

1  
2  
3

4 **Soil Conservation in the 21<sup>st</sup> Century: Why we need Smart**  
5 **Agricultural Intensification**

6

7 Gerard Govers<sup>1</sup>, Roel Merckx<sup>1</sup>, Bas van Wesemael<sup>2</sup>, Kristof Van Oost<sup>2</sup>

8

9 <sup>1</sup> KU Leuven, Department of Earth and Environmental Sciences, Celestijnenlaan 200E, 3001 Leuven, Belgium

10 <sup>2</sup> Université Catholique de Louvain, Earth and Life Insititute, 3 Place Louis Pasteur, B-1348 Louvain-la-Neuve,  
11 Belgium

12 *Correspondence to:* Gerard Govers (gerard.govers@kuleuven.be)

13

14

15 **Abstract.** Soil erosion severely threatens the soil resource and the sustainability of agriculture. After decades of  
16 research this problem persists, despite the fact that adequate technical solutions now exist for most situations. This  
17 begs the question as to why soil conservation is not more rapidly and more generally implemented. Studies show  
18 that the implementation of soil conservation measures depends on a multitude of factors but it is also clear that  
19 rapid change in agricultural systems only happens when a clear economic incentive is present for the farmer.  
20 Conservation measures are often more or less cost-neutral which explains why they are often less generally adopted  
21 than expected. This needs to be accounted for when developing a strategy on how we may achieve effective soil  
22 conservation in the Global South, where agriculture will fundamentally change in the next century. In this paper  
23 we argue that smart intensification is a necessary component of such a strategy. Smart intensification will not only  
24 allow to make soil conservation more economical, but will also allow to make significant gains in term of soil  
25 organic carbon storage, water efficiency and biodiversity, while at the same time lowering the overall erosion risk.  
26 While smart intensification as such will not lead to adequate soil conservation, it will facilitate it and, at the same  
27 time, allow to offer the farmers of the Global South a more viable future.

## 28 **Introduction**

29 The terrestrial land surface provides critical services to humanity and this is largely possible because soils are  
30 present. Humanity uses ca. 15 million km<sup>2</sup> of the total Earth's surface as arable farmland (Ramankutty et al., 2008).  
31 Besides this, ca. 30 million km<sup>2</sup> is being used as grazing lands: on all these lands grow plants which are either  
32 directly (as food) or indirectly (as feed, fibre or fuel) used by humans for nutrition and a large range of economic  
33 activities. Agricultural areas, especially areas used as arable land, have often been selected because they have soils  
34 that make them suitable for agriculture. But it is not only the soils on agricultural land that provide humanity with  
35 essential services. Also on non-agricultural land soils provide the necessary rooting space for plants, store the  
36 water necessary for their growth and provide nutrients in forms that plants can access. Both on agricultural and  
37 non-agricultural land soils are host to an important fauna whose diversity is, by some measures, larger than that of  
38 its aboveground counterpart (De Deyn and Van der Putten, 2005). Both on agricultural and non-agricultural land  
39 soils store massive amounts of organic carbon, the total amount of which (ca. 2500 Gt, Batjes, 1996; Hiederer and  
40 Köchyl, 2012) is much larger than the amount of carbon present in the atmosphere (ca. 800 Gt). Importantly,  
41 organic carbon storage per unit area is generally much higher on non-agricultural land (Poeplau et al., 2011;  
42 Hiederer and Köchyl, 2012). By allowing plants to grow, soils significantly contribute to the terrestrial carbon  
43 sink, which removes an amount equal to 30-40% of the carbon annually emitted by humans from the atmosphere  
44 (Le Quere et al., 2009). Soils, both those on agricultural and non-agricultural lands, are therefore a vital part of  
45 humanity's global life support system, just like the atmosphere and the oceans. An Earth without soils would be  
46 fundamentally different from the Earth as we know it and would, in all likelihood, not be able to support human  
47 life as we know it.

48 No further arguments should be necessary to protect soils from the different threats posed to them by modern  
49 agriculture and other human activities. Yet, as is the case with many other natural resources, soils are under  
50 intensive pressure. Organic carbon loss, salinization, compaction and sealing all threaten the functioning of soils  
51 to different extents in different areas of the world. One of the most important and perhaps the ultimate threat posed  
52 to soils is accelerated erosion due to agricultural disturbance. When soils are used for farming their natural  
53 vegetation cover is removed and they are often disturbed by tillage. The result is that, under conventional tillage,  
54 erosion rates by water on arable land are, on average, up to two orders of magnitude higher than those observed  
55 under natural vegetation. This acceleration creates a major imbalance as soil production is outstripped by soil  
56 erosion by a factor 10-100 so that soil is effectively mined (Johnson, 1987; Montgomery, 2007; Vanacker et al.,  
57 2007b). Eroded soil is, in many cases, truly lost and cannot be restored (although there are exceptions to this rule),  
58 which explains why land prices in areas heavily affected by erosion may remain lower than expected, even when  
59 excessive erosion has been halted for several decades (Hornbeck, 2012).

60 It is rather surprising that agricultural soil erosion still is such an important problem. Pre-industrial societies such  
61 as the Inca already understood that erosion threatened agricultural productivity and used soil conservation  
62 techniques such as terracing for centuries (Krajick, 1998). In France, environmental degradation by excessive  
63 water erosion of mountain hillslopes literally ruined the livelihood of entire mountain communities at the end of  
64 the 19<sup>th</sup> century (Robb, 2008). A similar situation developed in Iceland where excessive wind and water erosion  
65 forced entire villages to be abandoned in the same period. In both countries overexploitation of the natural  
66 environment by subsistence farmers through excessive deforestation and overgrazing were key factors. Both  
67 countries responded to this situation: in Iceland the first soil conservation service of the world was founded in

68 1907 (Arnalds, 2005), while France started an extensive programme to restore its mountain environments (RTM)  
 69 as early as 1860 (Lilin, 1986). In the United States, the Dust Bowl years (1930s) moved the erosion problem high  
 70 up the political agenda: President Franklin Roosevelt not only erected a Soil Conservation Service but also,  
 71 famously, said ‘A nation that destroys its soils destroys itself’ (FAO and ITPS, 2015).

72 One might therefore expect that, by now, detailed information would exist on the status of the global soil resource  
 73 and the necessary measures would have been taken to stop soil degradation due to human action and/or mitigate  
 74 the consequences. Yet, this is clearly not the case: recent estimates of human-induced agricultural erosion amount  
 75 to 25-40 Gt yr<sup>-1</sup> for water erosion, ca. 5 Gt yr<sup>-1</sup> for tillage erosion and 2-3 Gt yr<sup>-1</sup> for wind erosion (Van Oost et al.,  
 76 2007; Govers et al., 2014). Measured soil production rates are, on average, ca. 0.036±0.04 mm yr<sup>-1</sup> (Montgomery,  
 77 2007) and are even lower on most agricultural soils because agricultural soils have a certain thickness and soil  
 78 production rates decrease with increasing soil depth (Stockmann et al., 2014). Thus, over all agricultural land  
 79 (arable and pasture) total soil formation would amount to maximum ca. 2 Gt yr<sup>-1</sup> which implies that the global soil  
 80 reservoir is depleted by erosion at a rate which is ca. 20 times higher than the supply rate. Although these numbers  
 81 are only an approximation (for instance, they do not account for the fact that eroded soil may be re-deposited on  
 82 agricultural land) they clearly illustrate that we are still far away from a sustainable situation: the rate at which the  
 83 soil resource is being depleted is, over the longer term, a clear threat to agricultural productivity (FAO and ITPS,  
 84 2015). The loss of mineral soil is not the only issue: soil erosion also mobilises 23-42 Tg yr<sup>-1</sup> of nitrogen and 14-  
 85 26 Tg yr<sup>-1</sup> of phosphorus (Quinton et al., 2010). These numbers may be compared with the annual application rate  
 86 of mineral fertilizers, which are ca. 122 Tg yr<sup>-1</sup> for N and ca. 18 Tg yr<sup>-1</sup> of mineral P respectively. At 2013 USA  
 87 mineral fertilizer prices of ca. 1.35 USD (kg N)<sup>-1</sup> and ca. 4.75 USD (kg P)<sup>-1</sup>, ([http://www.ers.usda.gov/data-](http://www.ers.usda.gov/data-products/fertilizer-use-and-price.aspx)  
 88 [products/fertilizer-use-and-price.aspx](http://www.ers.usda.gov/data-products/fertilizer-use-and-price.aspx)) the annual amount of fertilizers mobilised by soil erosion is equivalent to  
 89 ca. 35 billion US \$ for N and ca. 80 billion US \$ for P: this is a significant financial loss, even if one considers that  
 90 the total global agricultural food production is nowadays valued at ca. 4000 billion US \$  
 91 (<http://faostat.fao.org/site/613/DesktopDefault.aspx?PageID=613#anchor>). Most of these soil and nutrient losses  
 92 take place in the hilly and mountain areas in the so-called Global South: a recent scientific appraisal by FAO and  
 93 the ITPS (the Intergovernmental Technical Panel on Soils) showed that erosion problems are still increasing in  
 94 Africa, Latin-America and Asia (FAO and ITPS, 2015). The situation is perceived to be improving in Europe and  
 95 North America (FAO and ITPS, 2015), albeit that also in these regions soil losses are often still above the tolerable  
 96 level (Verheijen et al., 2009). Thus, it is especially the agriculture in the Global South (Latin America, Africa, the  
 97 developing nations of Asia and the Middle East), where it is often one of the main economic activities, which  
 98 suffers excessively from these losses.

Region	Condition	Trend
Asia	Poor	Negative
Latin America	Poor	Negative
Near East and North Africa	Very Poor	Negative
Sub-Saharan Africa	Poor	Negative
Europe and Eurasia	Fair	Positive
Northern America	Fair	Positive
Southwest Pacific	Fair	Positive

99 **Table 1 Conditions and trends with respect to soil erosion as assessed by experts (data from FAO and ITPS, 2015)**

100 In this paper we reflect on why, despite these clear facts, effective soil conservation is not yet a done deal and what  
101 might be done about this. We argue that there is a need for a novel vision on soil conservation in the Global South,  
102 shifting the focus away not only from the technical issues of soil conservation but also away from soil conservation  
103 as such. Soil conservation efforts need to be framed into a general vision on how agriculture will develop in the  
104 South: this vision needs to account for soil protection, but must also guarantee food security and allow the  
105 development of an agricultural system that does provide a sufficient income to farmers. We will first assess  
106 possible reasons as to why soils do not yet get the protection they deserve. Thereafter we will discuss the building  
107 blocks of a vision on future soil conservation.

