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1 **Review: Natural Capital and Ecosystem Services, Developing an Appropriate Soils**
2 **Framework as a basis for Valuation.**

3

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24 **Running head: Soil natural capital and ecosystem services**

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27

28 ABSTRACT

29 Natural capital and ecosystem service concepts are embodied in the ecosystems
30 approach to sustainable development, which is a framework being consistently adopted by
31 decision making bodies ranging from national governments to the United Nations. In the
32 Millennium Ecosystem Assessment soils are given the vital role of a supporting service, but
33 many of the other soil goods and services remain obscured. In this review we address this
34 using an earth-system approach, highlighting the final goods and services soils produce, in a
35 stock-fund, fund-service model of the pedosphere. We also argue that focusing on final goods
36 and services will be counterproductive in the long run and emphasize that final goods and
37 services are derived from an ecosystem supply chain that relies on ecological infrastructure.
38 We propose that an appropriate ecosystems framework for soils should incorporate soil
39 stocks (natural capital) showing their contribution to stock-flows and emergent fund-services
40 as part of the supply chain. By so doing, an operational ecosystems concept for soils can draw
41 on much more supporting data on soil stocks as demonstrated in a case study with soils data
42 from England and Wales showing stocks, gaps in monitoring and drivers of change. Although
43 the focus of this review is on soils, we believe the earth-system approach and principles of
44 the ecosystem supply chain are widely applicable to the ecosystems approach and bring
45 clarity in terms of where goods and services are derived from.

46

47 **1. Introduction**

48 Widespread concern about increasing pressures on the Earth's resources (Rockstrom
49 et al., 2009) has led many governments to focus on consideration of environmental
50 sustainability. Sustainable development is seen as desirable, though its proponents differ in
51 their views of what is to be sustained, what is to be developed, how to link the environment
52 and development, and over how long a time frame (Kates and Parris, 2003). However, there
53 is widespread agreement that if it is to be achieved, ecosystems, and the benefits their good
54 management brings, need to be better represented in decision-making tools and in indicators
55 of progress (such as Gross Domestic Product, GDP): this is the ecosystem approach to
56 sustainable development (Westman, 1977; Daily 1997). Monitoring and research in
57 environmental fields, including soil science, need to adapt to the changing policy landscape
58 brought about by this approach (Robinson et al., 2012).

59 In this paper we introduce the ecosystems approach in its broader context: ecosystem
60 services and natural capital: and suggest how soil scientists should interpret them in the
61 context of the earth-system. Moreover, we present a synthesis of ecological economics
62 approaches with ecological and soil concepts in a natural capital, stock-flow, fund-service
63 framework (Georgescu-Rogen 1971; Daly and Farley, 2011) pertinent to soils. The stock-
64 flows are the tangible goods that move around the earth-system and are materially
65 transformed into what they produce, and are a quantity. Fund-services are intangible, they do
66 not become embodied in the thing produced, but are emergent functions that arise as
67 something is produced, and as such they are measured in units of physical output per unit
68 time. We next discuss what these concepts mean for monitoring and research in soil science,
69 illustrating our points by presenting a synthesis of national-scale data (for England & Wales)
70 and describing how it might be developed to respond to the demands of the ecosystems
71 approach. Finally, we identify further challenges posed to soil science by the ecosystem
72 approach, and the next steps which we suggest should be taken.

73

74 **The ecosystems approach to sustainable development.**

75 The ecosystems approach to sustainable development ("the ecosystems approach")
76 has been promoted by many international organizations including: the Conference of the
77 Parties to the Convention on Biological Diversity (CBD), the Food and Agriculture
78 Organization of the United Nations (FAO), The Organisation for Economic Co-operation and
79 Development, the United Nations Environment Programme, and the United Nations
80 Development Programme. Moreover, countries such as the UK are adopting the ecosystems

81 approach for national-level environmental policy development (Defra, 2011). The CBD
82 defines the approach through 12 principles (Table 1). Two of the most important features of
83 the approach are that it is inherently anthropocentric and focuses on decision-making. Thus, it
84 recognises: the importance of managing ecosystems in a socio-economic context in order to
85 maintain ecosystem services for humans and that conservation of resources must be balanced
86 with their use (Principles 4, 5 & 10). Furthermore, it is argued that the power to choose the
87 ends of ecosystem management (not necessarily the means) should rest with society, not
88 scientists (Principle 1, also 11&12). Also of interest to soil scientists, is the recognition that
89 change is inevitable (Principle 9).

90

91 *1.1 Ecosystem services*

92 The concept of ecosystem services, though prominent within the ecosystems
93 approach, has proven even more influential on its own. Ecosystem services are the
94 foundational concept of the Millennium Ecosystem Assessment (MEA, 2005), The
95 Economics of Ecosystems and Biodiversity (TEEB) initiative and the Intergovernmental
96 Panel on Biodiversity and Ecosystem Services (IPBES), the so-called IPCC of biodiversity
97 (Marris, 2010); it is a concept that pervades all current discourse about the environment. The
98 success of ecosystem services means they cannot be ignored by any scientist working on any
99 part of the environment. However, creating an operational concept for research, monitoring
100 and management is deeply problematic and challenging.

101

102 *1.2 The fuzziness of ecosystem services*

103 Definitions of ecosystem services have abounded, since the concept developed from
104 papers such as Westman (1977). Fisher et al. (2009) provide a recent overview of how
105 ecosystem services are defined, indicating that the literature has no commonly accepted
106 consistent definition; the MEA (2005) definition is perhaps the most familiar: "the benefits
107 people obtain from ecosystems." In public discourse at least, MEA (2005) has been most
108 influential, yet several authors have criticised this rather loose definition. First, Boyd and
109 Banzhaf (2007), then Fisher and Turner (2008) argue that a service is not the same as a
110 benefit: that whereas ecosystem services are purely ecological phenomena, benefits are
111 produced when ecosystem services are combined with other forms of capital (human,
112 physical etc). Although Wallace (2007) and Boyd and Banzhaf (2007) believe that a single
113 unified definition of ecosystem services is necessary to allow proper accounting, Fisher and
114 Turner (2008) argue that different definitions may coexist for different purposes. The

115 ongoing debate over what ecosystem services are, combined with the near ubiquity of the
116 term, means that ecosystem services are a “fuzzy concept”: undoubtedly influential, but
117 problematic as an analytical concept. However, the lack of general agreement creates scope
118 for contributions from soil scientists to further develop the framework and ensure soil
119 functions, vital to the maintenance of the earth-system and human wellbeing, are dealt with
120 appropriately.

