOC as well as the CEC, with the CEC itself depending upon soil texture  
328 and mineralogy, as well as the SOC content. However, a range of other factors also influence  
329 soil nutrient cycling, including pH, soil depth, and the exogenous application of fertilizers and  
330 other amendments. Regardless, given the central role of SOC in nutrient cycling within soils,  
331 this parameter is often used when quantifying the contribution of soils to inherent nutrient  
332 cycling [for example, see Sandhu et al. (2008)]. As a result, for managed soils, where the  
333 nutrient cycling capacity has been degraded, it is possible to estimate the difference between  
334 the potential contribution to nutrient cycling and the actual contribution by estimating the loss  
335 of SOC.

336

337 2.4 *Biodiversity protection and habitat provision*

338 2.4.1 *Role of soil in biodiversity protection*

339 Soils are the most biologically diverse habitat on Earth with soil biota represented across all  
340 three domains in the tree of life, Bacteria, Archaea and Eukaryota, accounting for  
341 approximately one-quarter of total biodiversity (Bach and Wall 2017) and with > 40% of  
342 living organisms in terrestrial ecosystems associated directly with soils (Decaëns et al. 2006).  
343 Microorganisms are the most abundant component of the soil biota with a handful of soil  
344 containing billions of individual microbial cells, as well as meters of fungal hyphae and a  
345 variety of microfauna. For example, it has been estimated that there are ca.  $4.4 \times 10^{20}$   
346 nematodes (with a total biomass of ca.  $3 \times 10^8$  t) in global surface soils (van den Hoogen et al.  
347 2019). These soil fauna contribute to both carbon and nitrogen mineralization, with their  
348 contribution often being greater in soils with low fertility. Up to 40% of total net nitrogen  
349 mineralized is estimated to be due to soil fauna, with nematodes and protozoa contributing the  
350 most (Brussaard et al. 1996). At a global scale, the total mass of soil microorganisms (termed  
351 the microbial biomass) is influenced by the soil, climate and plant productivity, with soil  
352 biodiversity intricately linked to the SOC providing an energy source for growth and  
353 maintenance (Jones et al. 2019).

354

355 Within the soil, this biodiversity makes numerous critical contributions, many of which are  
356 related to the other functions of soil described in this review. Soil biodiversity contributes to  
357 nutrient cycling, food (biomass) production, the provision of water, climate regulation, and  
358 human health (FAO 2020). For example, ca. 80% of all antibacterial agents approved between  
359 1983 and 1994 originated from soils, whilst ca. 60% of all drugs approved between 1989 and  
360 1995 originated from soils (Mbila 2013). The total value of soil biodiversity is estimated to be  
361 US\$2.1 trillion per year (Jónsson and Davíðsdóttir 2016).

362



363 Soil biodiversity and the associated ecosystem multifunctionality cannot be ignored when  
364 establishing ecosystem protection priorities (Guerra et al. 2021). To protect soil biodiversity,  
365 it is imperative to understand the biogeographic patterns and the predictors of soil biodiversity  
366 at multiple trophic levels, as well as the role of multiple factors in driving soil functionalities  
367 and biodiversity (Rillig et al. 2019). Recent advances in molecular and sequencing  
368 technologies have marked the beginning of a new era in exploring the genetic diversity,  
369 genetic functions, and ecological preferences of soil organisms at global scales. Indeed, as  
370 noted by FAO (2020), “understanding the value of ecosystem services linked to soil  
371 organisms is vital for decision-makers when considering soil use and land management  
372 changes”.

373

#### 374 *2.4.2 Effects of anthropogenic land use change on soil biodiversity*

375 Land-use change, including the use of soils for agricultural production, results in a marked  
376 decrease in SOC and soil biodiversity (Marques et al. 2019; Newbold et al. 2015) and there  
377 are numerous reports showing that intensive agricultural production greatly reduces the  
378 complexity of soil food webs and reduces the mass of soil fauna (Geisen et al. 2019; Tsiafouli  
379 et al. 2015). For example, pesticides can control target pests and pathogens, but may harm  
380 non-target soil organisms and disturb soil food web interactions (Damalas and  
381 Eleftherohorinos 2011). Furthermore, excessive applications of fertilizer cause soil  
382 degradation and acidification with a negative impact on soil biodiversity (Guo et al. 2010;  
383 Savci 2012).