## 108 **The status of soil conservation**

### 109 **Do we have the necessary data to guide soil conservation?**

110 Investing in the application of soil conservation measures is only meaningful when erosion rates are higher than  
111 acceptable. This can most easily be established when erosion rates can reliably be quantified. Quantitative  
112 information is indeed available for North America and Europe (Cerdan et al., 2010; NRCS, 2010). However, the  
113 quality of our estimates of soil erosion rates by water for other areas on the globe is often poor. Sometimes,  
114 estimates are based on a limited number of data which are simply extrapolated to larger areas: this often leads to  
115 bias, simply because erosion rates are generally measured at locations where erosion intensity is much higher than  
116 average (Boardman, 1998; Cerdan et al., 2010). Also when models are used to make an extrapolation, estimates  
117 are often incorrect. This is due to two reasons: (i) the models that are used are often improperly calibrated, i.e.  
118 model parameters are set to values that are not appropriate for the location under consideration and (ii) the model  
119 parameterization may be correct but the spatial data used to drive the model are inappropriate. A typical example  
120 of the latter is when slope lengths are directly derived from a DTM so that the impact of slope breaks such as field  
121 borders is not accounted for (e.g. Yang et al., 2003). This can lead to a considerable overestimation of erosion  
122 rates (Desmet and Govers, 1996; Cerdan et al., 2010; Quinton et al., 2010). Erroneous predictions do not only  
123 make it difficult to identify the most vulnerable areas in which conservation measures are most urgent: they may  
124 also invalidate the cost-benefit evaluations of soil conservation programs and lead to disinformation of the general  
125 public about the extent and severity of the problem.

126 Although there is a clear need for better, quantitative data on erosion rates, the lack of such data is not the most  
127 important explanation as to why excessive soil erosion often still goes unchecked. While it may indeed be difficult  
128 to quantify erosion rates correctly, it is much easier to identify those areas where intense soil erosion is indeed a  
129 problem and where action is necessary, whatever the exact erosion rates are. This is, after all, what institutions  
130 such as the soil conservation services of Iceland and the United States did long before accurate erosion  
131 measurements were available. Simple visual observations on the presence of rills and gullies or wind deflation  
132 areas are clear indications that the implementation of conservation measures is necessary (Figure 1). Another  
133 reason why an exact quantification is not always necessary is that conservation measures generally are not  
134 proportional: Their implementation is most often of a yes/no type: one can decide whether or not to implement  
135 conservation tillage, but not by how much.



136

137 **Figure 1. The presence of a dense network of rills and of significant deposition at the footslope (here in Huldenberg,**  
138 **Belgium in July 2006) is a such sufficient proof for excessive soil erosion (in this case erosion exceeded 100 t ha<sup>-1</sup> in a**  
139 **single event)**

140 **Do we have the necessary technology for soil conservation?**

141 There is no doubt that soil conservation technology has matured over the last decades: we now have the tools to  
142 effectively reduce erosion rates to acceptable levels in many, if not all, agricultural systems. Conservation tillage  
143 is the tool of choice in many areas, especially in the Americas. This is hardly surprising: erosion plot research has  
144 consistently shown that water erosion rates under conservation tillage are reduced by one to two orders of  
145 magnitude in comparison to conventional systems (Montgomery, 2007; Leys et al., 2010). Moreover, the  
146 effectiveness of conservation tillage as calculated by plot studies is likely to be underestimated: for various reasons  
147 the effectiveness of conservation does increase if the slope length increases (Leys et al., 2010). As a consequence,  
148 water erosion rates under conservation tillage on moderate slopes are generally very low (< 1 t ha y) and often  
149 comparable to those occurring under natural vegetation (Montgomery, 2007). Conservation tillage may also be  
150 used to drastically control wind erosion not only because residue cover does reduce the shear stress to which soil  
151 particles are exposed but also because the presence of residue helps to keep the surface soil layer moist, thereby  
152 increasing its shear strength.

153 Conservation tillage is not always the best tool. It may be difficult or impossible to apply with certain crops, such  
154 as potatoes grown on ridges, and/or difficult to introduce into specific agricultural systems as it may affect the  
155 overall workload or the gender balance of the workload (Giller et al., 2009). It may also not be sufficient to  
156 implement conservation tillage as processes such as gully erosion may not be effectively controlled and may in  
157 some cases even be enhanced by conservation tillage as the latter is much more effective in reducing erosion than  
158 in reducing surface runoff (Leys et al., 2010). However, also in such cases technological solutions do exist: they  
159 can consist of infrastructural measures such as stone bunds and terrace building in combination or vegetation  
160 measures such as grassed waterways, but also proper land use allocation can make a significant difference. Water

161 and wind erosion rates can often be reduced to acceptable levels through the use of such measures in combination  
162 with modifications of tillage techniques and crop rotations (Sterk, 2003; Valentin et al., 2008; Nysse et al., 2009).  
163 Not only arable land can be affected by excessive erosion. Grazing lands may suffer from a drastic reduction in  
164 vegetation cover due to overgrazing and compaction, again resulting in excessive water and/or wind erosion with  
165 rates up to two orders of magnitude higher than those observed under natural conditions (Vanacker et al., 2007b).  
166 Reduction of grazing pressure (at least in a first stage) and the introduction of controlled grazing are key strategies  
167 (i) to restore the vegetation cover and (ii) to allow these lands to become productive again so that they can be  
168 sustainably used (Mekuria et al., 2007). Such measures can be further supported by the planting of trees (Sendzimir  
169 et al., 2011). Reforestation may also be a solution as it reduces erosion rates to near-natural levels but it has evident  
170 implications for the type of agriculture that can be supported (Vanacker et al., 2007b). Thus, as is the case on  
171 arable land, the key to erosion reduction on grasslands is in most cases the maintenance or restoration of a good  
172 vegetation cover, possibly supported by technical measures.

173 Erosion in agricultural areas is often not directly related to agricultural activities but also to the infrastructure  
174 related to these activities such as roads and field boundaries. Unpaved roads on sloping surfaces are not only  
175 important sources of sediment in many agricultural areas (Rijsdijk et al., 2007; Vanacker et al., 2007a) but also in  
176 cities (Imwangana et al., 2015). Water is often concentrated at field boundaries thereby leading to gully formation  
177 (Poesen et al., 2003). Again, the necessary technological know-how to control such erosion phenomena is  
178 available: check dams, better water drainage infrastructure, the implementation of field buffer zones and a better  
179 landscape organisation all help to reduce sediment production on road networks and in built-up areas.

#### 180 **Why then is soil conservation not more generally adopted?**

181 Thus, neither the lack of conservation technology nor the lack of data on the erosion hazard can fully explain why  
182 efficient soil conservation measures are still not implemented on most agricultural land, especially in the Global  
183 South. It has indeed long been clear that several factors other than (the lack of) scientific knowledge or data hamper  
184 the adoption of conservation tillage. These factors include the training level of the farmer, the farm size and work  
185 organisation as well as access to information. However, a thorough analysis by Knowler and Bradshaw (2007)  
186 showed that the effect of these variables was often ambiguous (when different studies are compared) and that few,  
187 if any, variables showed a consistent effect. One might conclude from this that changing farming practices must  
188 be inherently difficult, as our understanding of controlling factors is relatively poor and many barriers to the  
189 adoption of novel technology need to be overcome. This is not only a problem in the Global South: also in Europe  
190 the adoption of conservation tillage is slow in many countries due to a multitude of factors, including the fact that  
191 soil tillage is deeply rooted in the culture of many farmers (Lahmar, 2010).

192 Clearly, farming systems are, to some extent, 'locked in': they rely on well-trying technology, division of labour  
193 and crop types and are therefore difficult to change. There are, nevertheless, also cases where farming systems  
194 change rapidly and conservation technology is quickly adopted. Once the necessary technology was available,  
195 conservation tillage spread very rapidly through most of Argentina and Brazil: in Argentina, it took ca. 20 years  
196 (from 1990 to 2010) to bring ca. 80% of the arable land under no-till (Peiretti and Dumanski, 2014), thereby  
197 effectively halting excessive soil erosion on most of the arable land of the country. In Brazil, more than 25 million  
198 ha of land was under no-tillage in 2006, whereas the technique was virtually unused before 1990 (Derpsch et al.,  
199 2010). Rapid changes in agricultural systems are not limited to the adoption of conservation tillage. When

200 subsistence farmers in remote areas gain access to profitable markets, very rapid changes can occur, even in areas  
201 where existing technology is poor: such changes can have very negative effects in terms of soil degradation rates  
202 as a switch to cash cropping may introduce crops to which a much higher erosion risk is associated (Valentin et  
203 al., 2008). Thus, while cultural and technological barriers to change certainly do exist, farmers are most certainly  
204 capable of rapid change. Whether such rapid change occurs critically depends on whether farmers think change  
205 will bring them a personal gain.

206 This is where the problem lies. Under some conditions, the adoption of conservation technology is indeed clearly  
207 economically beneficial to the farmer: this appears to be true for large farming operations in (sub-) tropical regions  
208 growing cash crops such as soy beans (Peiretti and Dumanski, 2014). But in most other cases the direct benefits  
209 of the implementation of conservation agriculture and/or other soil conservation measures are small, if they exist  
210 at all. This appears to be the case for both large-scale mechanised agriculture in the temperate zone as well as for  
211 marginal hillslope farming in developing countries (Knowler et al., 2001). In both scenarios, potential savings are  
212 offset by additional costs: in mechanized systems the cost of machinery and agrochemicals offsets savings in fuel  
213 costs (Zentner et al., 1996; Janosky et al., 2002) while in traditional hillslope farming extra work hours are needed  
214 to maintain conservation structures and some land has to be sacrificed to implement these structures, thereby  
215 reducing overall yields (Nyssen et al., 2007; Quang et al., 2014). Importantly and contrary to common belief, crop  
216 yields do not rise significantly in conservation systems if no additional inputs are provided: this is true for advanced  
217 technological systems (Van den Putte et al., 2010; Pittelkow et al., 2015) as well as for tropical smallholder farming  
218 (Brouder and Gomez-Macpherson, 2014). As a consequence, farmers often do not have direct incentives to  
219 implement soil conservation measures and change becomes difficult to implement.

220 One may argue that benefits should not only be considered at the level of the individual farmer, but also at the  
221 societal level, where soil conservation may generate co-benefits. Often carbon storage and biodiversity protection  
222 under conservation systems are mentioned as important ecosystem services for which farmers could be paid.  
223 Research in the last decade has consistently shown that carbon storage gains in conservation systems are lower  
224 than was anticipated two decades ago and is generally well below 1 Mg C ha<sup>-1</sup> yr<sup>-1</sup> ((Oorts et al., 2007; Angers and  
225 Eriksen-Hamel, 2008; Christopher et al., 2009; Eagle et al., 2012; Govers et al., 2013). Furthermore, paying  
226 farmers to store carbon would only be viable at much higher carbon prices than the current market prices, which  
227 are around 10-15 USD ton<sup>-1</sup> (Grace et al., 2012; Govers et al., 2013). Paying farmers at current market prices can  
228 only generate a relatively small economic benefit for the farmer and prices would have to rise significantly for soil  
229 carbon storage to become an important element on the farmers' balance sheet. On the other hand, soil conservation  
230 generally has a positive impact on (soil) biodiversity on the farm land as soils are less frequently disturbed (Mader  
231 et al., 2002; Verbruggen et al., 2010). Where agriculture is interspersed with densely populated areas, additional  
232 co-benefits may consist of a reduction of flooding and/or siltation of sewage systems and water treatment plants,  
233 which are important problems in many areas in Europe (Boardman et al., 1994). These benefits, however, are  
234 difficult to convert to financial income for the farmer. This is not only because the economic value of increased  
235 biodiversity on farmland is difficult to quantify but also because such on-farm benefits in biodiversity have to be  
236 weighed against possible off-farm losses (see below). The reduction in flooding risk, on the other hand, will  
237 generally not be considered as a benefit by society but rather as damage repair: the problems were caused by  
238 agriculture in the first place.