121

122 *1.3 Natural Capital*

123 The earliest reference to natural capital we found dates to 1837 (Badgley, 1837), and
124 was more recently coined by Schumacher (1973), and used by Costanza and Daly, (1992) but
125 really brought to prominence by Costanza et al., (1997). Costanza et al. (1997) define it as,
126 “the stock of materials or information contained within an ecosystem”. Natural capital and
127 stocks are of obvious relevance to soil science, given the widespread assessment of soil
128 stocks through survey and inventory. However, references to ecosystem services have far
129 outstripped those to natural capital (Table 2), and continue to grow more rapidly, while
130 natural capital is not mentioned at all in the 12 principles of the ecosystems approach (Table
131 1); it is however, prominent in the UK government’s white paper on the environment (Defra,
132 2011). Perhaps surprisingly, natural capital appears to be particularly under-represented in the
133 soils literature (Table 2). The greater focus on final ecosystem service delivery (relative to
134 natural capital) raises the concern that the components of ecosystems such as biodiversity or
135 soils might be overlooked if their link to final ecosystem services cannot be clearly
136 demonstrated.

137

138 *1.4 Ecosystem services, natural capital, and decision-making*

139 The concepts of ecosystem services and natural capital have proved difficult to use in
140 valuation, and decision-making (decision-making implies valuation, whether explicit or not).
141 Although it is common to refer to the value of an ecosystem (i.e. natural capital) or its
142 services, careful economic valuation rarely produces anything of the kind, for three reasons.

143

144 1. As Fisher and Turner (2008) point out, it is the benefits which impact directly on human
145 welfare that are valued, and these are a combination of ecosystem services (or natural capital)
146 and human or physical capital.

147 2. It is the change in the ecosystem service or natural capital which is valued, not the
148 ecosystem service itself, and only at the smallest of scales will the two be identical. As

149 Toman (1998) has pointed out, any attempt to estimate the “total value of the world’s
150 ecosystem services and natural capital” (as per Costanza et al 1997) would be a “serious
151 underestimate of infinity”, and a similar criticism could be levelled at total valuations of a
152 nation’s ecosystem services.

153 3. Economic valuation is predominantly concerned with the effects on human welfare of
154 specific and plausible human actions, which may affect ecosystems, the services they
155 provide, or the way these services are used. It is really the human action or intervention
156 which is valued, not the ecosystem or ecosystem services which it affects.

157

158 Since virtually all ecosystems of interest are already in some way shaped (and in many cases
159 created) by human action, it is difficult to identify truly *natural* capital, or purely *ecological*
160 services: is soil that has been farmed and maintained for centuries really *natural* capital? Is it
161 worthwhile or even feasible to try to apportion ‘credit’ where it is due? There is a danger that
162 the ecosystem services concept may obscure the intricate co-existence in most parts of the
163 world between humans and their environment: that what ecosystem scientists are really
164 studying are socio-ecological systems, undermining the holism called for in the ecosystems
165 approach.

166 In summary, the concepts discussed above, particularly ecosystem services, have been
167 extremely influential in both public and academic discourse about the environment, which is
168 why soil science must engage in this debate and in the further development of concepts and
169 frameworks. These concepts may have served to alert a wider audience to what
170 environmental managers and soil scientists have known for a long time: that ecosystems, as
171 human-environmental systems, can make an enormous contribution to human wellbeing if
172 managed appropriately. In the next section we suggest how soil science can best respond to
173 the challenges posed by this evolving paradigm in environmental management.

174

175 **2. How should soil science respond to the ecosystems approach**

176

177 *2.1 Ecosystem services and natural capital in soil science*

178 The ecosystems approach has gained more traction in the agricultural context than soil
179 science *per-se*, probably because of the emphasis on final services like provisioning (Antle
180 and Stoorvogel, 2006; Dale and Polasky, 2007; Swinton et al., 2007; Zhang et al., 2007;
181 Power, 2010; Sandhu et al., 2010a; Stallman, 2011). In ongoing discussion of typologies and
182 classifications for ecosystem services, soils tend to be viewed in the context of supporting

183 above ground ecosystems, (De Groot et al., 2002, MEA, 2005) rather than for more specific
184 goods and services that soils themselves provide. A lack of consistent typology, means that
185 increasingly, properties, processes, functions, and services become used interchangeably,
186 leading to confusion and making the development of a consistent valuation approach
187 difficult. Daily et al. (1997) was perhaps the first to attempt to classify the ecosystem services
188 provided by soils in their own right and this has been followed by other classifications (Wall
189 et al., 2004; Andrews et al., 2004; Dominati et al., 2010), with many following the broad
190 provisioning, regulating, cultural and supporting typology from the MEA (2005). Many of
191 the articles have focused on promoting the importance of soil properties, processes and
192 functions (Andrews et al., 2004; Haygarth and Ritz 2009; Powlson et al., 2011), whilst there
193 is an increasing interest in the role of the below ground biota and microbial communities in
194 providing services (Wall et al., 2004; Bell et al., 2005; Barrios, 2007; de Bello et al., 2010;
195 Gianinazzi et al., 2010; Guimarães et al., 2010; Smukler et al., 2010; van Eekeren et al.,
196 2010).

197 Soil natural capital, with its focus on stocks, is perhaps more intuitive to soil science
198 as these are routinely measured and inventoried. Palm et al. (2007) defined soil natural capital
199 as texture, mineralogy and soil organic matter. This was followed by a more in-depth
200 definition involving ‘matter, energy and organization’ presented by Robinson et al., (2009).
201 The concepts of natural capital and ecosystem services are sometimes seen as competing
202 concepts but increasingly, especially with soils, they are seen as complimentary with the need
203 for synthesis into a single soil-based framework (Dominati et al., 2010). The need for a
204 consistent classification and framework within the ecosystems approach for soils is clear if
205 valuation is to be conducted, and will bring the benefits of better identifying and defining the
206 important soil stocks and services and communicating these to policy makers, especially in an
207 increasingly regulatory environment (Bone et al., 2010). In addition, classification provides a
208 language of communication, it helps us identify if things are missing, it will allow us to group
209 new services with existing ones, provide a common reference for those already identified,
210 and create better cross linkage with other ecosystem service to decision making frameworks.

211

212 *2.2 Ecosystem service frameworks*

213 Frameworks must incorporate soils so that society understands both the importance of
214 soils, and that soils change on policy relevant time scales (Robinson et al., 2012). Soils are a
215 dynamic system that continually evolves through soil formation and development and what
216 may be termed anthropogenic soil change (Richter et al., 2011): mankind’s intervention to

217 adapt, adjust and manage soils for human benefit. Any framework must convey: to what
218 extent change is inevitable, and how our interventions might accelerate or alter change.