384

385 Achieving sustainable agricultural production whilst halting (and reversing) the deleterious  
386 effects of agricultural production on soil biodiversity will require various approaches such as  
387 crop diversification, regenerative agriculture, organic fertilization, and biological control. For  
388 example, agricultural diversification – the intentional addition of functional biodiversity to

389 cropping systems to regenerate biotic interactions underpinning yield-supporting ecosystem  
390 services (Kremen et al. 2012), has emerged as a strategy to contribute to the Sustainable  
391 Development Goals (SDGs) of the United Nations. Although trade-offs regularly exist  
392 between crop yield and multiple ecosystem services (such as discussed throughout this  
393 review), a recent meta-analysis has demonstrated that agricultural diversification can actually  
394 promote biodiversity and the delivery of ecosystem services without compromising crop yield  
395 (Tamburini et al. 2020). Organic, conservation, and regenerative agriculture have distinct  
396 impacts on productivity, carbon sequestration, economic performance and ecosystem  
397 multifunctionality. A recent study conducted in Europe found that organic and conservation  
398 cropping promoted ecosystem multifunctionality including biodiversity preservation, soil and  
399 water quality, and climate mitigation, along with economic benefits (Wittwer et al. 2021). In  
400 addition, the crop microbiome, as the second genome of its host, promotes the host's  
401 phenotype such as growth and tolerance to pathogens, pests, and environmental stresses. For  
402 example, root-associated fungi, such as mycorrhiza and plant growth promoting bacteria are  
403 beneficial for nutrient acquisition and cycling (Richardson et al., 2009). This plant-  
404 microbiome interaction is largely unexplored but has great potential to achieve sustainable  
405 agriculture and ameliorate threats to soil biodiversity (Chen et al. 2021).

406

#### 407 *2.4.3 Quantifying the contribution of soils in biodiversity protection*

408 Soil biodiversity can be measured through a range of approaches, including species richness,  
409 diversity indices, or the presence of keystone species and functional diversity (Vogel et al.  
410 2019). However, a key challenge remains to relate these measures of soil biodiversity to the  
411 actual functions of the soil, and to understand how to relate changes in soil biodiversity to soil  
412 functioning.

413

414 Soil biodiversity depends upon a large number of factors, including SOC, the water balance,  
415 temperature, texture, bulk density, and pH. However, it is increasingly clear that, within any  
416 given soil, biodiversity is very closely linked to SOC content, such as shown throughout  
417 Europe where it has been reported that “high SOC was a common attribute amongst croplands  
418 with a high biodiversity habitat provision” (Vazquez et al. 2021). This is perhaps not  
419 surprising given that the SOC is the energy source that drives soil communities. Thus,  
420 changes in biodiversity are often most closely related to the changes in SOC (both quality and  
421 concentration) caused by changes in land use or management.

422

## 423 2.5 *Water cycling*

### 424 2.5.1 *Role of soil in water cycling*

425 Soils are the largest store of fresh water in the terrestrial ecosystem (McColl et al. 2017).  
426 Globally, soil can store 121,800 km<sup>3</sup> of water (Webb et al. 1993); and yet on average, soils  
427 contain only about a tenth of its capacity (approximately 17,000 km<sup>3</sup>), which is still larger  
428 than that held in the atmosphere (13,000 km<sup>3</sup>) and living organisms (1 km<sup>3</sup>) (Oki and Kanae  
429 2006). This interface between the atmosphere, plant and groundwater is an essential part of  
430 the hydrological cycle, providing services of: storing and supplying water to plants,  
431 transmitting and filtering water for storage in groundwater, supporting runoff generation to  
432 rivers, exchanging water in the soil-plant-atmosphere system, moderating drought and flood  
433 potentials (Wu et al. 2015), and a buffer in climate change’s impact on the hydrological cycle.