239 **The way forward**

240 How then should we proceed to stimulate a more rapid adoption of soil conservation measures to protect the  
241 world's soil resource? The answer to this question will obviously depend on the characteristics of the local agro-  
242 ecological system. Agricultural systems show a large variety so that not only the factors impeding the adoption of  
243 conservation tillage vary locally (Knowler and Bradshaw, 2007) but also the tools that societies have at their  
244 disposal to reduce it.

245 Western societies with highly developed information systems tackle the problem by a policy combining regulation  
246 (e.g. by forbidding the cultivation of certain crops on land that is very erosion-prone) and subsidies or  
247 compensations in combination with well-guided campaigns to inform farmers on the potential benefits and risks  
248 for themselves as well as for the broader society. Such combined approaches do have demonstrable success in  
249 various parts of Europe and North America where farmers are not only well trained and highly specialized but also  
250 depend to a large extent on subsidies, giving the administrations the necessary financial leverage to stimulate or  
251 even coerce farmers (Napier et al., 1990). As a result erosion rates in North America have gone down considerably  
252 over the last decades and are still declining (Kok et al., 2009). One may therefore assume that in these societies  
253 erosion rates can be reduced to tolerable levels provided that the necessary policies are maintained and/or  
254 strengthened. Countries having a strong central government that can impose decisions on land use and soil  
255 conservation, as is the case in China, can successfully reduce erosion: the excessive erosion rates on the Chinese  
256 Loess Plateau were strongly reduced through massive government programs implementing erosion control  
257 measures (Chen et al., 2007; Zhao et al., 2016)

258 These approaches are, at present, not possible in most countries of the Global South. Many governments in the  
259 Global South are not able to implement a successful soil conservation policy as they do not dispose of the necessary  
260 data and/or the necessary political and societal instruments to do so. At first sight it may therefore appear unlikely  
261 that soils will become effectively protected in most of the developing world within a foreseeable time span. Yet  
262 this conclusion foregoes the fact that agriculture in the Global South, and especially in sub-Saharan Africa, will  
263 see fundamental changes in the next decades. At least three fundamental tendencies can be identified that will  
264 change the nature of agriculture in the Global South in the 21<sup>st</sup> century: these should be accounted for when  
265 developing a vision on soil conservation.

266 *In many areas where soils are most seriously threatened, the human population will continue to grow strongly.* In  
267 the next decades, the locus of world population growth will shift in an unprecedented manner. Population growth  
268 in the North has stopped and many regions in the Global South will follow suit in the next decades: Asia is expected  
269 to reach its maximum population around 2050. China's population will peak around 2030 and that of India no later  
270 than 2070. Latin America will follow around 2060 (<http://esa.un.org/unpd/wpp/>, Lutz and KC, 2010; Gerland et  
271 al., 2014). Sub-Saharan Africa is a different matter: here the demographic transition started only after the Second  
272 World War and the population will continue to grow rapidly during most of the 21<sup>st</sup> century. As a result of these  
273 diverging tendencies the distribution of the world's population will have changed beyond recognition in 2100:  
274 Europe's share in the global population will have fallen from its maximum of ca. 22 % in 1950 down to ca. 6 %  
275 in 2100, while the share of Africa will rise from ca. 9 % in 1950 to ca. 39 % in 2100 (<http://esa.un.org/unpd/wpp/>).

276 *The population in the South will also become more urban.* By 2050 ca. 2/3 of the global population is expected to  
277 live in cities (as compared to ca. 55% at this moment). Urbanisation rates are especially high in Africa where the  
278 fraction of urban population is expected to increase from 40% in 2014 to 55% in 2050 and in Asia, where

279 urbanisation will increase from ca. 47.5% to ca. 65% over the same period (United Nations, 2014). There is no  
280 alternative for this evolution: despite all their problems, cities are the engines of modern economic development  
281 as they allow a population to create the added value that is so desperately needed through advantages of scale,  
282 intense interaction and exchange (Glaeser, 2011). This is the fundamental reason of the attractiveness of cities and  
283 the major factor explaining rural to urban migration: poor rural populations perceive the city as a place of  
284 opportunity and moving there as an opportunity to improve their own lives or at least those of their children  
285 (Perlman, 2006; Saunders, 2011). A consequence of this massive migration movement is that rural populations  
286 rapidly age and that the average farm worker is significantly older than the average non-farm worker (40 vs. 34  
287 years in Africa, <http://www.gallup.com/poll/168593/one-five-african-adults-work-farms.aspx>). Clearly the  
288 evolution sketched above is a generalisation: local dynamics depend, amongst others, on the presence of attractive  
289 labour opportunities in the cities and the local availability of land (Ellis-Jones and Sims, 1995).

290 It is not overly optimistic to expect that, while population growth continues, at the same time *these populations*  
291 *will gain in purchase power*. While incomes in southern Asia and especially sub-Saharan Africa are nowadays  
292 much smaller than those in the North, their growth rates are, fortunately, much bigger. For example, Ethiopia's  
293 economy has, over the last decade, consistently been growing at 8 to 10% per year, leading to a rise of the per  
294 capita Gross National Income from 110 US \$ (2015 dollars) in 2004 to 550 US \$ in 2015  
295 (<http://data.worldbank.org/country/ethiopia>).

296 Combined, these tendencies will lead to an increased market demand for food. Furthermore, diets will move away  
297 from a diet largely based on cereals towards a more varied (but not necessarily healthier) food palate in which  
298 meat is likely to have a larger share than is currently the case. Global estimates therefore sometimes predict that  
299 global food production (in terms of kcal) will increase more or less double in the first half of the 21<sup>st</sup> century  
300 (Tilman et al., 2011) but an increase in demand by 60-70% is more likely (Alexandratos and Bruinsma, 2012). As  
301 (relatively) more people will live in cities, there will be relatively fewer people working on the land to produce the  
302 food that is necessary. Furthermore, as most of future population growth will take place in sub-Saharan Africa,  
303 food demand will rise most rapidly in this area.

304 Thus, agriculture in the Global South will be fundamentally different from what it is now in less than a century.  
305 More food will have to be produced with less people and the increasingly urban population will more and more  
306 rely on markets to obtain the food it needs. This begs the basic question: how can we make sure that the soils  
307 necessary to produce all this food are sustainably managed and preserved for future generations?

### 308 **Soil conservation in a changing global context**

309 Two contrasting pathways can be followed to meet the expected increase in food demand in the Global South.  
310 More food can be produced either by extending the area over which current food production systems are applied  
311 or by agricultural intensification, i.e. by increasing the amount of food produced per unit of land.

312 Both pathways are, in principle, possible: until present, Africa has followed the first path. Over the last five  
313 decades, the increasing food demand of African populations has mainly been met by increasing the area used for  
314 farming, while yields per unit of surface area remained stable and very low (Henao and Baanante, 2006). This  
315 evolution sharply contrasts with the one observed in most parts of Asia: here agricultural production was mainly  
316 increased through intensification (Henao and Baanante, 2006). In Asia, the Green Revolution led to a dramatic

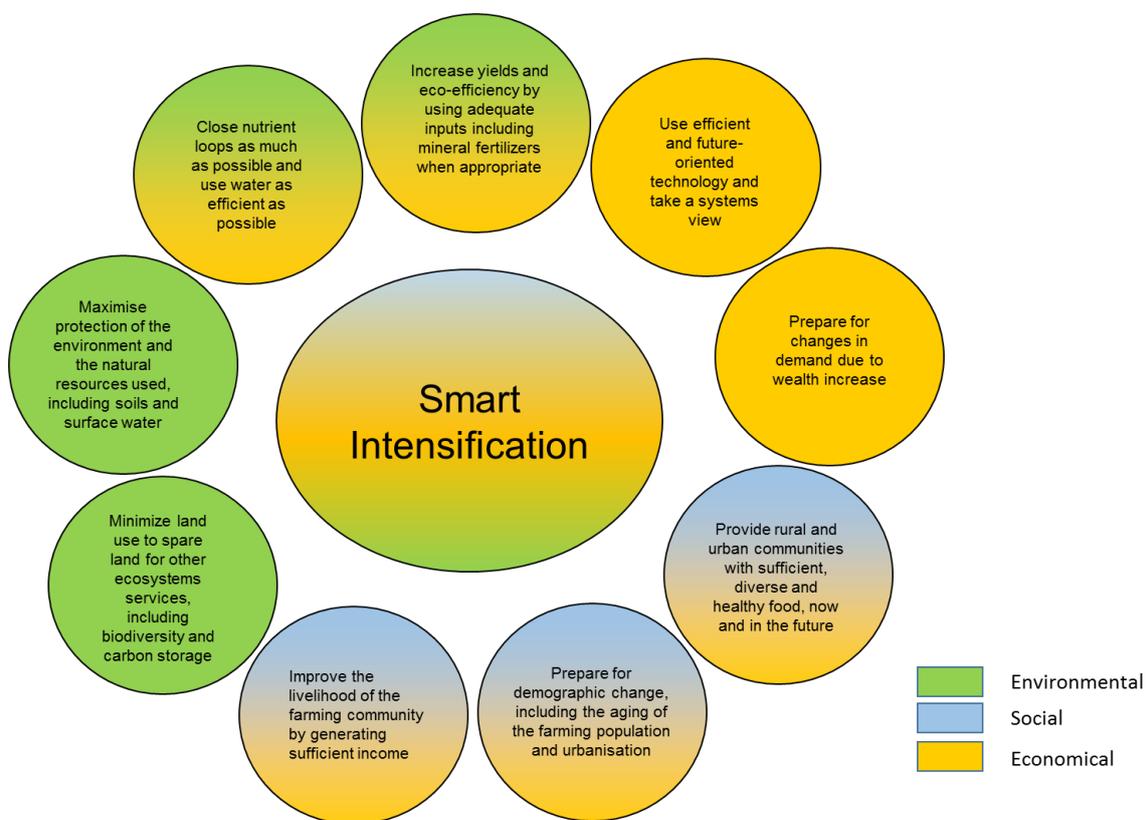
317 rise in agricultural yields through the combination of new crop varieties, better farming technology and the  
318 increased use of fertilizers. As a consequence, Asia now manages to feed its population much better than it did in  
319 1970: the amount of available kcal per person rose from ca. 2000 kcal to ca. 2400 kcal (South Asia) or even 3000  
320 kcal (East Asia) in 2005 (Alexandratos and Bruinsma, 2012) despite the fact that the amount of land used for  
321 agriculture did only marginally increase (Henao and Baanante, 2006) and despite the fact that the population in  
322 these regions increased from 0.98 billion to 1.53 billion (East Asia) and from 1.06 billion to 2.20 billion (South  
323 Asia) over the same period (<http://esa.un.org/unpd/wpp/>).