219 One of the major drawbacks of the current ecosystem service framework with regard
220 to soil is that it focuses on the flows of final goods and services and is biosphere centric. If
221 our ‘policy ends’ are to better manage the earth-system, and its resources, we need to take an
222 earth-system perspective and set soils and the pedosphere in this context. Currently in the
223 MEA soils that contribute to final goods and service delivery are easily overlooked. This has
224 caused either a lack of engagement with the soils community, or a response such as that of
225 Lavelle et al.’s (2006), who stated, “Invertebrates play significant, but largely ignored, roles
226 in the delivery of ecosystem services by soils at plot and landscape scales.” An impediment
227 for soil science is that soils provide limited flows of final goods: peat, topsoil, turf and
228 minerals perhaps being the most easily identified, and as a result feature little in the
229 ecosystem services framework and any subsequent valuation as a distinct entity; but they are
230 fundamental in the delivery of many final services by which they are subsumed.

231 Dominati et al. (2010) recognized that a combined natural capital and ecosystem
232 service approach is needed for soils. Focusing solely on final goods and services can lead to a
233 problem analogous to that of using GDP as a welfare indicator: since GDP measures only
234 flows, it tells one nothing of the sustainability of resource use, or what resource remains.
235 Similarly, focusing only on final goods and services, tells little about the state of the
236 ecosystem service delivery mechanisms. The recent UK National Ecosystem Assessment
237 (NEA, 2011), presents a conceptual framework (NEA, Fig 2.2) that expands on the MEA
238 (2005). The NEA framework has soil formation and primary production as a starting point on
239 which processes act such as nutrient cycling, supporting the delivery of final ecosystem
240 services, and then providing goods that are valued. This recent work develops the supporting
241 services area which is essentially a black box in the MEA, and moves us closer to what might
242 be considered an ecosystem service supply chain.

243 We maintain that it is vital that our overarching frameworks are holistic, embody an
244 earth-system approach, and that soils in the form of the pedosphere are a fundamental
245 component if the ‘policy end’ is to be improved earth-system management. We spend the rest
246 of this section synthesizing soil and MEA concepts into the increasingly used ecological
247 economic stock-flow and fund-service framework (Van Dyke, 2008; Daly and Farley, 2011,
248 Farley and Costanza, 2010). The stock-flow and fund-service framework is particularly
249 appealing because of its focus on earth-system management of scarce resources (Daly and
250 Farley, 2011). This framework helps to differentiate between the tangible goods we obtain

251 from ecosystems, and the intangible services, but also recognizes that ultimate classification
252 as a good or service depends on use. In conventional economics the production of an output
253 requires ‘factors of production’ which are the inputs. For instance in car manufacture this
254 might include the raw materials, steel, plastic, wood, and rubber etc. as well as the assembly
255 line, robots, presses and other machines. The raw materials are fundamentally transformed
256 and used up in production, whereas the machines in the assembly line are basically unaltered
257 by the process, just a little worn, but not fundamentally altered. So it is with ecosystems,
258 according to the MEA (2005) there are provisioning goods that we harvest from ecosystems,
259 such as food, feed and fibre; and regulating, cultural and supporting services, these clean,
260 buffer, deliver, and filter but are not used up. In the stock-flow and fund-service framework
261 the stocks result in flows of raw materials, some of which we harvest and are the structural
262 components of an ecosystem, whilst processes act on multiple stocks within the ecosystem
263 resulting in functions that are an emergent behaviour of the ecosystem resulting in fund-
264 services. Taking an earth-system approach (Fig 1.), environmental scientists recognize the
265 major compartments of the earth-system as spheres, the atmosphere; hydrosphere, including
266 oceans, surface and ground water and lakes; the terrestrial biosphere with its plants and
267 animals; the pedosphere, the thin skin of soil around the earth, and the geosphere, containing
268 rocks and minerals. In addition, we identify an anthroposphere, recognizing we live in a
269 coupled human-environment system.

270 Soils in the pedosphere are set in the context of the earth-system in Fig. 1. The
271 building blocks of the pedosphere are soil natural capital stocks, which we can differentiate
272 as abiotic and biotic in the brown box at the base of the figure. The natural capital framework
273 of Robinson et al. (2009) is adapted to highlight the abiotic and biotic components of the soil
274 ecosystem. Within the soil ecosystem the abiotic components provide the raw materials
275 which are processed by the biotic component. Within the soil ecosystem there is constant flux
276 of energy and materials and the reorganization and formation of new soil by physical,
277 chemical and biological processes (S-F 3&4). The soil biota performs as the engine powering
278 biogeochemical cycling in the earth system. This internal cycling creates outputs to the other
279 spheres, hydro, bio and atmosphere of intermediate goods such as water, nutrients and gases
280 (S-F 6) and is fuelled in part by outputs from other spheres in the earth-system in terms of
281 wastes, exudates or weathering products for example (S-F 5).

282 Human intervention from the anthroposphere harvests goods from the environment.
283 Soils are not often considered in terms of the harvested products they supply as final
284 provisioning goods, but these should be recognized and include commodities of economic

285 importance, such as topsoil, subsoil, turf grass and minerals (Fig.2). The US turf grass
286 industry alone is considered to contribute more than \$1 billion to the US economy annually
287 (Christians, 2011). Soil biota is also harvested through extraction in the search for new
288 biomedical resources. The soil ecosystem provides a vital, underappreciated, gene pool and
289 biological resource from which many of our antibiotics have been derived (D'Costa et al.,
290 2006). Methods of extracting, growing and reapplying soil biological crusts are also being
291 investigated as a means of stabilizing soil surfaces to reduce dust emissions, something they
292 have always done in the natural environment. Only a fraction of the soil biota has been
293 explored, and many organisms remain to be discovered that can be of benefit to our existence
294 in a known capacity.

295 All the processing and use of final and intermediate goods produces output/waste
296 streams (S-F 2,4 and 5). Moreover, the anthroposphere produces manufactured inputs such as
297 fertilizer and soil stabilizers. Although the movement of outputs is a stock-flow, the
298 transformation of outputs is a fund-service, and one worth singling out. Soils are commonly
299 used as the waste absorption repository for both anthropogenic derived outputs, and non-
300 anthropogenic outputs. A vital aspect of this is the output/waste absorption capacity, as
301 output transformation has a fixed upper level to its processing rate. The only way to alter the
302 rate is to build up the natural capital and increase the quantity and functional biodiversity of
303 organisms that process outputs; which adds to the argument for making natural capital and
304 ecological infrastructure highly visible in frameworks. This is one of the often overlooked
305 aspects of current agricultural systems where fertilizer substitutes soil derived nutrients for
306 plants. This is the problem with short-term single use management, in this case increased
307 production. Production increases obtained using fertilizers, pesticides and tillage reduced
308 organic matter levels, reducing the soil natural capital stocks of carbon, and organisms that it
309 supports, as a result the soils ability to absorb waste and assimilate it back into ecosystem
310 becomes more limited. This is especially the case with nitrogen, where nitrogen pollution is
311 common-place (Rockstrom et al., 2009).