434

435 Soil aggregation is largely responsible for water regulation where water is held and  
436 transmitted in the soil due to its unique pore size distribution expressed by the soil water  
437 retention curve, with this soil aggregation occurring due to a range of processes including  
438 interplays between the soil biodiversity and SOC. No other porous material can hold water  
439 over the energy range that many soils are able to. The pore network of the soil simultaneously

440 controls gaseous and solute flow (Ghezzehei et al. 2019; Young and Ritz 2000) and provides  
441 a habitat for soil microbes in the water-films and bio-films surrounding the organo-mineral  
442 components of soil. These water films in the pore network can restrict oxygen flow through  
443 the pore network and thus affect biological activity. Conversely, soil microorganisms such as  
444 nematodes, protozoa and bacteria rely on water films for their movement through the soil.  
445 Fungi however rely on a moist atmosphere in soil with good air connectivity to extend their  
446 hyphae. Thus, soil architecture controls the hydrological cycle as well as critical microbially  
447 mediated processes.

448

#### 449 *2.5.2 Effects of anthropogenic land use change on soil water cycling*

450 Land use change and conventional agricultural practices have severely impacted these soil  
451 water cycling functions. Both tillage and the loss of SOC, together with other factors, have  
452 caused compaction and the associated loss of soil aggregation. In turn, this degradation has  
453 enhanced runoff, reduced infiltration, increased evaporation, lessened water storage, and  
454 reduced recharge. Land use not only affects the physical condition of the soil and its ability to  
455 transmit and store water, but also has an impact on the hydrological cycle of the area. For  
456 example, in a semiarid area in southwestern Australia, a 750 km rabbit proof fence established  
457 around 1901-1907 that separated natural vegetation from agricultural land provided a  
458 comparison between soils under native vegetation and agriculture. Observations from this site  
459 have demonstrated that agricultural land, compared to natural vegetation, has distinct  
460 characteristics such as albedo, surface roughness, and canopy resistance. These, in turn, affect  
461 the energy balance and decrease cloud formation and precipitation on agricultural land (Lyons  
462 2002). The impact of land use on the availability and loss of water through precipitation and  
463 runoff will continue to be further impacted locally by climate change, and combined with the  
464 condition of the soil, will cause soil moisture droughts (Samaniego et al. 2018).

465

466 Conservation agriculture, including the use of minimum tillage, stubble retention, and cover  
467 crops, has been found to reduce the deleterious effect of land use related to water  
468 management. These beneficial practices result in increased soil aggregation and macropores,  
469 which in turn increased water infiltration into the soil, higher water storage and reduced soil  
470 erosion, and act as natural flood management infrastructure (Palm et al. 2014; Thomas et al.  
471 2007). Nevertheless, the relationships between conservation tillage, SOC and soil water  
472 parameters are not always clear. Increased organic matter has been widely promoted to  
473 increase soil water retention or available water capacity. However, a detailed analysis of  
474 experimental data from Minasny and McBratney (2018) reveals that organic matter only  
475 affects large pores and hence has only a small effect on available water capacity.  
476 Additionally, the classic concept of more organic matter means more water retention is no  
477 longer held – ongoing research is also showing that organic matter can exhibit significant  
478 repellence, with this directly impacting upon water ingress into the soil (particularly on sandy  
479 soils) and subsequent water distribution (Hallett et al. 2001) with preferential flow of water  
480 leaving large volumes of soil dry. Furthermore, although comparisons between conventional  
481 tillage and no-tillage systems often show a higher infiltration rate in the no-till system, other  
482 studies show the reverse (Palm et al. 2014). These apparently conflicting results suggest that  
483 we cannot measure soil functions using few parameters, rather soil needs to be studied as a  
484 system to understand all the complexities and interactions.

485

### 486 2.5.3 *Quantifying the contribution of soils in water cycling*

487 For any given soil, the actual contribution to water cycling depends upon the climate, a range  
488 of soil physical properties (including texture, aggregation, porosity, and water retention), and  
489 various chemical properties (including SOC content). Quantifying water cycling is  
490 challenging as water in soil is highly dynamic. The most commonly quantified parameter is

491 water holding capacity, which is related to biomass production. A fully quantified function  
492 should balance minimal runoff and erosion, persistence of moisture storage, and drainage.