324 While the challenge for African agriculture is not dissimilar to that of Asia in the 1960s, Africa does not necessarily  
325 have to go down the same route. In principle, it could continue to follow the areal extension strategy policy for  
326 some time to come. At present, ca. 290 million ha of agricultural land is in use in Africa, but another 400 million  
327 ha of African land is suitable (good) or very suitable (prime) for agriculture (Alexandratos and Bruinsma, 2012).  
328 Therefore, there is scope for a strategy whereby significantly more land would be used for agriculture than is the  
329 case at present although this would pose important problems: a large fraction of the suitable land is located in  
330 politically unstable countries and/or far from existing markets (Chamberlin et al., 2014).

331 An extension strategy may, at first sight, be attractive from the point of view of soil conservation. One might  
332 indeed argue that this would be based on agricultural technology that has been in use for decades, and may  
333 therefore be best suited to increase agricultural production without causing excessive soil degradation. Indeed, the  
334 occurrence of erosion in mechanised, intensive agricultural systems is often attributed to the loss of traditional soil  
335 conservation methods (Bocco, 1991). Averting intensification and aiming at area extension may therefore seem a  
336 suitable solution to avoid excessive soil degradation as traditional farming methods can be maintained and  
337 optimised to be as environmentally friendly as possible. Many organisations do indeed stress environmental  
338 protection and sustainability as key issues to be addressed in the further development of African agriculture and  
339 explicitly state that Africa should indeed follow a path different from the Asian Green Revolution (De Schutter,  
340 2011).

341 While it is evident that we should learn from agricultural developments in Asia and avoid the dramatic negative  
342 effects the Asian Green Revolution had in some places, we argue here that tropical smallholder farming does need  
343 intensification for soil conservation to become successful. This intensification should be smart: it not only needs  
344 to be sustainable and to avoid jeopardising the capability of the natural resources to meet the needs of future  
345 generations. Intensification strategies should also maximise the opportunities of current and future farmers to  
346 generate an acceptable income by providing them with access to profitable markets and supplying them with the  
347 necessary knowledge and technology to produce for these markets. Smart intensification requires an approach that  
348 does not focus on the conservation of natural resources alone but also on the creation of added value using a future-  
349 oriented perspective and the quantity and quality of food production and supply. Clearly, improving the livelihood  
350 of the farmers and farming communities should be a key element. However, the capability of this farming  
351 community to provide the necessary agricultural supplies to an ever growing non-farming population also needs  
352 to be taken into account. Thus, it is not only important to consider the current socio-economic conditions but also  
353 how demographic and socio-economic conditions are likely to change in the future. We argue that smart  
354 intensification will not only make soil conservation more achievable but that it would also allow to reap additional  
355 environmental benefits that may be lost when a less intensive or less future-oriented development path is chosen.

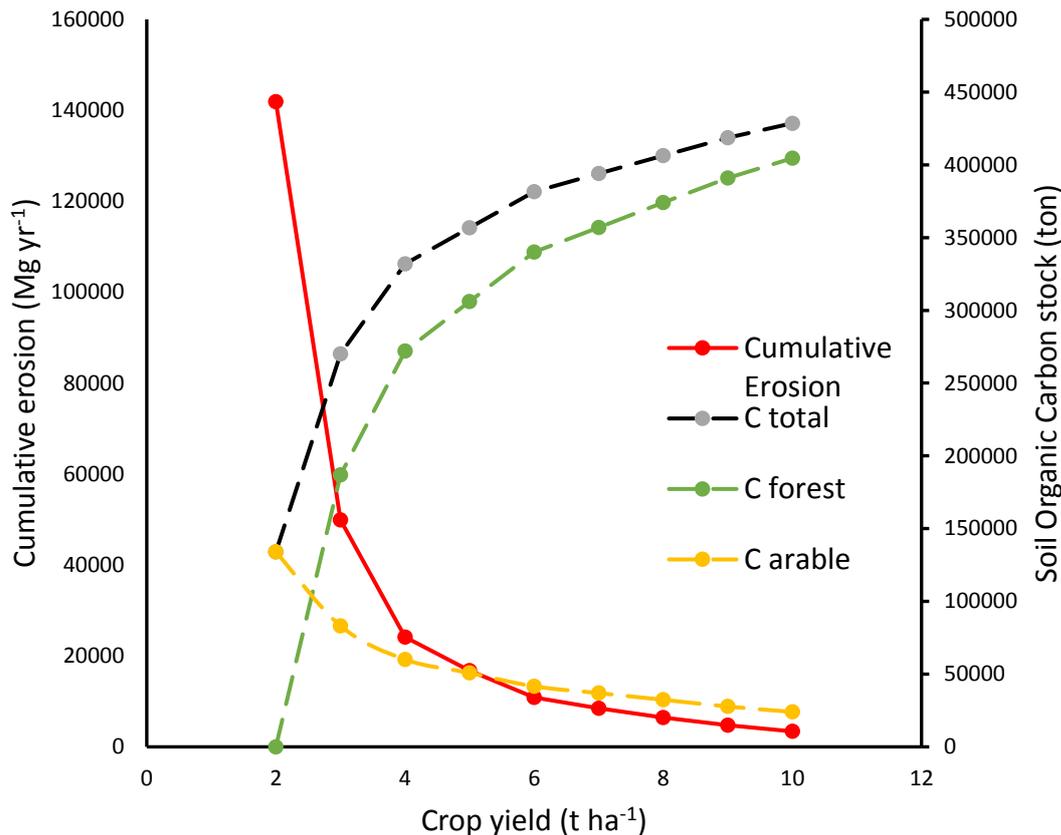
356 As is the case for ‘smart cities’, we do not believe a single, all-encompassing definition of smart intensification  
 357 can be formulated. However we summarized the components that we consider to be essential in Figure 2. In the  
 358 rest of the paper we focus the discussion on how soil conservation may benefit from smart intensification.



359  
 360 **Figure 2 Different aspects of smart agricultural intensification. Colouring refers to main reason as to why each aspect**  
 361 **is important.**

362 *Smart intensification will allow to spare the most erosion-prone land from agriculture thereby reducing landscape-*  
 363 *scale erosion rates.* When farmers select land for arable production, they will select the most suitable land that is  
 364 available. In general this means that, for obvious reasons, flatter land is preferred over steeper land. (Van Rompaey  
 365 et al., 2001; Bakker et al., 2005). Steep lands are generally much more difficult to cultivate than flatter areas and  
 366 yields can be expected to be lower in comparison to yields (for the same amount of inputs) on flat land, because  
 367 soils are intrinsically less productive and/or because soil productivity is negatively affected by accelerated erosion  
 368 (Stone et al., 1985; Ellis-Jones and Sims, 1995; Lu and van Ittersum, 2004). The combination of both effects (more  
 369 labour required and lower yields) invariably implies that the net returns of arable farming decrease with increasing  
 370 terrain steepness. The total amount of erosion as well as the amount of erosion per unit of crop yield will therefore  
 371 necessarily increase when area expansion is preferred over intensification (Figure 3, Figure 5).

372



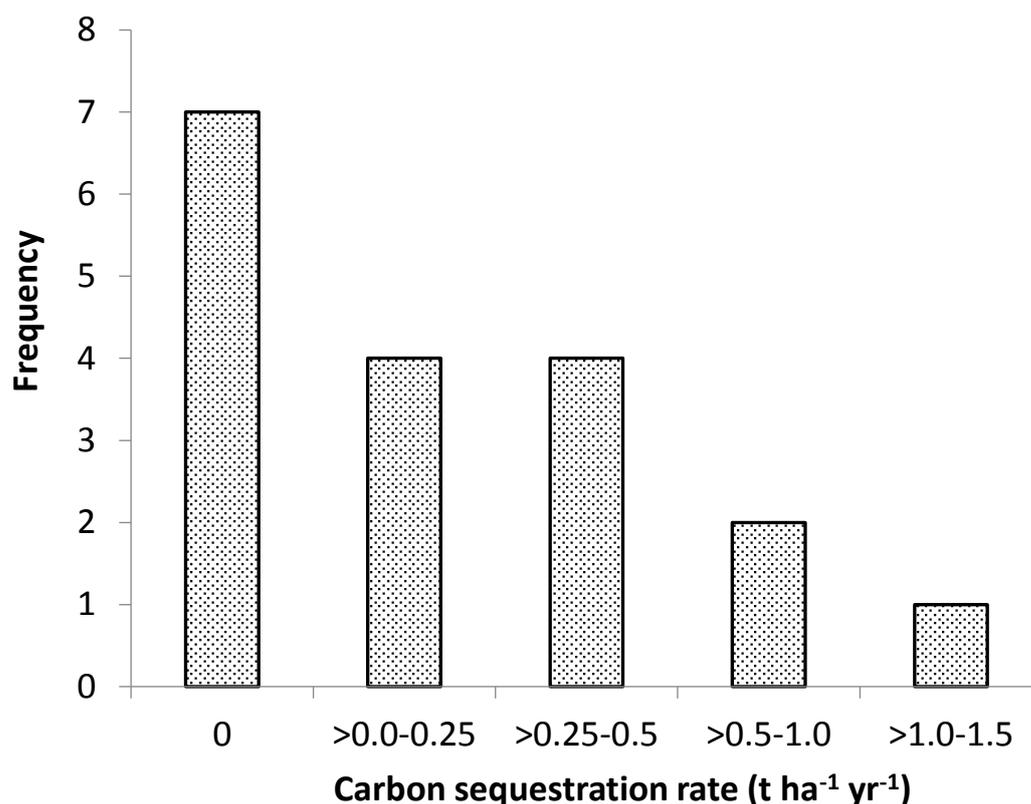
373

374 **Figure 3 Modelled cumulative erosion (left axis) and soil organic carbon stocks (right axis) vs. crop yield per ha for a**  
 375 **hypothetical test area of 2900 ha and assuming a total cereal production of 5000 ton. We assumed that slope gradients**  
 376 **(sin  $\theta$ ) were uniformly distributed between 0.02 and 0.58, i.e. an area of 100 ha in each 0.02 slope class. The crop yield**  
 377 **shown is the crop yield on a zero slope and relative crop yield ( $P$ ) is assumed to vary with slope:  $P=1-(\sin\theta)^{0.5}$ . Erosion**  
 378 **( $E$ ) is assumed to vary with slope gradient according to the slope function derived by Nearing (1997):**  
 379  **$E \sim -1.5+17/[1+\exp(2.3-6.1 \sin\theta)]$ , and an erosion rate of 10t ha<sup>-1</sup> y<sup>-1</sup> is assumed on a 0.09 slope. Soil organic carbon**  
 380 **stocks per unit area are assumed to be 40 t ha<sup>-1</sup> on arable land and 170 t ha<sup>-1</sup> under forest (Poaplau et al., 2011). The**  
 381 **total soil organic carbon stock ( $C$  total) in the area strongly increases with increasing crop yield because the gain in soil**  
 382 **organic carbon stocks on forested land ( $C$  forest) is much more important than the loss on arable land ( $C$  arable).**

383 Increasing agricultural production in Africa through areal extension alone would therefore imply that overall soil  
 384 losses would increase much more rapidly than agricultural production would. If, on the other hand agricultural  
 385 yields on good agricultural land would be improved, it may be possible to set aside some of the marginal land that  
 386 is currently used for arable farming. The somewhat counterintuitive result of this will be that, even if erosion rates  
 387 on the arable land that remains in production would increase due to intensification, the overall soil loss (at the  
 388 landscape scale) would still decrease (Figure 3).