312 The fund-services are shown above the stock-flows in Fig.1, a company class
313 typology illustrates services commonly identified with the anthroposphere (F-S 7). These are
314 the types of services commonly dealt with in national accounts as well as policy making. The
315 environmental stock-flows result in a range of environmental fund-services (F-S 9,10 & 11).
316 Both the internal and external stock-flows, involving the pedosphere (S-F 3-6), result in soil
317 formation (F-S 9), termed supporting services in the MEA. In this earth-system approach to
318 ecosystem services, ecosystem formation is an important fund-service, be it the diversity and

319 complexity in a soil, forest, lake, marine or prairie ecosystem. Intermediate fund-services (F-
320 S 10) are those with no recognized direct benefit to the anthroposphere, but are often
321 important to the functioning of the ecosystem.

322 Soils contribute to a wide range of other emergent fund-services through interaction
323 of the pedosphere with other compartments of the earth-system. Some of the more important
324 ones are listed (Fig. 2). We now know that soils are a major store of global carbon and
325 regulate GHG emissions, but we are also beginning to understand the important role of soil
326 moisture as a buffer to extremes of heat and cold (Seneviratne et al., 2006). Both the strength
327 and persistence of heatwaves in terms of loss of life, and cold spells, causing damage to
328 infrastructure, especially by deeper frost penetration affecting pipe work; these have serious
329 financial consequences for society. Given that the majority of our infrastructure is supported
330 by, or surrounded by soil, slips, slides, and shrink swell affect costs, as does chemical
331 weathering of concrete by the soil solution.

332 Soil biota contributes a major part to fund-services, soil is simply not soil without the
333 biotic component. Biodiversity is recognized by some as a final ecosystem service in its own
334 right (Eigenbrod et al. 2010). There is no doubt that whether as a final, supporting or
335 intermediate service contributing to final services, soil biota and especially their functional
336 diversity are a key component of the functioning of the earth-system. Barrios (2007) has
337 explored this in great detail, identifying key functional groups that are involved with both
338 intermediate and final services. He identifies 6 major functional groups which appear in the
339 biotic compartment of the soil natural capital in fig. 1: the microsymbionts involved with
340 nutrient uptake by plants; decomposers and elemental transformers involved with nutrient
341 cycling; ecosystem engineers that modify soil structure sequestering carbon, enhancing
342 aggregation, which affects hydrological and GHG regulation, dust emission etc; then there
343 are the soil borne pests and diseases which result in disservices, but are regulated by the
344 micro-regulators. By adopting this earth-system approach, soils, as well as all other
345 compartments of the earth-system, play a much more visible role in the supply chain for
346 ecosystem goods and services (Bristow et al., 2010; Jury et al., 2011). Thus this synthesized
347 framework, in part, begins to address the role of soils in both and earth-system context and in
348 terms of ecosystem goods and service delivery.

349

350 *2.3 Decision-making and valuation for management*

351 In this section we focus on ecosystem services in the context of decision making and
352 tradeoffs rather than national accounts. Soil management for single functions can often be

353 assessed based on empirical evidence and observed relationships, and attempts have been
354 made to value or determine value systems for particular soil components (Decaens et al.,
355 2006; Clothier et al., 2008; Rabotyagov, 2010; Sandhu et al., 2010b). However, optimising
356 the multifunctional use of soils requires both models and monitoring in an integrated package
357 that gives the best understanding of the response of the soil system within its ecosystem
358 context, as well as a series of tools that can be used to assess tradeoffs for decision making. It
359 is questionable whether such models currently exist: InVest (Nelson et al., 2009) and
360 Polyscape (Pagella et al., 2011) are attempts to address this integrated modelling approach,
361 but these are limited mostly to soil hydrological and carbon flux assessment for soils. Soil
362 biodiversity and structural dynamics are not currently incorporated, and it remains extremely
363 challenging to derive meaningful estimates of net-benefits for management decisions
364 involving complex ecosystem service supply (Fig. 1). These models also focus on assessing
365 ecosystem functions: combining them with economic assessment has yet to be done in any
366 meaningful way. Cost benefit analysis (CBA), is often viewed with suspicion by those
367 working with the environment, and yet there is much to learn from it as a framework which
368 may help to systematically, and coherently identify the effects of a certain measure, using
369 valuation as a means of making things comparable (Hansjurgens, 2004).

370 CBA allows us to compare alternative management actions. To do this we need to
371 understand the dependence of final ecosystem service provision on ecological infrastructure
372 (and how this is affected by human actions) by having a good understanding of the ecosystem
373 service supply chain, its quality and health, and the consequences of adapting and modifying
374 the supply chain. Perhaps a convenient way to do this is to model components and function of
375 the ecosystem at an appropriate scale. This itself raises a challenge for soil science, to
376 develop integrated soil system function models that describe 'soil system behaviour' for the
377 provision of all services in the ecosystem context at a desired scale. We have detailed water,
378 gas and heat flow models (Simunek et al., 2008), and nutrient cycling models (Johnson et al.,
379 2000), but these tend to be stand-alone and are not linked to biodiversity or ecosystem
380 models, and moreover not linked to management. A suite of soil science models are needed
381 that are able to predict the effects of specific management actions on soil functioning
382 (Cichota and Snow, 2009). Thus they don't just need to describe how soils currently function,
383 but how that changes if we do something. In order to understand ecosystem service provision
384 it might be time to step back, and instead of making models more detailed, make general
385 models more holistic. These models should recognize the important soil stocks and
386 infrastructure in the ecosystem service supply chain. Soil science and those who manage soils

387 for provisioning and regulating services intuitively understand the importance of soil
388 infrastructure, which is why many monitoring programs measure soil stocks as indicators of
389 soil performance (Emmett et al., 2010).

390

391 **3. Monitoring and measurement**

392 *3.1 Soil state and change*

393 One risk in focusing too much on final ecosystem services is that the stocks and
394 intermediate services that are responsible for final delivery may be overlooked (Fig. 1). This
395 is detrimental if stocks decline unnoticed in support of final ecosystem goods and service
396 delivery, e.g. nutrient stripping in crop production, leading to a positive feedback with
397 declining final services. There are two further reasons that stocks are important for
398 monitoring the state-and-change of soils (Emmett et al., 2010). First because flows can be
399 inferred from stocks but stocks cannot be inferred from flows without a baseline assessment
400 of stocks. The counter argument, often in the context of carbon emissions, is that it is the flux
401 in or out of soils that matters, i.e. determining if they are a source or sink. However, it is only
402 through a stock assessment that we can determine the magnitude, of for instance, the soil
403 carbon pool, and whether it is likely to continue to be a significant source of GHG if not
404 managed properly. Knowing the size of the available nutrient stock in soils is also of strategic
405 value. In the case of peak phosphorus (Clabby, 2010), it is important to know soil reserves,
406 the rate at which these will be released into the available soil solution pool, and the amount
407 removed and returned during crop production if we are to plan for a sustainable future. In the
408 same way, knowing the stock of soil moisture is of value to a farmer in determining when to
409 irrigate. Any monitoring scheme will always be more powerful if both stock and flux are
410 determined and used to cross check with each other in the assessment of change (Richter et
411 al., 2007).