493

### 494 **3 Optimizing trade-offs in soil functions to ensure planetary survivability: A central** 495 **role for soil carbon as an indicator of functioning**

496 It is clear from the preceding discussion that whilst we rely on agricultural production systems  
497 for our survival and the functioning of our economies, the land-use change that has occurred,  
498 and continues to occur, to produce this food is having profound effects on the ability of soil to  
499 provide other critical functions related to human wellbeing and quality of life. Given the  
500 existential threats humanity now faces, it is critical that we increase our focus on the multiple  
501 globally-important functions that soil provides. For this, there is an urgent need to develop  
502 predictive, multiscale models that quantify soil functional complexity to guide policy and  
503 decision-making processes (Lehmann et al. 2020). These multiscale models are required  
504 because information is required at scales that are broad enough to facilitate policy  
505 interventions whilst simultaneously being local enough to reflect the functional complexity of  
506 the specific soils (Lehmann et al. 2020).

507

508 Multiple studies have examined approaches for quantifying and predicting soil functioning  
509 (Greiner et al. 2017; Jónsson and Davíðsdóttir 2016; Vogel et al. 2019; Zwetsloot et al. 2021).  
510 However, despite the extreme complexity of soil functions, it is clear that SOC plays a central  
511 role and is a master indicator for examining changes in soil functioning. Indeed, within any  
512 given soil, SOC is the primary indicator of climate regulation by soils, it is central for nutrient  
513 storage and cycling, and is closely linked to soil biodiversity. For example, consider a  
514 managed system where anthropogenic use of the soil has resulted in a substantial decrease in  
515 SOC stocks. In this system, differences in C stocks between the actual state (i.e. the current,  
516 degraded state of the managed system) and the potential state (i.e. an estimate of the state if

517 the soil was restored) (Vogel et al. 2019) can be used to estimate the additional capability  
518 (value) (McBratney et al. 2019) of a soil to regulate the climate, protect biodiversity, and  
519 cycle nutrients. However, the mechanisms by which increased SOC fulfills these functions in  
520 quantitatively poorly understood. The most prominent role of managing soil C is the  
521 possibility to link the mitigation of climate changes with beneficial effects in agricultural  
522 production, thus closing yield gaps (Amelung et al. 2020). These authors demonstrate that the  
523 potential of soils to store additional C, and thus provide beneficial effects on the multitude of  
524 soil functions discussed above, strongly depends upon the specific ecoregion, with this  
525 differing between soil types and land use history. As land use, together with soil type, soil  
526 structure, and soil mineral composition, directly determine the capacity of soils to store and  
527 sequester C (Wiesmeier et al. 2019), future research has to address the mechanistic  
528 underpinnings of these relationships.

529

530 Thus, we contend that a focus should be given to better understanding the factors driving C  
531 persistence in soils (both biotic and abiotic), along with the dynamics of labile pools. Both are  
532 needed to predicting how SOC stocks change depending upon management, land-use, and  
533 other stressors such as climate change, and to understand the multiple soil functions related to  
534 biological activity. Economic considerations should be coupled to such an approach to  
535 determine the consequences of alteration of multiple soil functions for human societies. In this  
536 regard, it is clear that we need novel management approaches to increase soil functionality,  
537 and it is also imperative that we identify areas where the environmental benefits obtained by  
538 restoring degraded soils, and hence allowing them to maximize provision of other functions,  
539 exceeds their value when continuing to be used for food, fiber, and energy.

540

541 **4 Knowledge gaps**

542 In order to effectively develop multiscale models that quantify the functional complexity of  
543 soils and their contributions to broad ecosystem services sustaining the wellbeing of human  
544 societies, it is clear that there are multiple knowledge gaps that must be addressed.