389 *Smart intensification will conserve soil carbon which will, on its turn, reduce erosion risks.* Over the last decades,  
 390 a significant body of scientific literature has emerged on the potential of agricultural land to store additional soil  
 391 organic carbon through the use of appropriate management techniques. While studies do suggest that some gains  
 392 are indeed possible, most studies report modest gains at best. Reported average sequestration rates under  
 393 conservation tillage in Canada are between 0 and 0.14 t C ha<sup>-1</sup> yr<sup>-1</sup> in Canada (VandenBygaart et al., 2010) while  
 394 an average sequestration rate of 0.12 t C ha<sup>-1</sup> yr<sup>-1</sup> has been calculated for the USA (Eagle et al., 2012). In a study  
 395 covering 12 study sites in three Midwestern states of the USA Christopher et al. (2009) did not find any significant  
 396 increase in soil organic carbon storage under no-till in real farming conditions. Experimental studies also showed

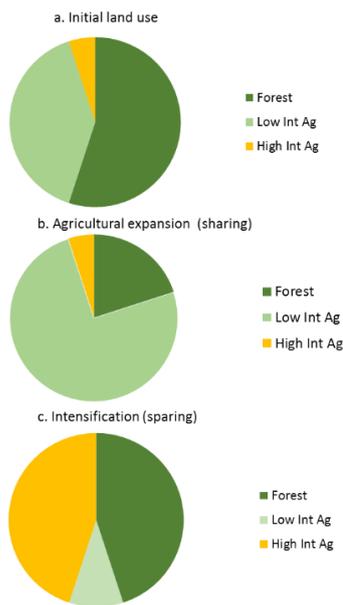
397 that under agroforestry gains in soil organic carbon are small, with an average of  $0.25 \text{ t C ha}^{-1} \text{ yr}^{-1}$  (Govers et al.,  
 398 2013). These findings contrast not only with claims in the literature (Ramachandran Nair et al., 2009), but also  
 399 with the observation that soil carbon stocks on natural (or undisturbed) land are generally much higher (often more  
 400 than three times higher) than those observed on arable land (e.g. Poeplau et al., 2011; Hiederer and Köchyl, 2012).



401  
 402 **Figure 4** Frequency distribution of experimentally observed carbon sequestration rates under agroforestry. Data from  
 403 **18** paired field studies in both (sub-)tropical and temperate climates (details and references of studies in (Govers et al.,  
 404 2013)). The average soil organic carbon sequestration rate reported over all 18 studies is  $0.25 \pm 0.33 \text{ Mg ha}^{-1} \text{ yr}^{-1}$ .

405 The latter is related to two main factors: (i) biomass is not removed from natural land, which results in larger  
 406 organic carbon inputs and (ii) these lands are not mechanically disturbed which reduces carbon respiration rates.  
 407 Thus, more soil carbon will be conserved when the extent of agricultural land is reduced and more land is preserved  
 408 under or restored towards natural conditions. An additional beneficial effect of the latter is that soil organic carbon  
 409 stocks may increase on agricultural land with increasing agricultural yields, provided that the residual biomass is  
 410 adequately managed (VandenBygaart et al., 2010; Minasny et al., 2012): this, in turn, will reduce the erosion and  
 411 degradation risk (Torri and Poesen, 1997). Thus, intensification will allow to preserve more carbon than areal  
 412 extension (Figure 3, Figure 5). The fact that intensification is beneficial for soil carbon conservation has also been  
 413 demonstrated at the global level: agricultural intensification has allowed to avoid ca. 161 Gt of carbon emissions  
 414 from the soil to the atmosphere between 1960 and 2005 (Burney et al., 2010).

## Land use distribution



415

416 **Figure 5 Semi-quantitative illustration of the effects of a significant increase of agricultural production through smart**  
 417 **intensification (sparing land) vs. agricultural expansion (sharing land) on soil organic carbon stocks, the erosion risk**  
 418 **and biodiversity. We assume that in a given area the required increase in agricultural production is such that, if yields**  
 419 **are not increased, the entire area that is potentially suitable for agriculture (80% of the total area) has to be used for**  
 420 **agriculture and that smart intensification would reduce the area needed to ca. 55% of the total area. The bar graphs**  
 421 **give a semi-quantitative assessment, at the landscape scale, of the impact of these alternatives according to current**  
 422 **scientific insights. Smart intensification is beneficial with respect to soil organic carbon storage because soil organic**  
 423 **stocks under natural forest are much higher than under arable land (e.g. Pooplau et al., 2011) . Smart intensification**  
 424 **will reduce total soil erosion because less marginal (sloping) land needs to be taken into production (e.g. Van Rompaey**  
 425 **et al., 2002). Finally, smart intensification is beneficial for biodiversity because more forest is preserved and the**  
 426 **biodiversity of undisturbed forests is much higher than that of land used for agriculture (e.g. Phalan et al., 2011a).**

427 *Smart intensification will help to make agriculture in the South more water-efficient. Agriculture is by far the*  
 428 *largest global consumptive user of blue water (water extracted from rivers and groundwater): at the global scale,*  
 429 *over 80% of all consumptive water use is related to agricultural activities (e.g. Doll et al., 2009). As the amount*  
 430 *of available water will not significantly increase in the future, a more efficient water use is a prerequisite to increase*  
 431 *agricultural production in the South. Less productive systems are often more water-intensive, i.e. more units of*  
 432 *water are needed for each unit of crop that is produced. Striving towards higher yields will remedy this problem*  
 433 *as it allows to increase the amount of crop produced per unit of water (Rockström et al., 2007). Higher yields are*  
 434 *therefore a means to increase water conservation and to make sure that more water is available for the functioning*  
 435 *of non-agricultural ecosystems. Clearly, the realisation of this potential requires other measures as well such as a*  
 436 *realistic pricing of water and water use monitoring in areas where water scarcity is a problem so that inefficient*  
 437 *use of this scarce resource can be prevented. Again, the implementation of such systems will be far more efficient*  
 438 *in high-yield systems as the return per unit of capital cost will be higher.*

439 *Smart intensification is beneficial for biodiversity at the landscape scale. Environments where intensive*  
 440 *agriculture is dominant are often very poor in terms of biodiversity. One might therefore suggest that, in order to*  
 441 *preserve biodiversity, one should avoid intensification and maintain a certain biodiversity on agricultural lands.*  
 442 *Again, such a strategy would necessarily imply that more land would be needed to produce the same amount of*  
 443 *agricultural goods. Recent studies have consistently shown that such a strategy is not beneficial for biodiversity at*  
 444 *a larger scale: the biodiversity gained on agricultural land is, in general, not sufficient to compensate for the*

445 additional biodiversity loss due to agricultural land expansion (e.g. Phalan et al., 2011b; De Beenhouwer et al.,  
446 2013; Schneider et al., 2014). Thus, land sparing and concentrating intensive agriculture on designated areas is  
447 generally a better strategy than land sharing with low-intensity agriculture that will occupy a much larger fraction  
448 of the available land (Figure 5). Sparing will not always be the best strategy as this will depend on local conditions:  
449 for instance, wildlife-friendly agriculture may be the best solution in the buffer zones around wildlife reserves.

450 *Smart intensification will increase the added value of the land used for agricultural production and hence make*  
451 *the implementation of conservation measures economically sound.* Clearly the economic value of a good such as  
452 arable land depends on the economic return that can be gained from the use of it. Intensification will allow to  
453 increase these returns. This is especially true for sub-Saharan Africa where yields are still abysmally low  
454 (Neumann et al., 2010). While there are many reasons for this, a key factor is that African soils are chronically  
455 underfertilized (Henao and Baanante, 2006; Keating et al., 2010). The amount of fertilizer used per unit of surface  
456 area of agricultural land in Africa is only 10% of what is being used in Europe or the United States: the consequence  
457 is that, in many cases, the nutrient balance of many African agricultural systems is negative, i.e. more nutrients are  
458 removed through harvesting than there are supplied by fertilization (Smaling et al., 1993; Henao and Baanante,  
459 2006). This negative balance is further aggravated by soil erosion, which annually mobilises more nutrients than  
460 are applied in sub-Saharan Africa (Quinton et al., 2010). Even a modest increase in fertilizer use may therefore  
461 allow to significantly boost agricultural yields in sub-Saharan Africa, at least if this increase would be accompanied  
462 by other measures such as the introduction of high-yield varieties and the necessary training for the farmers  
463 (Sanchez, 2010; Twomlow et al., 2010; Mueller et al., 2012).

464 Higher agricultural yields will increase the added value that may be produced per unit of agricultural land and  
465 hence its value. A consequence of this is that the economic stimulus to implement conservation measures on this  
466 land will increase as land will become a more precious resource. Furthermore, intensification will also reduce the  
467 overall conservation investment that has to be made as the acreage that needs to be treated will be smaller which  
468 will allow to concentrate the available resources on a smaller area. Finally, many conservation strategies are based  
469 on the use of crop residue (i) to return nutrients and carbon to the soil and (ii) to reduce the soil erosion risk. Such  
470 strategies are likely to be more successful when more residue per unit of area is available. Case studies have  
471 repeatedly shown that the mechanisms described above can indeed lead to more effective soil conservation under  
472 increasing intensification and population pressure (e.g. Tiffen et al., 1994; Boyd and Slaymaker, 2000)

473 *Smart intensification will help to create the market opportunities needed for sustainable agriculture.* The dramatic  
474 increase in population that will occur in the South over the next century, in combination with rapid urbanisation  
475 and economic growth, make the transition towards a market-oriented agriculture inevitable. This is not a bad thing:  
476 all too often we have a far too rosy view on the potential of subsistence agriculture. The truth is that subsistence  
477 farming does not generate the necessary financial means for the farmers to get out of poverty, although  
478 improvements in agricultural technology may contribute to increased food security (Harris and Orr, 2014). Only  
479 when farmers have access to markets they can generate an income that allows them to fully participate in society  
480 so that they can not only benefit from the material perks of modern life but also provide a high quality education  
481 to their children and the necessary health care to those who need it: soil conservation as such cannot achieve this  
482 (Posthumus and Stroosnijder, 2010). Case studies support that a symbiosis between the development of a market-  
483 oriented agriculture and soil conservation is indeed likely as market access provides farmers with the economic  
484 incentives to implement soil conservation measures (Boyd and Slaymaker, 2000). Again, the transition from a

485 subsistence to a market-oriented system will almost inevitably have to be accompanied by intensification as the  
486 latter will allow a better return on both capital and input investment.