412 The second argument for focusing on soil stocks is to ensure continuity with historical
413 data which, for soils, has tended to focus on soil stocks. In the United Kingdom LandIS, the
414 land information system run by the National Soil Resources Institute (NSRI), a centre within
415 Cranfield University, G-BASE (Simpson et al., 1996) from the British Geological Survey and
416 Countryside Survey (Emmett et al., 2010) from the Centre for Ecology and Hydrology all
417 have data that goes back decades, which if we stopped monitoring stocks would be almost
418 redundant for this purpose. This wealth of data may help us to determine how soils have
419 changed over time, especially following anthropogenic activity. Focusing simply on MEA
420 final ecosystem goods and services can overlook this resource. Concurrently, soil monitoring

421 needs to assess if it is fully capturing soil change, not just current state. We need to re-
422 evaluate our monitoring in the light of the ecosystem approach: are we measuring the things
423 which matter? Will our monitoring inform management for society's objectives? The soil
424 natural capital framework (Fig. 1) (Robinson et al., 2009) provides an opportunity to
425 determine which stocks are currently being monitored and which are not. Knowing these
426 variables is of value in assessing soil performance. In the following section we present a case
427 study for England and Wales identifying data sets that contribute to soil stock state-and-
428 change monitoring, which could form the basis of a national soil natural capital assessment.

429

430 *3.2 Exemplar datasets for assessing natural capital in England and Wales*

431 To illustrate the importance of both soil natural capital and ecosystem services in an
432 ecosystems approach, we assess the current state of soil monitoring for England and Wales,
433 countries adopting a national ecosystem approach (Defra, 2011).

434 Society, through EU, UK and Welsh Government policy and regulation increasingly
435 intervenes in land management with regard to balancing a range of pressures from food
436 production to climate change (Haygarth and Ritz 2009), in line with an ecosystem approach.
437 In order to develop effective monitoring and assessment appropriate to answering questions
438 derived from an ecosystems approach, we must have appropriate frameworks in place to
439 allow valuation for decision-making, and feed the desired valuation results back. No agreed
440 framework exists to date, and so this section identifies the steps and relevant information
441 required to attain an appropriate ecosystem approach for soils.

442 Robinson et al (2012) identified four key research areas needing attention for
443 communicating soils research effectively in an ecosystems context:

444

- 445 1) Framework development, one that gives a balanced emphasis to stocks and flows.
- 446 2) Quantifying changes to the soil resource. This can be achieved through monitoring
447 and modelling of stocks, fluxes, and transformations, and identifying appropriate indicators
448 that can be used in monitoring schemes to tie modelling to reality.
- 449 3) Valuing the net benefits to society from alternative soil management options.
- 450 4) Developing management strategies and decision-support tools.

451

452 A brief review of soil survey in England and Wales shows that most of the
453 information held describes soil stocks, and as stated previously to focus solely on final
454 services and ignore this wealth of stock information would be detrimental. Therefore, any

455 framework should achieve a balanced recognition of stocks and services. Secondly, scale is
456 an important consideration within an ecosystems approach (Hein et al., 2006). Decisions are
457 made for different scales and Defra (2007) has identified: local (local government), regional
458 (government offices) and national (England or Wales) scales as being important to their
459 decision making. For most land managers we can add the farm scale to this also; whilst the
460 ultimate aim may be to have scales of tens of meters helping individual householders and
461 companies. Soil stocks alter in both space and time, and it is likely that stocks may contribute
462 differently to soil function at different scales, this may have implications for valuation. For
463 the purposes of this synthesis we focus on national and regional scales and consider soil
464 stocks appropriate for these scales.

465 The soil resource: Defra identified the following soil functions as being of major
466 national importance: 1) food and fibre production, 2) environmental interaction, 3)
467 biodiversity and habitat, 4) protection of cultural heritage, 5) platform for construction, and 6)
468 raw materials (Defra, 2009) (Table 3). Sustaining these functions is an important aspect of
469 soil management. Maintaining and enhancing soil function requires policy developed from
470 the best understanding of soil stocks, the services they deliver and soil behaviour, this
471 requires spatio-temporal mapping and modelling of soils, within the correct ecological,
472 hydrological, geological and landuse context that includes static and dynamic soil stocks.

473 Soil resources have been quantified for England and Wales by a number of soil
474 inventories for different purposes which include, the (i) NSRI, LandIS database linked to the
475 National Soil Map (NATMAP), which for England and Wales is based on soils found at 5691
476 points on a 5-km grid, (ii) NSRI resampling survey, (iii) Countryside Survey (CS), (iv)
477 Representative Soil Sampling Survey (RSSS); (v) the Environmental Change Network
478 (ECN), and (vi) Biosoil. Table 3a-c synthesizes data from these surveys into the matter,
479 energy, and organisation natural capital framework (Fig. 1), then links them to the soil
480 functions identified above and identifies drivers of change. The tables (3a-c) indicate that
481 there is a lot of potential information available that fits well into a soil stocks framework.
482 Classifying the available data according to the natural capital typology also allows us to
483 identify gaps in monitoring; these include lack of more dynamic data such as soil moisture
484 data which relates to understanding fund-services such as flood and drought potential, and
485 heat-wave persistence and intensity (Seneviratne et al., 2006). Micronutrients represent
486 another gap relating to food and fibre production and ecosystem health. Data is beginning to
487 emerge on soil organisms but this is still in its infancy and remains a gaping hole in
488 monitoring. Quantity and diversity results are available (Emmett et al., 2010) which underpin

489 many functions, and the provisioning of biomedical resources; this is certainly an area where
490 more work is needed, especially functional diversity and capacity, and linking these resources
491 to valuation. No survey of soil gases is currently undertaken, this is primarily constrained by
492 technology. Oxygen levels are important for plant growth (Letey, 1985), whilst carbon
493 dioxide, methane and nitrous oxide are all important for understanding climate change.
494 Measuring gases *in-situ* is difficult, though methods are becoming available (Turcu et al.,
495 2005), whilst measuring fluxes is feasible but expensive using eddy flux towers, e.g. the
496 American Ameriflux network (Falge et al., 2001). The structural components of soils,
497 macroporosity, aggregation and connectivity are more difficult to assess: LandIS gives some
498 assessment of the connection of soils with the landscape in the form of mapping units which
499 are based on expert opinion and are unsatisfactory for determining change; moreover
500 structure and its change at the scale of the pedon, for example, pores, peds and aggregate
501 information is not available. Maintaining the aggregate stock has important impacts on final
502 services such as carbon storage, flood regulation, and food provisioning for example.