545

546 *4.1 Understanding carbon persistence in soils and the scaling of information*

547 Given the central role of SOC across multiple soil functions, we need not only to develop a  
548 better understanding of the factors controlling the behavior and persistence of C in soils but  
549 also to assess the importance and dynamics of labile pools. Although the critical importance  
550 of SOC has long been recognized, soil scientists are now refuting the traditional assumptions  
551 that SOC is based on ‘humic substances’, with these previous assumptions having now  
552 diverted research efforts for multiple decades (Lehmann and Kleber 2015). Rather, there is  
553 now increasing evidence that C persistence is driven by molecular diversity, spatial  
554 heterogeneity, and temporal variability intimately related to microbial accessibility (Lehmann  
555 et al. 2020). However, much remains only poorly understood in this regard with a concerted  
556 research effort required to continue probing the factors determining SOC dynamics in soils,  
557 including in subsoils, which remain comparatively understudied. Such information is critical  
558 in developing ‘models with intent’ in order to predict how changes in land use, management,  
559 or other stressors (such as climate change) alter SOC concentrations and persistence  
560 (Lehmann et al. 2020), with this being central to predicting soil functionality.

561

562 In addition, we currently do not have an adequate, multiscale, theoretical framework that  
563 bridges the gap from the fine scales (nano-scale to micro-scale) where C accumulates, to the  
564 large scales which are relevant for C-management policy (kilometer-scale) (Lehmann et al.  
565 2020). Similarly, observations of soil C at the field and regional scale cannot be linked back  
566 to the processes at the nano-scale. One possible solution to bridge these scales is through the



577 application of statistical physics framework that could describe how the mineral and organic  
578 components intervene in aggregation using an equilibrium thermodynamic model of self-  
579 assembly. This framework had been successfully developed for protein spontaneous  
580 formation (Sartori and Leibler 2020), and thus the assembly of aggregates based on physical  
581 and chemical potential and binding energy could be described in a set of parameters through  
582 algebraic relations that enabled scaling laws to be applied. Thus, we can link how nanoscale  
583 interactions of minerals and organic matter affect water and gas flow, biodiversity interactions  
584 and biogeochemical processes are relevant to regional and national scale assessment of soil  
585 functional change.

586

#### 587 4.2 *Soil biodiversity and functionality*

588 Although soil biodiversity contributes substantially to multiple critical soil processes and  
589 hence to the provision of functions that support human well-being, much remains unknown  
590 about soil biodiversity. Of utmost importance, we require an understanding of how measures  
591 of soil biodiversity (such as species richness or diversity indices) relate to the functioning of  
592 the soil, and critically, to understand how human-induced changes in soil biodiversity impact  
593 upon soil functioning. In this regard, Young and Bengough (2018) stated: “in perhaps the  
594 most exhaustive analysis and review of research on soil biodiversity, (there were) no  
595 consistent links between soil species diversity and function”. For example, it remains unclear  
596 how the decreasing complexity of soil food webs observed in intensive agricultural systems  
597 (Geisen et al. 2019; Tsiafouli et al. 2015) impacts upon the provision of soil functions such as  
598 nutrient cycling, biomass production, or SOC stocks.

589

590 Indeed, it is imperative that we gain a better understanding of how modifying uses of soils by  
591 humans alters soil biodiversity, their interactions with environments, and most importantly,  
592 the effect of these impacts on their ability to provide long-term soil functioning. It is also

593 important to understand how the soil matrix and rhizosphere microbial community interact via  
594 their effects on water availability and nutrient cycling from both inorganic and organic  
595 sources, with this potentially allowing optimization of plant productivity whilst also  
596 mitigating greenhouse gas emissions.

597

#### 598 *4.3 Novel approaches for increasing multifunctional capacity of soils*

599 Poor management and climate change are degrading soils and having detrimental effects on  
600 soil C and productivity. A range of management approaches have been developed to  
601 ameliorate degraded soils, but detailed analysis of their effect on soil properties and how the  
602 effects vary across scales are missing. This information is critical for improving existing  
603 management approaches and developing new strategies. There is an urgent need to develop  
604 new strategies to alleviate degraded soils and optimize SOC dynamics leading to increased  
605 soil C sequestration and productivity, with this generating new ways to rejuvenate and  
606 regenerate soil functionalities and its resilience. Such approaches might include methods to  
607 optimize the soil matrix functionality throughout the entire profile, design novel rhizosphere  
608 systems, or find new methods to minimize greenhouse gas emissions whilst maintaining soil  
609 productivity.