487 *Smart intensification will not be sufficient to achieve adequate soil conservation (but it will help).* The points raised  
488 above illustrate that adequate soil conservation is much more likely to be achieved if more intensive agricultural  
489 systems are developed in the Global South as the economic and environmental stimuli to implement soil  
490 conservation measures will be much larger. Yet, the experiences in Europe and Northern America illustrate that  
491 this may not be sufficient to achieve adequate soil conservation and that government stimulation (through financial  
492 measures) and/or coercion may be necessary to further reduce soil degradation. It is, however, the magnitude of  
493 such efforts and their effectiveness that should be considered. The societal efforts and costs that will be needed to  
494 achieve adequate soil conservation will be far smaller when less land is used for agriculture as much less land will  
495 need treatment. Furthermore, one may also imagine that efforts to convince farmers to adopt conservation  
496 measures will be more successful in an intensive, market-oriented agricultural system as they will, generally, be  
497 more open to changes and both governments and other stakeholders will have more leverage in discussions on  
498 how the agricultural system needs to be organised. This is, obviously, no guarantee for success as potential direct  
499 financial benefits may seduce the stakeholders to neglect the necessary investments to achieve long-term  
500 sustainability. The latter is a problem that occurs everywhere where environmental and economic concerns conflict  
501 and, while general principles to resolve such problems have been formulated (Ostrom, 2009), specific policies to  
502 deal with this conflict will depend on local conditions.

### 503 **Conclusions**

504 All too often, soil conservation is discussed in isolation, whereby much attention is given to the effectiveness of  
505 technical solutions in reducing excessive soil and water losses at a given location. Agriculture, however, is a system  
506 wherein lateral connections at different scales are very important: actions at a specific location will necessarily  
507 have implications at other locations. Agricultural systems are also subject to constant change as they respond to  
508 changes in population numbers, population distribution, economic wealth and cultural preferences. A coherent  
509 vision on the development of soil conservation in 21<sup>st</sup> century needs to account for this context and needs to  
510 consider both the spatial and temporal dynamics of agricultural systems.

511 While it is certainly true that conservation technology can be further developed other considerations may be more  
512 important for the successful implementation of soil conservation programs. In our view, smart intensification is an  
513 essential ingredient of any strategy seeking efficient soil conservation while at the same time meeting the growing  
514 food demands of a strongly increasing, more urbanised global population. Smart intensification will help to reduce  
515 the land surface area exposed to a high soil degradation risk while it will, at the same time, increase the return on  
516 the soil conservation measures that will still be necessary. Smart intensification will also allow to reap additional  
517 environmental benefits in terms of soil organic carbon storage, biodiversity and water availability. It will also be  
518 directly beneficial to the farmer, allowing her/him to produce food for more people and to achieve an acceptable  
519 income. It is therefore no surprise that, when considering these other angles, other researchers have reached similar  
520 conclusions, stating that agriculture in the Global South and particularly in Africa needs to intensify and that the  
521 exclusive focus on smallholders as engines for growth needs to change (Collier and Dercon, 2009).

522 Intensification is not a panacea that magically solves all problems. Striving towards higher crop yields will require  
523 the use of more external inputs, including the use of mineral fertilizers. This is often assumed to be detrimental to  
524 the environment: yet this only will be true if fertilizers are used excessively, as is the case now in many areas of  
525 the world (Sattari et al., 2012; Lassaletta et al., 2014; Zhang et al., 2015). If correctly used, the environmental  
526 benefits of judicious mineral fertilizer use will more often than not outweigh their potential negative impacts by  
527 reducing the amount of land needed for agricultural production (Tilman et al., 2011). Furthermore, intensification  
528 will require higher energy and capital inputs per unit of surface area: these extra investments will partly be  
529 compensated by the fact that a smaller area of land needs to be cultivated but access to markets will often be  
530 essential to make intensification profitable.

531 Smart intensification as such will not be sufficient to reduce soil loss to acceptable levels: also in intensive systems,  
532 soil losses are often higher than is tolerable and conflicts between (long-term) environmental and (short-term)  
533 economic goals will be present. Yet, they will be easier to tackle when we give smart intensification adequate  
534 consideration in any plan on future agricultural development in the Global South.

### 535 **Acknowledgement**

536 This paper greatly benefited from the critical comments of Martin Van Ittersum and an anonymous referee. The  
537 financial support of STAP (Scientific and Technical Advisory Panel of the Global Environmental Facility) and the  
538 IUAP project SOGLO (The Soil System under Global Change, IUAP P7/24) is gratefully acknowledged.  
539

540 **References**

- 541 Alexandratos, N., and Bruinsma, J.: World agriculture towards 2030/2050: The 2012 revision, ESA Working  
542 paper, 2012.
- 543 Angers, D. A., and Eriksen-Hamel, N. S.: Full-inversion tillage and organic carbon distribution in soil profiles: A  
544 meta-analysis, *Soil Science Society of America Journal*, 72, 1370-1374, doi: 10.2136/sssaj2007.0342, 2008.
- 545 Arnalds, A.: Approaches to Landcare—a century of soil conservation in Iceland, *Land Degradation &*  
546 *Development*, 16, 113-125, 2005.
- 547 Bakker, M. M., Govers, G., Kosmas, C., Vanacker, V., van Oost, K., and Rounsevell, M.: Soil erosion as a driver  
548 of land-use change, *Agriculture Ecosystems & Environment*, 105, 467-481, doi: 10.1016/j.agee.2004.07.009,  
549 2005.
- 550 Batjes, N. H.: Total carbon and nitrogen in the soils of the world, *European Journal of Soil Science*, 47, 151-163,  
551 doi: 10.1111/j.1365-2389.1996.tb01386.x, 1996.
- 552 Boardman, J., Ligneau, L., de Roo, A., and Vandaele, K.: Flooding of property by runoff from agricultural land in  
553 northwestern Europe, *Geomorphology*, 10, 183-196, 1994.
- 554 Boardman, J.: An average soil erosion rate for Europe: Myth or reality?, *Journal of Soil and Water Conservation*,  
555 53, 46-50, 1998.
- 556 Bocco, G.: Traditional knowledge for soil conservation in central Mexico, *Journal of soil and water conservation*,  
557 46, 346-348, 1991.
- 558 Boyd, C., and Slaymaker, T.: Re-examining the “more people less erosion” hypothesis: Special case or wider  
559 trend, *Natural Resource Perspective*, 63, 1-6, 2000.
- 560 Brouder, S. M., and Gomez-Macpherson, H.: The impact of conservation agriculture on smallholder agricultural  
561 yields: A scoping review of the evidence, *Agriculture, Ecosystems & Environment*, 187, 11-32, 2014.
- 562 Burney, J. A., Davis, S. J., and Lobell, D. B.: Greenhouse gas mitigation by agricultural intensification,  
563 *Proceedings of the National Academy of Sciences*, 107, 12052-12057, doi: 10.1073/pnas.0914216107, 2010.
- 564 Cerdan, O., Govers, G., Le Bissonnais, Y., Van Oost, K., Poesen, J., Saby, N., Gobin, A., Vacca, A., Quinton, J.,  
565 Auerswald, K., Klik, A., Kwaad, F., Raclot, D., Ionita, I., Rejman, J., Rousseva, S., Muxart, T., Roxo, M. J., and  
566 Dostal, T.: Rates and spatial variations of soil erosion in Europe: A study based on erosion plot data,  
567 *Geomorphology*, 122, 167-177, doi: 10.1016/j.geomorph.2010.06.011, 2010.
- 568 Chamberlin, J., Jayne, T. S., and Headey, D.: Scarcity amidst abundance? Reassessing the potential for cropland  
569 expansion in Africa, *Food Policy*, 48, 51-65, doi: <http://dx.doi.org/10.1016/j.foodpol.2014.05.002>, 2014.
- 570 Chen, L., Wei, W., Fu, B., and Lü, Y.: Soil and water conservation on the Loess Plateau in China: review and  
571 perspective, *Progress in Physical Geography*, 31, 389-403, doi: 10.1177/0309133307081290, 2007.
- 572 Christopher, S. F., Lal, R., and Mishra, U.: Regional study of no-till effects on carbon sequestration in the  
573 midwestern United States, *Soil Science Society of America Journal*, 73, 207-216, doi: 10.2136/sssaj2007.0336,  
574 2009.
- 575 Collier, P., and Dercon, S.: African agriculture in 50 years: Smallholders in a rapidly changing world? , 13 p.,  
576 2009.
- 577 De Beenhouwer, M., Aerts, R., and Honnay, O.: A global meta-analysis of the biodiversity and ecosystem service  
578 benefits of coffee and cacao agroforestry, *Agriculture, Ecosystems & Environment*, 175, 1-7, 2013.
- 579 De Deyn, G. B., and Van der Putten, W. H.: Linking aboveground and belowground diversity, *Trends in Ecology*  
580 *& Evolution*, 20, 625-633, doi: 10.1016/j.tree.2005.08.009, 2005.