503 Capturing and understanding ‘soil change’ is an important component of
504 understanding how final ecosystem service provision affects the soil infrastructure and stock
505 levels for sustainable soil ecosystem service provision. We also need to understand how to
506 differentiate between how different drivers of change impact the soil final good and service
507 supply chain and ultimately affect benefits and value. This is where Fig. 1 helps to begin to
508 locate where drivers of change might impact along the supply chain. Countryside Survey was
509 designed to assess state and change of above and below ground ecosystems (Smart et al.,
510 2003; Black et al., 2003; Griffiths et al., 2011), whilst attempts have also been made to
511 understand change by resampling the original soil survey data (Bellamy et al., 2005; Kirk et
512 al., 2010). Assessment of change is increasingly important for determining how interventions
513 impact, both at local and regional scales and underpins valuation. This may require regional
514 monitoring, and monitoring of specific interventions to differentiate between large scale
515 drivers of soil change and soil change due to intervention at local scales.

516 Soil, as seen from fig. 2, produces its own final goods and makes major contributions
517 to the delivery of many final ecosystem fund-services. However, the important question is
518 how do we recognize the role of soil in this delivery? The first step, presented here is
519 recognizing the importance of all earth-system compartments in the delivery of final goods
520 and services, not just focusing on the biosphere. We need to understand how changes in soil
521 management for example affect these final fund-services. Another important question is: how
522 sustainable is the supply chain for continued fund-service delivery, are we managing the

523 stocks from which they are generated appropriately? This is where the combined stock-flow,
524 fund-service model helps. Data is required that shows the stock and change over a suitable
525 period of time, and links both flows and fund-services back to changes in stock in all
526 compartments of the earth-system, which is why tables 3a-c are important in determining
527 what stocks we monitor. We therefore propose that fig. 1 using an earth-system approach
528 provides a more complete basis for identifying the contribution of soil ecosystems to
529 ecosystem services, and provides a template for valuation advancing some of the concepts
530 proposed in Dominati et al. (2010).

531

532 **4. Future steps**

533 Given the discourse in section 3, the soils community must build consensus to refine
534 and promote a common soil natural capital / ecosystem service framework, such as the earth-
535 system stock-flow, fund-service approach proposed here (Fig. 1). Appropriate bodies for
536 addressing this might be professional societies or the newly formed Global Soil Partnership
537 (GSP) supported by FAO, with the aim of developing an inter-governmental panel on soil
538 (IPS) (FAO, 2011). The advances required with the ecosystems approach complement the
539 five main pillars of action proposed by the GSP (Table 4).

540 In addition to the four scientific challenge areas outlined in Robinson et al., (2012) for
541 soils, much scientific and economic evidence is unsuited to improving decision-making about
542 ecosystem management. To do this, we need to estimate the costs and benefits resulting from
543 a change in management. This means understanding the incremental effects of that change,
544 especially on ecological infrastructure and supply chains, on ecosystems and on society.
545 Because it would be prohibitively expensive to carry out scientific and economic studies for
546 every decision, we need to be able to efficiently apply the results of past studies to new
547 problems, a process known as benefits transfer in economic valuation. Yet this process is
548 often hampered in several ways as detailed in the following paragraphs.

549 First, natural science research and monitoring is frequently directed towards testing
550 hypotheses about how ecosystems function, rather than predicting the effects of specific
551 changes in management, and the evidence base for many management decisions is often
552 surprisingly weak, even in apparently well-studied systems. Monitoring of soil characteristics
553 over time is of little use if changes cannot be related to their causal factors. The strong focus
554 on statistical significance, as opposed to the shape of “dose-response” functions, in many
555 natural science fields, often makes it difficult to interpret research in an applied setting.

556 Second, published studies, in the natural and social sciences, usually present only
557 summary results, which are rarely sufficient to allow re-analysis for application to a new
558 context, and the needs for ecosystem service analysis can be quite data intensive.
559 Requirements for data archiving vary between journals, organisations and disciplines.
560 Government organisations often fulfil an important and underappreciated role in archiving
561 data as a component of their national capability and new journals focusing on environmental
562 data sets are an important contribution to sustaining collective memory. Facilitating data
563 access is an important step toward integrated ecosystem service modelling and evaluation.

564 For soil science, the challenge is clear: the development of a clear, operational
565 framework to convey soils research within the ecosystems approach, but that also shows how
566 soils interlink with the atmosphere, biosphere, hydrosphere and geosphere in supplying
567 emergent fund-services, something we feel this paper contributes towards, so that soil science
568 can advance toward valuation of soil goods and services, fully communicating the vital role
569 of soils in sustaining the coupled human-earth system.

570

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Table 1. CBD Principles of the Ecosystem Approach (abridged from CBD <http://www.cbd.int/ecosystem/principles.shtml>)

CBD Principles of the Ecosystem Approach

1. The objectives of management of land, water and living resources are a matter of societal choices.
 2. Management should be decentralised to the lowest appropriate level.
 3. Ecosystem managers should consider the effects of their activities on adjacent and other ecosystems.
 4. There is usually a need to understand and manage the ecosystem in an economic context.
 5. Conservation of ecosystem structure and functioning, in order to maintain ecosystem services, should be a priority.
 6. Ecosystems must be managed within the limits of their functioning.
 7. The ecosystem approach should be undertaken at the appropriate spatial and temporal scales.
 8. Management should be set for the long term.
 9. Management must recognise that change is inevitable.
 10. The ecosystem approach should seek the appropriate balance between conservation and use.
 11. The ecosystem approach should consider all forms of relevant information, including scientific and indigenous.
 12. The ecosystem approach should involve all relevant sectors of society and scientific disciplines.
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Table 2 Articles or web pages referring to either ecosystem services or natural capital.

Note: wild card characters were used to search for plurals.

	“ecosystem services”	“natural capital”	Ratio ecosystem services: natural capital
Google	1,190,000	493,000	2.4
Google Scholar	55,800	35,800	1.6
Web of Knowledge	3,338	659	5:1
Web of Knowledge with “AND soil*” as an additional qualifier	793	56	14:1

Table 3a. Soil mass stocks and potential soil data sets that might contribute to baseline stock assessment. Major data sources include (i) the land information system (LandIS); the National Soil Map (NATMAP); NSI resampling survey (NSI); Countryside survey (CS); Representative Soil Sampling Survey (RSSS); the Environmental Change Network (ECN), and the forest soil monitoring (Biosoil). Defra Soil functions: 1) Food and fiber production, 2) Environmental interaction, 3) Biodiversity and habitat, 4) Protection of cultural heritage, 5) Platform for construction, 6) Raw material.