610

#### 611 *4.4 Refine models for ecosystem services to incorporate multifunctionality of soils*

612 Due to the complexity of the soil system, the multifunctionality of soil has generally been  
613 excluded from broader models that assess interactions between humans and the environment.  
614 Indeed, most models of ecosystem services include a maximum of one or two soil-based  
615 functions (Greiner et al. 2017). While these models may address individual problems,  
616 optimization of systems by focusing on only one or two soil-based functions will result in  
617 unknown and unintended consequences. This requires the expansion of models to be truly  
618 multifunctional, with this necessitating the identification of indicators that can be easily

619 monitored for evaluating the soil's multifunctionality. Such an approach will ultimately  
620 expose the trade-offs that are being made when certain land-use and management options are  
621 prioritized over others. Furthermore, these indicators not only need to meet the requirements  
622 and rigor of the biophysical sciences, but also provide data and information that is valued by  
623 the economic and policy arenas, with this requiring a clear multidisciplinary effort. Such  
624 models will be implemented locally, whilst their outputs need be mapped across broader areas  
625 to identify which soil functions are threatened (i.e. multiscale). From this present review, we  
626 identify SOC as being a master indicator for multiple soil functions given that it is responsive  
627 to the impacts of land-use change and is a biophysical indicator that is valued and relevant to  
628 assessments made by the economic and social sciences (Dowell et al. 2020; Pascual et al.  
629 2015; Sykes et al. 2020).

630

## 631 **5 Conclusions**

632 As befits the most complex biomaterial on the planet, there are no easy solutions to solving  
633 the ongoing soil security crisis of the planet. We need to find innovative practices that ensure  
634 the survival of future generations by sustainably using soils for the wide range of functions  
635 highlighted in this review. To do this, we need a highly collaborative effort across basic  
636 science, where new discoveries await to be revealed, and translational science, where we  
637 better connect laboratory and field. The answers do not lie in any one discipline, but rather, in  
638 a close cooperation across disciplines, connecting experimental research with the broader  
639 modelling community to ensure accurate predictions of the state of soils as we use them for  
640 food production and more general, but equally important, functions.