- 581 De Schutter, O.: Agroecology and the Right to Food. Report presented at the 16th Session of the United Nations  
582 Human Rights Council, Geneva, Switzerland, United Nations Human Rights Council, 2011.
- 583 Derpsch, R., Friedrich, T., Kassam, A., and Li, H.: Current status of adoption of no-till farming in the world and  
584 some of its main benefits, *International Journal of Agricultural and Biological Engineering*, 3, 1-25, 2010.
- 585 Desmet, P. J. J., and Govers, G.: A GIS procedure for automatically calculating the USLE LS factor on  
586 topographically complex landscape units, *Journal of Soil and Water Conservation*, 51, 427-433, 1996.
- 587 Doll, P., Fiedler, K., and Zhang, J.: Global-scale analysis of river flow alterations due to water withdrawals and  
588 reservoirs, *Hydrology and Earth System Sciences*, 13, 2413-2432, 2009.
- 589 Eagle, A. J., Henry, L. R., Olander, L. P., Haugen-Kozyra, K., Millar, N., and Robertson, G. P.: Greenhouse Gas  
590 Mitigation Potential of Agricultural Land Management in the United States: A synthesis of the literature, Nicholas  
591 Institute for Environmental Policy Solutions, Duke University, 2012.
- 592 Ellis-Jones, J., and Sims, B.: An appraisal of soil conservation technologies on hillside farms in Honduras, Mexico  
593 and Nicaragua, *Project Appraisal*, 10, 125-134, 1995.
- 594 FAO, and ITPS: Status of the World's Soil Resources - Main Report, FAO and ITPS, 608, 2015.
- 595 Gerland, P., Raftery, A. E., Ševčíková, H., Li, N., Gu, D., Spoorenberg, T., Alkema, L., Fosdick, B. K., Chunn, J.,  
596 Lalic, N., Bay, G., Buettner, T., Heilig, G. K., and Wilmoth, J.: World population stabilization unlikely this  
597 century, *Science*, 346, 234-237, doi: 10.1126/science.1257469, 2014.
- 598 Giller, K. E., Witter, E., Corbeels, M., and Tittonell, P.: Conservation agriculture and smallholder farming in  
599 Africa: The heretics' view, *Field Crops Research*, 114, 23-34, doi: 10.1016/j.fcr.2009.06.017, 2009.
- 600 Glaeser, E.: *Triumph of the City: How Our Greatest Invention Makes Us Richer, Smarter, Greener, Healthier and  
601 Happier*, Pan Macmillan, 2011.
- 602 Govers, G., Merckx, R., Van Oost, K., and van Wesemael, B.: *Managing Soil Organic Carbon for Global Benefits:  
603 a STAP Technical Report*, Global Environmental Facility, Washington, D.C., 70, 2013.
- 604 Govers, G., Van Oost, K., and Wang, Z.: Scratching the Critical Zone: The Global Footprint of Agricultural Soil  
605 Erosion, *Procedia Earth and Planetary Science*, 10, 313-318, doi: <http://dx.doi.org/10.1016/j.proeps.2014.08.023>,  
606 2014.
- 607 Grace, P. R., Antle, J., Aggarwal, P. K., Ogle, S., Paustian, K., and Basso, B.: Soil carbon sequestration and  
608 associated economic costs for farming systems of the Indo-Gangetic Plain: A meta-analysis, *Agriculture  
609 Ecosystems & Environment*, 146, 137-146, doi: 10.1016/j.agee.2011.10.019, 2012.
- 610 Harris, D., and Orr, A.: Is rainfed agriculture really a pathway from poverty?, *Agricultural Systems*, 123, 84-96,  
611 2014.
- 612 Henao, J., and Baanante, C.: *Agricultural production and soil nutrient mining in Africa: implications for resource  
613 conservation and policy development*, IFDC-AN International Center for Soil Fertility and Agricultural  
614 Development, 2006.
- 615 Hiederer, R., and Köchyl, M.: Global soil organic carbon estimates and the harmonized world soil database,  
616 *Luxembourg EUR 25225EN*, 79, 2012.
- 617 Hornbeck, R.: The enduring impact of the American dust bowl: Short-and long-run adjustments to environmental  
618 catastrophe, *The American Economic Review*, 1477-1507, 2012.
- 619 Imwangana, F. M., Vandecasteele, I., Trefois, P., Ozer, P., and Moeyersons, J.: The origin and control of mega-  
620 gullies in Kinshasa (DR Congo), *Catena*, 125, 38-49, 2015.
- 621 Janosky, J. S., Young, D. L., and Schillinger, W. F.: Economics of conservation tillage in a wheat-fallow rotation,  
622 *Agronomy Journal*, 94, 527-531, 2002.

- 623 Johnson, L. C.: Soil loss tolerance: Fact or myth, *Journal of Soil and Water Conservation*, 42, 155-160, 1987.
- 624 Keating, B. A., Carberry, P. S., Bindraban, P. S., Asseng, S., Meinke, H., and Dixon, J.: Eco-efficient agriculture:  
625 Concepts, challenges, and opportunities, *Crop Science*, 50, S-109-S-119, doi: 10.2135/cropsci2009.10.0594, 2010.
- 626 Knowler, D., Bradshaw, B., and Gordon, D.: The economics of conservation agriculture, Land and Water Division,  
627 FAO, Rome, 2001.
- 628 Knowler, D., and Bradshaw, B.: Farmers' adoption of conservation agriculture: A review and synthesis of recent  
629 research, *Food Policy*, 32, 25-48, doi: <http://dx.org/10.1016/j.foodpol.2006.01.003>, 2007.
- 630 Kok, H., Papendick, R., and Saxton, K. E.: STEEP: Impact of long-term conservation farming research and  
631 education in Pacific Northwest wheatlands, *Journal of Soil and Water Conservation*, 64, 253-264, 2009.
- 632 Krajick, K.: Green farming by the Incas?, *Science*, 281, 322-322, 1998.
- 633 Lahmar, R.: Adoption of conservation agriculture in Europe: lessons of the KASSA project, *Land Use Policy*, 27,  
634 4-10, 2010.
- 635 Lassaletta, L., Billen, G., Grizzetti, B., Anglade, J., and Garnier, J.: 50 year trends in nitrogen use efficiency of  
636 world cropping systems: the relationship between yield and nitrogen input to cropland, *Environmental Research  
637 Letters*, 9, doi: 10.1088/1748-9326/9/10/105011, 2014.
- 638 Le Quere, C., Raupach, M. R., Canadell, J. G., Marland, G., Bopp, L., Ciais, P., Conway, T. J., Doney, S. C.,  
639 Feely, R. A., Foster, P., Friedlingstein, P., Gurney, K., Houghton, R. A., House, J. I., Huntingford, C., Levy, P. E.,  
640 Lomas, M. R., Majkut, J., Metzl, N., Ometto, J. P., Peters, G. P., Prentice, I. C., Randerson, J. T., Running, S. W.,  
641 Sarmiento, J. L., Schuster, U., Sitch, S., Takahashi, T., Viovy, N., van der Werf, G. R., and Woodward, F. I.:  
642 Trends in the sources and sinks of carbon dioxide, *Nature Geoscience*, 2, 831-836, doi: 10.1038/ngeo689, 2009.
- 643 Leys, A., Govers, G., Gillijns, K., Berckmoes, E., and Takken, I.: Scale effects on runoff and erosion losses from  
644 arable land under conservation and conventional tillage: The role of residue cover, *Journal of Hydrology*, 390,  
645 143-154, doi: 10.1016/j.jhydrol.2010.06.034, 2010.
- 646 Lilin, C.: Histoire de la restauration des terrains en montagne au 19<sup>ème</sup> siècle, *Cahiers ORSTOM. Série Pédologie*,  
647 22, 139-145, 1986.
- 648 Lu, C. H., and van Ittersum, M. K.: A trade-off analysis of policy objectives for Ansai, the Loess Plateau of China,  
649 *Agriculture, Ecosystems & Environment*, 102, 235-246, doi: <http://dx.org/10.1016/j.agee.2003.09.023>, 2004.
- 650 Lutz, W., and KC, S.: Dimensions of global population projections: what do we know about future population  
651 trends and structures?, *Philosophical Transactions of the Royal Society B: Biological Sciences*, 365, 2779-2791,  
652 doi: 10.1098/rstb.2010.0133, 2010.
- 653 Mader, P., Fliessbach, A., Dubois, D., Gunst, L., Fried, P., and Niggli, U.: Soil fertility and biodiversity in organic  
654 farming, *Science*, 296, 1694-1697, doi: 10.1126/science.1071148, 2002.
- 655 Mekuria, W., Veldkamp, E., Haile, M., Nyssen, J., Muys, B., and Gebrehiwot, K.: Effectiveness of exclosures to  
656 restore degraded soils as a result of overgrazing in Tigray, Ethiopia, *Journal of Arid Environments*, 69, 270-284,  
657 doi: <http://dx.org/10.1016/j.jaridenv.2006.10.009>, 2007.
- 658 Minasny, B., McBratney, A., Hong, S. Y., Sulaeman, Y., Kim, M. S., Zhang, Y. S., Kim, Y. H., and Han, K. H.:  
659 Continuous rice cropping has been sequestering carbon in soils in Java and South Korea for the past 30 years,  
660 *Global Biogeochemical Cycles*, 26, 1-8, doi: 10.1029/2012GB004406, 2012.
- 661 Montgomery, D. R.: Soil erosion and agricultural sustainability., *Proceedings of the National Academy of Sciences  
662 of the United States of America*, 104, 13268-13272, doi: 10.1073/pnas.0611508104, 2007.
- 663 Mueller, N. D., Gerber, J. S., Johnston, M., Ray, D. K., Ramankutty, N., and Foley, J. A.: Closing yield gaps  
664 through nutrient and water management, *Nature*, 490, 254-257, 2012.

665 Napier, T. L., Boardman, J., Foster, I., and Dearing, J.: The evolution of US soil-conservation policy: from  
666 voluntary adoption to coercion, *Soil erosion on agricultural land. Proceedings of a workshop sponsored by the*  
667 *British Geomorphological Research Group, Coventry, UK, January 1989.*, 1990, 627-644,

668 Nearing, M. A.: A single, continuous function for slope steepness influence on soil loss, *Soil Science Society of*  
669 *America Journal*, 61, 917-919, 1997.

670 Neumann, K., Verburg, P. H., Stehfest, E., and Müller, C.: The yield gap of global grain production: A spatial  
671 analysis, *Agricultural Systems*, 103, 316-326, 2010.

672 NRCS: 2007 National Resources Inventory - Soil Erosion on Cropland, 29, 2010.

673 Nyssen, J., Poesen, J., Gebremichael, D., Vancampenhout, K., D'Aes, M., Yihdego, G., Govers, G., Leirs, H.,  
674 Moeyersons, J., Naudts, J., Haregeweyn, N., Haile, M., and Deckers, J.: Interdisciplinary on-site evaluation of  
675 stone bunds to control soil erosion on cropland in Northern Ethiopia, *Soil & Tillage Research*, 94, 151-163, doi:  
676 10.1016/j.still.2006.07.011, 2007.

677 Nyssen, J., Clymans, W., Poesen, J., Vandecasteele, I., De Raets, S., Haregeweyn, N., Naudts, J., Hadera, A.,  
678 Moeyersons, J., Haile, M., and Deckers, J.: How soil conservation affects the catchment sediment budget - a  
679 comprehensive study in the north Ethiopian highlands, *Earth Surface Processes and Landforms*, 34, 1216-1233,  
680 doi: 10.1002/Esp.1805, 2009.

681 Oorts, K., Bossuyt, H., Labreuche, J., Merckx, R., and Nicolardot, B.: Carbon and nitrogen stocks in relation to  
682 organic matter fractions, aggregation and pore size distribution in no-tillage and conventional tillage in northern  
683 France, *European Journal of Soil Science*, 58, 248-259, doi: 10.1111/j.1365-2389.2006.00832.x, 2007.

684 Ostrom, E.: A general framework for analyzing sustainability of social-ecological systems, *Science*, 325, 419-422,  
685 doi: 10.1126/science.1172133, 2009.

686 Peiretti, R., and Dumanski, J.: The transformation of agriculture in Argentina through soil conservation,  
687 *International Soil and Water Conservation Research*, 2, 14-20, doi: [http://dx.org/10.1016/S2095-6339\(15\)30010-](http://dx.org/10.1016/S2095-6339(15)30010-1)  
688 [1](http://dx.org/10.1016/S2095-6339(15)30010-1), 2014.

689 Perlman, J. E.: The metamorphosis of marginality: four generations in the favelas of Rio de Janeiro, *The Annals*  
690 *of the American academy of Political and Social Science*, 606, 154-177, 2006.

691 Phalan, B., Balmford, A., Green, R. E., and Scharlemann, J. r. P. W.: Minimising the harm to biodiversity of  
692 producing more food globally, *Food Policy*, 36, Supplement 1, S62-S71, 2011a.