Soil Stocks	Drivers of Change	Data Sources	Comments
<p>Matter – solid Inorganic material</p> <p>Mineral stock Texture / mineralogy / soil depth / volume / mass /</p> <p>Link to soil functions: 1,2,3,4,5,6</p>	<p><i>Long time scale –</i> Weathering, bed rock lowering.</p> <p><i>Short-medium-long time scale –</i> Erosion through wind, precipitation or cultivation. Engineering and construction.</p>	<p><i>Quantity: Soil texture:</i> LandIS has original data. BGS has high resolution PSD data for East Midland region of England using G-BASE.</p> <p><i>Soil depth:</i> No systematic map of total soil / regolith depth is available for the UK. LandIS stops at ~1.2m. ECN will re-survey changes in soil horizon depths but only 12 sites nationally. BIOSOIL examines horizons of organic and mineral soils to a depth of 80cm.</p> <p><i>Quality: Soil mineralogy:</i> BGS has basic mineralogy data held in Soil Parent Material Map database. However, it is geology based rather than measured soil data.</p>	<p><i>Soil texture:</i> Is likely to be a reasonably static or very slowly changing dynamic variable. It could be substantially more spatially variable than LandIS sampling resolution. Landuse change may affect soil depth the most, particularly if soil becomes more susceptible to erosion. There is relatively little information on soil production rates. There is no current erosion map of Eng. & Wales, although Defra has undertaken monitoring programs in the past. Obtaining soil depth information may help with stock assessment.</p> <p><i>Mineralogy:</i> Very little information on rates of mineral weathering and natural fertility replacement for Eng. & Wales. Skolkloster classes designed to assess mineral soils short term acid buffering capacity have been used to identify and map soils sensitive to acidification.</p>
<p>Matter – solid Inorganic material</p> <p>Nutrient stock Link to soil functions: 1,2,3,6</p>	<p>Nutrient mining from crop production, loss of topsoil from erosion, leaching, change of vegetation.</p>	<p><i>Quantity:</i> LandIS contains K and P, extractable K measured through RSSS scheme for agricultural land. CS monitors soil P and mineral N. Biosoil monitors N as well as Ca, Mg, K, H, & Al.</p>	<p>Link between nutrient source areas, mineral weathering rates and soil nutrient stocks not well established. Monitoring of soil micronutrients is sparse.</p>
<p>Matter – solid Organic material</p> <p>Organic Carbon Link to soil functions: 1,2,3,6</p>	<p>Landuse change, especially vegetation or cultivation practice. Possible climate change response via bacterial Q₁₀ relationships. Water logging (increase), aeration (decrease).</p>	<p><i>Quantity:</i> Both LandIS and the CS have undertaken the resampling of SOC. Biosoil monitors forest soil C.</p> <p><i>Quality:</i> It is yet to be determined how to assess this, studies on fractions may help.</p>	<p>NSRI indicated soil carbon stocks were decreasing, CS couldn't confirm this.</p>
<p>Matter – solid Organic material</p> <p>Organisms Link to soil functions: 1,2,3,6</p>	<p>Pollution, landuse change, especially vegetation and cultivation practice, soil physico-chemical properties, climate change.</p>	<p><i>Quantity:</i> CS records state and change of selected broad invertebrate taxa and more specifically mites, springtails and collembolan.</p>	<p>Initial research suggests that soil microbial population spatial distribution may be correlated with soil pH. Maps of soil organisms have not generally been developed.</p>
<p>Matter – Soil liquid</p> <p>Soil water content Link to soil functions: 1,2,3,4,5</p>	<p>Climate change, land use and management change.</p>	<p><i>Quantity:</i> LandIS has information relating to soil series soil water content at different suctions in its inventory.</p> <p><i>Quality:</i> CS contains data for soil pH and its change. Some information on redox status can be determined from gleys in the LandIS data.</p>	<p>Soil moisture is the pool of water for life, it is an important environmental moderator by controlling soil microbial activity, gas content and redox.</p>
<p>Matter – Soil gas</p> <p>Soil gas content Link to soil functions: 1,2,3,4</p>	<p>Compaction changes in bulk density, changes in moisture regime.</p>	<p><i>Quantity:</i> No survey of soil gas composition undertaken. CS has information on bulk density from which porosity is determined. NSRI have bulk density values for soil series and horizons in LandIS</p> <p><i>Quality:</i> assessment of individual gasses, such as O₂, CO₂, CH₄ and NO_x is difficult but new sensor technologies may help.</p>	<p>Oxygen is required for plant growth. Soils form an important buffer for climate regulation and are a big sink/potential source for greenhouse gases.</p>

Table 3b. Soil energy stocks and potential soil data sets that might contribute to baseline stock assessment.

Soil Stocks	Drivers of Change	Surveys	Comments
Thermal Energy Soil temperature Link to soil functions: 1,2,3,4	Climate change, changes in moisture regime from drainage/wetting.	<i>Quantity:</i> The Met Office monitors soil temperature at some of its weather station network. ECN sites also include soil temperature monitoring.	Will be one of the major changes with climate change. The MET office has soil temperature maps (0-30cm) averaged over 30 years for each month and season.
Biomass energy Organic carbon Link to soil functions: 1,2,3,4	Landuse change, cultivation practice, clay content. Possible climate change response via bacterial Q ₁₀ relationships	<i>Quantity:</i> Both NSRI and the CS have undertaken the resampling of SOC. Biosoil monitors forest soil C. <i>Quality:</i> It is yet to be determined how to assess this.	NSRI indicated soil carbon stocks were decreasing, CS couldn't confirm this.

Table 3c. Soil organization / spatio-temporal structure of stocks and potential soil data sets that might contribute to baseline organization assessment.

Soil Stocks	Drivers of Change	Surveys	Comments
Physicochemical structure Aggregation / soil structure Link to soil functions: 1,2,3,5	Change in carbon status, organism dynamics, or wetting and drying regime. Management and trafficking. In coastal and high pH areas, sodium %.	LandIS would include this information at the time of sampling.	Soil structure is difficult to quantify, aggregate stability may be one direct method, determining the water release characteristic may provide an indirect method.
Biotic structure Biological diversity, food web structure and community organization Link to soil functions: 1,2,3	Pollution, landuse change / management, wetting and drying climate change,	The CS monitors soil invertebrates and makes measures of biodiversity. Information of foodweb structure may develop this area.	Reports results according to Broad Habitat, aggregate vegetation class and soil organic matter
Spatial-temporal Structure Landscape metrics Link to soil functions: 1,2,3,5	Erosion, construction	LandIS contains soil boundary information based on surveyor interpretation.	We have little understanding of how linear features, ranging from hedgerows to roads, impact soil biological function and movement and flow of mass and energy through the landscape.