641

## 642 **6 Acknowledgements**

643

644

645 **7 References**

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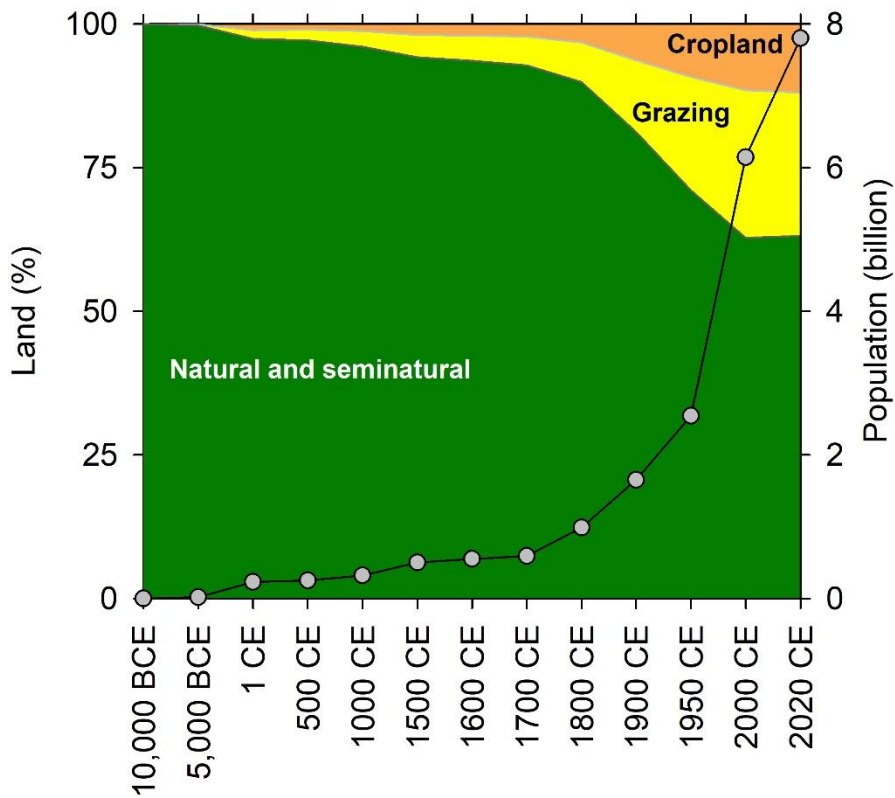
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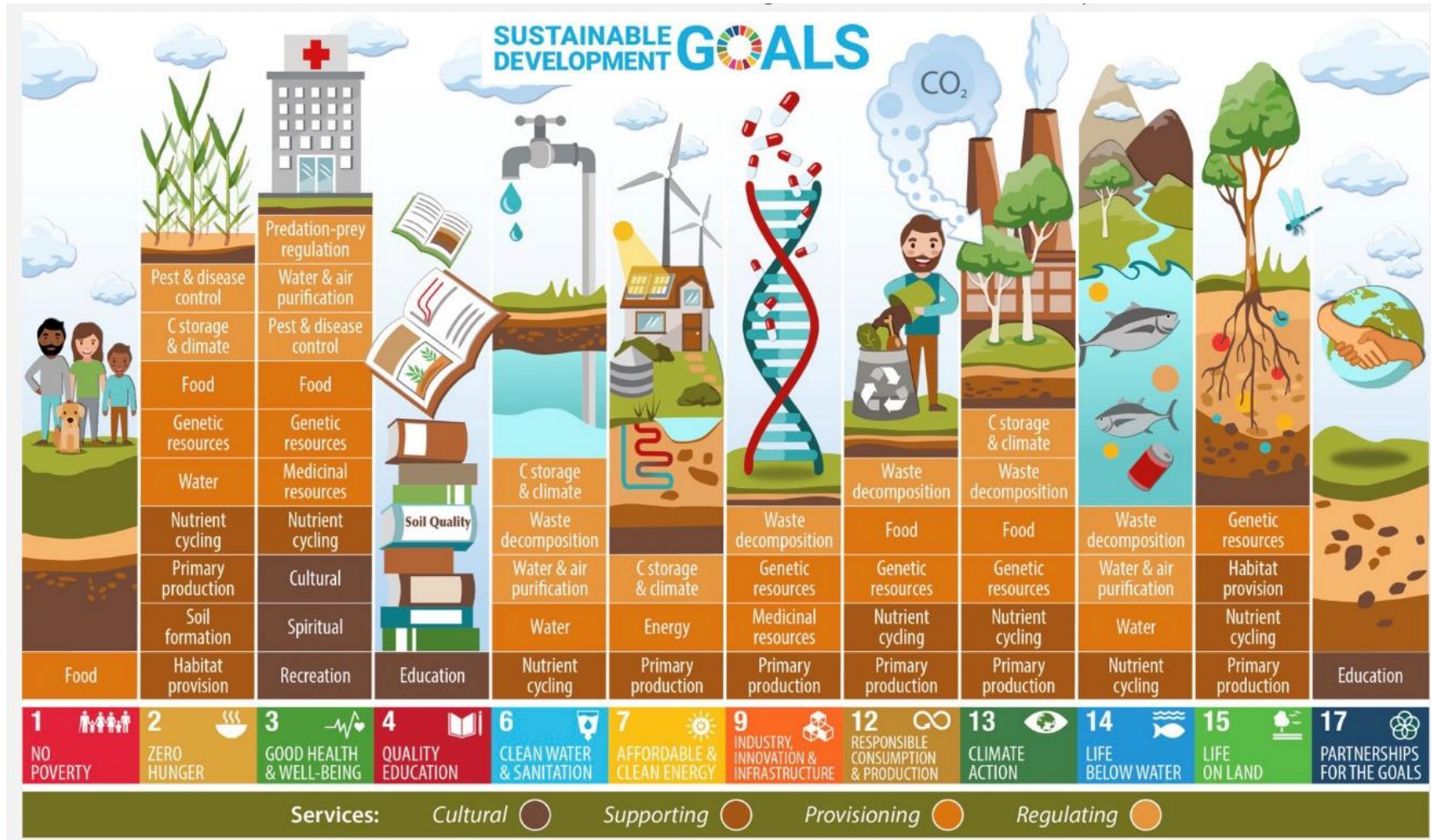
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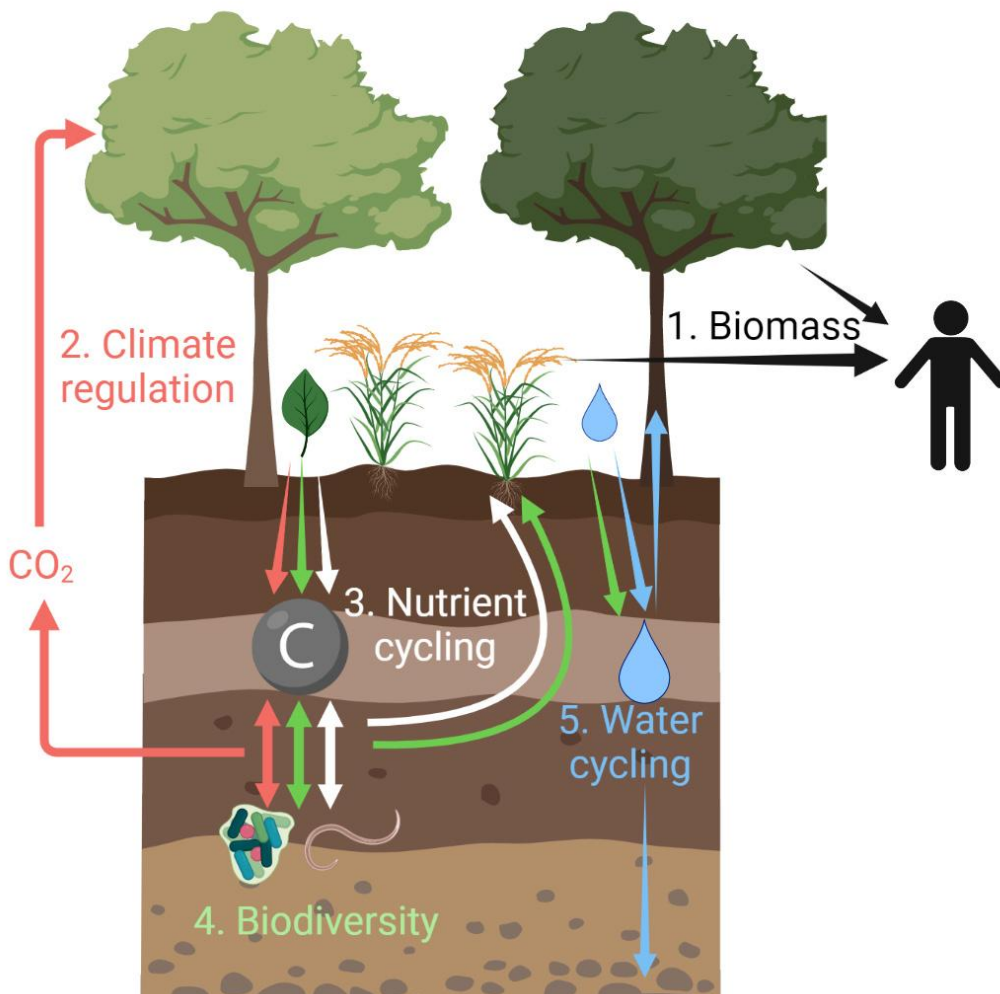
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**Figure 1.** Land-use changes for cropland and grazing as a percentage of the global ice-free land (shaded areas) and the change in human population (grey points). Data were obtained using the HYDE 3.2 database (Klein Goldewijk et al. 2017) and updated from Kopittke et al. (2019).



**Figure 2.** The role of soil functions in supporting at least 12 of the 17 sustainable development goals (SDGs) of the United Nations.



**Figure 3.** A simplified diagram illustrating the five interconnected key dimensions describing soil multifunctionality, being (1) provision of biomass (black), (2) climate regulation (red), (3) nutrient cycling (white), (4) biodiversity (green), and (5) water cycling (blue).