693 Phalan, B., Onial, M., Balmford, A., and Green, R. E.: Reconciling food production and biodiversity conservation:  
694 Land sharing and land sparing compared, *Science*, 333, 1289-1291, doi: 10.1126/science.1208742, 2011b.

695 Pittelkow, C. M., Linqvist, B. A., Lundy, M. E., Liang, X., Van Groenigen, K. J., Lee, J., Van Gestel, N., Six, J.,  
696 Venterea, R. T., and Van Kessel, C.: When does no-till yield more? A global meta-analysis, *Field Crops Research*,  
697 183, 156-168, 2015.

698 Poeplau, C., Don, A., Vesterdal, L., Leifeld, J., Van Wesemael, B., Schumacher, J., and Gensior, A.: Temporal  
699 dynamics of soil organic carbon after land-use change in the temperate zone - carbon response functions as a model  
700 approach, *Global Change Biology*, 17, 2415-2427, doi: 10.1111/j.1365-2486.2011.02408.x, 2011.

701 Poesen, J., Nachtergaele, J., Verstraeten, G., and Valentin, C.: Gully erosion and environmental change:  
702 importance and research needs, *Catena*, 50, 91-133, doi: Pii S0341-8162(02)00143-1, 2003.

703 Posthumus, H., and Stroosnijder, L.: To terrace or not: the short-term impact of bench terraces on soil properties  
704 and crop response in the Peruvian Andes, *Environment, Development and Sustainability*, 12, 263-276, 2010.

705 Quang, D. V., Schreinemachers, P., and Berger, T.: Ex-ante assessment of soil conservation methods in the uplands  
706 of Vietnam: An agent-based modeling approach, *Agricultural Systems*, 123, 108-119, doi:  
707 10.1016/j.agsy.2013.10.002, 2014.

- 708 Quinton, J. N., Govers, G., Van Oost, K., and Bardgett, R. D.: The impact of agricultural soil erosion on  
709 biogeochemical cycling, *Nature Geoscience*, 3, 311-314, doi: 10.1038/Ngeo838, 2010.
- 710 Ramachandran Nair, P. K., Mohan Kumar, B., and Nair, V. D.: Agroforestry as a strategy for carbon sequestration,  
711 *Journal of Plant Nutrition and Soil Science*, 172, 10-23, doi: 10.1002/jpln.200800030, 2009.
- 712 Ramankutty, N., Evan, A. T., Monfreda, C., and Foley, J. A.: Farming the planet: 1. Geographic distribution of  
713 global agricultural lands in the year 2000, *Global Biogeochemical Cycles*, 22, doi: 10.1029/2007GB002952, 2008.
- 714 Rijdsdijk, A., Bruijnzeel, L. A. S., and Sutoto, C. K.: Runoff and sediment yield from rural roads, trails and  
715 settlements in the upper Konto catchment, East Java, Indonesia, *Geomorphology*, 87, 28-37, doi:  
716 10.1016/j.geomorph.2006.06.040, 2007.
- 717 Robb, G.: *The discovery of France*, Pan Macmillan, 2008.
- 718 Rockström, J., Lannerstad, M., and Falkenmark, M.: Assessing the water challenge of a new green revolution in  
719 developing countries, *Proceedings of the National Academy of Sciences*, 104, 6253-6260, doi:  
720 10.1073/pnas.0605739104, 2007.
- 721 Sanchez, P. A.: Tripling crop yields in tropical Africa, *Nature Geoscience*, 3, 299-300, 2010.
- 722 Sattari, S. Z., Bouwman, A. F., Giller, K. E., and van Ittersum, M. K.: Residual soil phosphorus as the missing  
723 piece in the global phosphorus crisis puzzle, *Proceedings of the National Academy of Sciences*, 109, 6348-6353,  
724 2012.
- 725 Saunders, D.: *Arrival City: How the Largest Migration in History Is Reshaping Our World*, Knopf Doubleday  
726 Publishing Group, 2011.
- 727 Schneider, M. K., Lüscher, G., Jeanneret, P., Arndorfer, M., Ammari, Y., Bailey, D., Balázs, K., Báldi, A., Choisis,  
728 J.-P., and Dennis, P.: Gains to species diversity in organically farmed fields are not propagated at the farm level,  
729 *Nature communications*, 5, 2014.
- 730 Sendzimir, J., Reij, C. P., and Magnuszewski, P.: Rebuilding resilience in the Sahel: greening in the Maradi and  
731 Zinder regions of Niger, *Ecology and Society*, 16, 1, 2011.
- 732 Smaling, E. M. A., Stoorvogel, J. J., and Windmeijer, P. N.: Calculating soil nutrient balances in Africa at different  
733 scales, *Fertilizer research*, 35, 237-250, doi: 10.1007/bf00750642, 1993.
- 734 Sterk, G.: Causes, consequences and control of wind erosion in Sahelian Africa: a review, *Land Degradation &  
735 Development*, 14, 95-108, 2003.
- 736 Stockmann, U., Minasny, B., and McBratney, A. B.: How fast does soil grow?, *Geoderma*, 216, 48-61, 2014.
- 737 Stone, J. R., Gilliam, J. W., Cassel, D. K., Daniels, R. B., Nelson, L. A., and Kleiss, H. J.: Effect of erosion and  
738 landscape position on the productivity of Piedmont soils, *Soil Science Society of America Journal*, 49, 987-991,  
739 1985.
- 740 Tiffen, M., Mortimore, M., and Gichuki, F.: *More People, Less Erosion: Environmental Recovery in Kenya*, John  
741 Wiley & Sons Ltd, 1994.
- 742 Tilman, D., Balzer, C., Hill, J., and Befort, B. L.: Global food demand and the sustainable intensification of  
743 agriculture, *Proceedings of the National Academy of Sciences*, 108, 20260-20264, doi: 10.1073/pnas.1116437108,  
744 2011.
- 745 Torri, D., and Poesen, J.: Predictability and uncertainty of the soil erodibility factor using a global dataset, *Catena*,  
746 31, 1-22, 1997.
- 747 Twomlow, S., Rohrbach, D., Dimes, J., Rusike, J., Mupangwa, W., Ncube, B., Hove, L., Moyo, M., Mashingaidze,  
748 N., and Mahposa, P.: Micro-dosing as a pathway to Africa's Green Revolution: evidence from broad-scale on-  
749 farm trials, *Nutrient Cycling in Agroecosystems*, 88, 3-15, 2010.

- 750 United Nations: World Urbanization Prospects 2014: Highlights, United Nations Publications, 2014.
- 751 Valentin, C., Agus, F., Alamban, R., Boosaner, A., Bricquet, J.-P., Chaplot, V., De Guzman, T., De Rouw, A.,  
752 Janeau, J.-L., and Orange, D.: Runoff and sediment losses from 27 upland catchments in Southeast Asia: Impact  
753 of rapid land use changes and conservation practices, *Agriculture, Ecosystems & Environment*, 128, 225-238,  
754 2008.
- 755 Van den Putte, A., Govers, G., Diels, J., Gillijns, K., and Demuzere, M.: Assessing the effect of soil tillage on crop  
756 growth: A meta-regression analysis on European crop yields under conservation agriculture, *European Journal of*  
757 *Agronomy*, 33, 231-241, doi: 10.1016/j.eja.2010.05.008, 2010.
- 758 Van Oost, K., Quine, T. A., Govers, G., De Gryze, S., Six, J., Harden, J. W., Ritchie, J. C., McCarty, G. W.,  
759 Heckrath, G., Kosmas, C., Giraldez, J. V., da Silva, J. R. M., and Merckx, R.: The impact of agricultural soil  
760 erosion on the global carbon cycle, *Science*, 318, 626-629, doi: 10.1126/science.1145724, 2007.
- 761 Van Rompaey, A. J. J., Govers, G., Van Hecke, E., and Jacobs, K.: The impacts of land use policy on the soil  
762 erosion risk: a case study in central Belgium, *Agriculture Ecosystems & Environment*, 83, 83-94, 2001.
- 763 Van Rompaey, A. J. J., Govers, G., and Puttemans, C.: Modelling land use changes and their impact on soil erosion  
764 and sediment supply to rivers, *Earth Surface Processes and Landforms*, 27, 481-494, doi: 10.1002/Esp.335, 2002.
- 765 Vanacker, V., Molina, A., Govers, G., Poesen, J., and Deckers, J.: Spatial variation of suspended sediment  
766 concentrations in a tropical Andean river system: The Paute River, southern Ecuador, *Geomorphology*, 87, 53-67,  
767 doi: 10.1016/j.geomorph.2006.06.042, 2007a.
- 768 Vanacker, V., von Blanckenburg, F., Govers, G., Molina, A., Poesen, J., Deckers, J., and Kubik, P.: Restoring  
769 dense vegetation can slow mountain erosion to near natural benchmark levels, *Geology*, 35, 303-306, doi:  
770 10.1130/G23109a.1, 2007b.
- 771 VandenBygaart, A. J., Bremer, E., McConkey, B. G., Janzen, H. H., Angers, D. A., Carter, M. R., Drury, C. F.,  
772 Lafond, G. P., and McKenzie, R. H.: Soil organic carbon stocks on long-term agroecosystem experiments in  
773 Canada, *Canadian Journal of Soil Science*, 90, 543-550, doi: 10.4141/cjss10028, 2010.
- 774 Verbruggen, E., Roling, W. F. M., Gamper, H. A., Kowalchuk, G. A., Verhoef, H. A., and van der Heijden, M. G.  
775 A.: Positive effects of organic farming on below-ground mutualists: large-scale comparison of mycorrhizal fungal  
776 communities in agricultural soils, *New Phytologist*, 186, 968-979, doi: 10.1111/j.1469-8137.2010.03230.x, 2010.
- 777 Verheijen, F. G., Jones, R. J., Rickson, R., and Smith, C.: Tolerable versus actual soil erosion rates in Europe,  
778 *Earth-Science Reviews*, 94, 23-38, 2009.
- 779 Yang, D. W., Kanae, S., Oki, T., Koike, T., and Musiak, K.: Global potential soil erosion with reference to land  
780 use and climate changes, *Hydrological Processes*, 17, 2913-2928, doi: 10.1002/hyp.1441, 2003.
- 781 Zentner, R., McConkey, B., Campbell, C., Dyck, F., and Selles, F.: Economics of conservation tillage in the  
782 semiarid prairie, *Canadian journal of plant science*, 76, 697-705, 1996.
- 783 Zhang, X., Davidson, E. A., Mauzerall, D. L., Searchinger, T. D., Dumas, P., and Shen, Y.: Managing nitrogen for  
784 sustainable development, *Nature*, 528, 51-59, doi: 10.1038/nature15743, 2015.
- 785 Zhao, J., Oost, K. V., Chen, L., and Govers, G.: Moderate topsoil erosion rates constrain the magnitude of the  
786 erosion-induced carbon sink and agricultural productivity losses on the Chinese Loess Plateau, *Biogeosciences*,  
787 13, 4735-4750, 2016.
- 788