Table 4. The Global Soil Partnership has proposed focusing on five main pillars of action to achieve its objectives (FAO, 2011)

PILLARS OF THE GLOBAL SOIL PARTNERSHIP	
1.	Harmonizing and establishing guidelines and standards of methods, measurements and indicators
2.	Strengthening of soil data and information: data collection, validation, reporting, monitoring and integration of data with other disciplines
3.	Promoting targeted soil research and development focusing on identified gaps and priorities and synergies with related productive, environmental and social development actions
4.	Promoting sustainable management of soil resources and improved global governance for soil protection and sustainable productivity
5.	Encouraging investment and technical cooperation in soils

Figure 1. The coupled human-environment system; with solar radiation and heat from the earth's core powering the system. Stocks flow from the environment to the anthroposphere when harvested (S-F 1&2); internally between abiotic and biotic pools shown here for the pedosphere (S-F 3&4), and across boundaries between earth system compartments, with the outer boundary of the pedosphere illustrated by S-F 5&6. Stock-flows are tangible, representing stocks which are the natural capital, and the flows of this capital that can be internal or external to a sphere. Fund-services are the intangible emergent services that result from stock-flow processes, in the human sphere (7) these may range from water regulation by dams and weirs to cultural services such as gardens. Each environment sphere provides a supporting service of ecosystem formation (9), in this case soil formation and a range of final regulating and cultural ecosystem services of human benefit (11). Intermediate services (8&10) are also generated, but as yet are not recognized as providing direct benefits to human welfare. The stock-flows represent the ecological or earth system infrastructure, which in combination with the resulting fund-services form an ecosystem service supply chain.

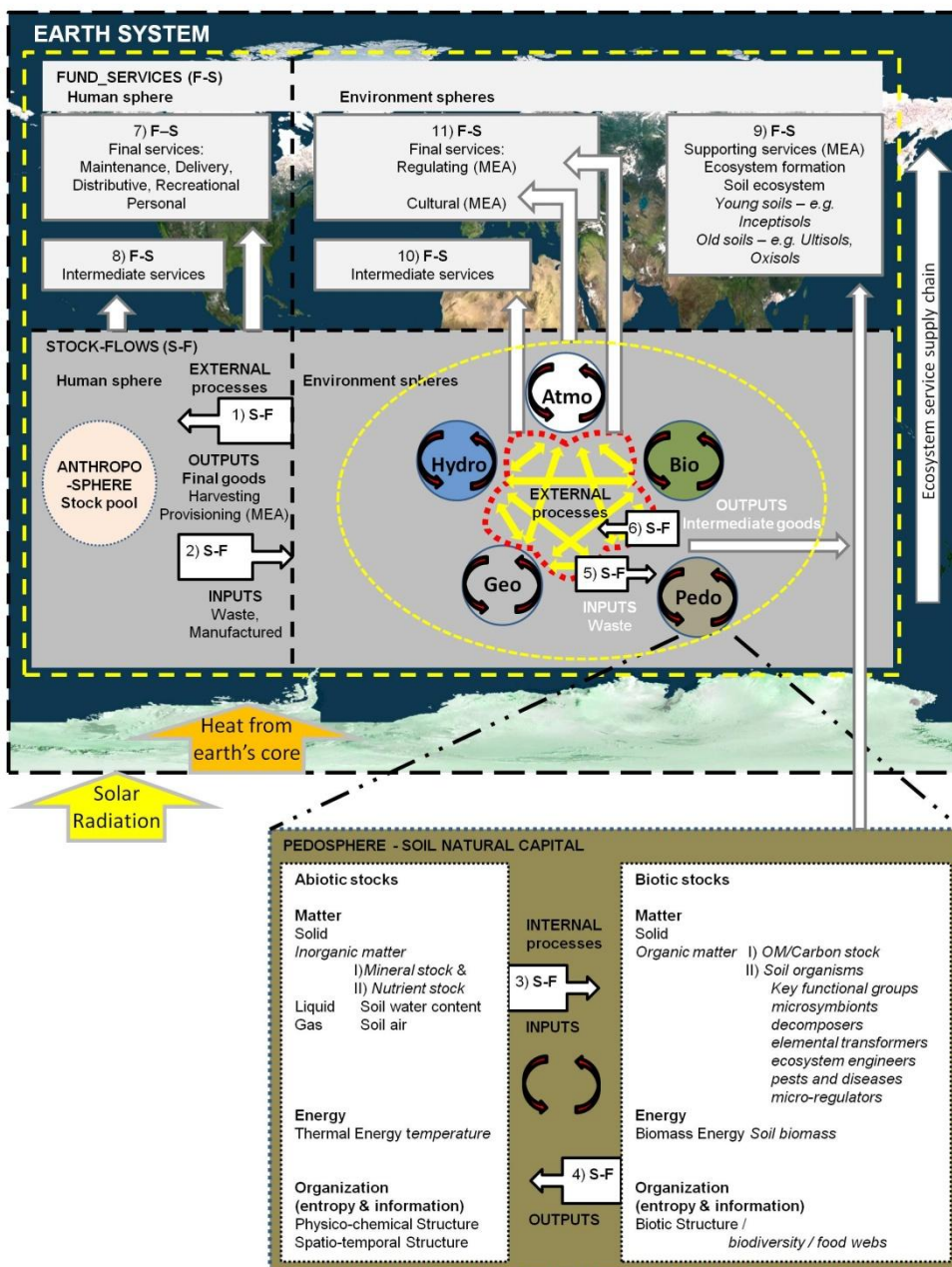


Figure 2. A more detailed view of the stock-flows and fund-services derived from the pedosphere and linked to the MEA (2005) typology; the numbers link to the compartments in fig.1. Waste processing services are an important fund-service and occur at all scales, it is worth remembering that they operate at a fixed rate with a fixed absorption capacity and are highlighted below.

<p>1) Stock - Flow</p> <p>Provisioning goods (MEA) Topsail Peat Turf Sand / clay minerals Biomedical Resources Bio-resources, soil stabilizers, biological crust</p>
<p>11) Fund – Service</p> <p>Regulating services (MEA) Climate regulation <i>Buffering extremes of cold or heat</i> <i>GHG regulation</i> Hydrological regulation <i>Buffering floods and droughts</i> <i>Water filtration</i> Hazard regulation <i>Structural support buffering, shrink/swell</i> <i>Landslides / slumps</i> <i>Liquifaction</i> <i>Dust emissions</i> Disease Regulation <i>Human pathogens</i> <i>Disease transmission & vector control</i> Biodiversity <i>Gene pool</i> <i>Pathogens</i></p> <p style="padding-left: 40px;">Waste processing services Cleaning, degradation, transformation</p> <p>Cultural services (MEA) Sports field recreational surfaces Preservation of historic artifacts Landscape aesthetics Burial grounds</p> <p>9) Fund – Service</p> <p>Supporting (MEA) Soil formation and genesis</p>