1 **Spatio-temporal trends and trade-offs in ecosystem services: An**

2 **Earth observation based assessment for Switzerland between**

3 **2004 and 2014**

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18 **Abstract**

19 Understanding and monitoring pressures on ecosystems and their consequences for

20 ecosystem services (ES) is essential for management decisions and verification of

21 progress towards national and international policies (e.g. Aichi Biodiversity Targets,

22 Sustainable Development Goals). Remote sensing (RS) offers a unique capability to

23 assess ES systematically and regularly across spatial and temporal scales. We aim to

24 evaluate the benefits of RS to monitor spatio-temporal variations of ES by assessing

25 several ES in Switzerland between 2004 and 2014. We coupled mechanistic ES

26 models and RS data to estimate time series of three regulating (i.e. carbon dioxide

27 regulation (CO_2 R), soil erosion prevention (SEP), and air quality regulation (AQR))

28 and one cultural ES (recreational hiking (RH)). The resulting ES were used to assess

29 spatial and temporal changes, trade-offs and synergies of ES potential supply and

30 flow in Switzerland between 2004 and 2014. Resulting ES trends showed diverse

31 spatial patterns across Switzerland with largest changes in CO_2 R and AQR. ES

32 interactions revealed a scale and elevation dependency. We identified weak to strong

33 synergies between all ES combinations except for trade-offs between CO_2 R–AQR

34 and AQR–RH at Swiss scale. Spatially, all ES interactions revealed a heterogeneous

35 mix of synergies and trade-offs within Switzerland.

36 Our results demonstrate the strength of RS for systematic and regular spatio-temporal

37 ES monitoring and contribute insights to the large potential of RS, which will be

38 extended with future Earth observation missions. Derived spatially explicit ES

39 information will facilitate decision-making in landscape planning and conservation

40 and will allow examining progress towards environmental policies.

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44

45   1. Introduction

46   Safe planetary boundaries of several Earth system processes, in particular

47   biogeochemical flows of phosphorus and nitrogen, land use change, climate change,

48   and freshwater use have already been crossed (Steffen et al., 2015). Associated and

49   often irreversible environmental change influences ecosystems and the services (ES)

50   they supply in multiple ways. These modifications emphasize the need and

51   importance of monitoring and protecting ecosystems and their services (MA, 2005).

52   Additionally, assessing changes in ecosystem services has become crucial for current

53   environmental policies like IPBES (Díaz et al., 2015), the Aichi Biodiversity Targets

54   (Convention on Biological Diversity, 2010), the European Union Biodiversity

55   Strategy (European Commission, 2011) and the Sustainable Development Goals

56   (United Nations, 2015) that aim to ensure sustainable development of socio-

57   ecological systems. Such environmental policies particularly require regular and

58   systematic monitoring of ES to improve management decisions and to verify progress

59   towards environmental policies and effectiveness of conservation measures and

60   payment schemes (Scullion et al., 2011). However, required ES information is often

61   complex as not only a single ES is of interest, but knowledge of multiple ES and their

62   interactions is needed (Bennett et al., 2009). Additionally, appropriate methods

63   linking ES to processes in ecosystems are still lacking (Lavorel et al., 2017). As

64   consequence, dedicated monitoring systems for regular and systematic monitoring of

65   ES are still missing.

66 One promising concept for assessing spatio-temporal changes in ecosystems and

67 related ES to foster sustainable development is ecosystem accounting (European

68 Commission et al., 2013). It is considered as an accounting framework that

69 complements existing national accounts thereby acting as global comprehensive

70 statistical standard for measuring economic activity. The development of ecosystem

71 accounting as complementing framework to national accounts involves valuing the

72 contribution of ES to human well-being in biophysical and economic terms.

73 Ecosystem accounting relies on approaches to spatially measure and continuously

74 monitor the conditions of ecosystems, their capacity to sustainably provide ES, and

75 the effective flow of ES to society (Hein et al., 2015). Ensuring sustainable

76 development of socio-ecological systems requires understanding and assessing the

77 spatial and temporal changes in ES for improved management decisions and

78 verification of progress towards national and international policies (e.g. Aichi

79 Biodiversity Targets, Sustainable Development Goals). To accomplish this, the

80 guidelines of the System for Environmental Economic Accounts Experimental

81 Ecosystem Accounting (SEEA EEA) stress the need to capture spatial heterogeneity

82 in ecosystems and related services (European Commission et al., 2013). The

83 Ecosystem Accounting framework differentiates between ES flow, the amount of a

84 service used by humans in a given time period, and potential supply defined as

85 amount of a service generated by an ecosystem irrespective of its human use (Hein et

86 al., 2016). Investigating both aspects is important to assess independently changes in

87 ecosystem processes and in human use of ES.

88 Spatial ES modeling and mapping approaches have rapidly evolved in the past two

89 decades covering a wide range of ES mapping approaches across various spatial

90 scales (Burkhard et al., 2012; Maes et al., 2016; Malinga et al., 2015; Rabe et al.,

91 2016; Schröter et al., 2014). Information of intra- and inter-ecosystem variability and

92 related ES is essential to ensure sustainable development of socio-ecological systems,

93 e.g. by improved management decisions and by the implementation of ecosystem

94 accounting. However, there is a lack of accurate spatially explicit ES quantifications

95 at larger scales (Lavorel et al., 2017). This justifies the request for new ES mapping

96 approaches providing quantitative ES data compared to existing proxy indicators or

97 models relying on land cover and expert judgments (Remme et al., 2014).

98 We argue that the use of remote sensing (RS) data offers new pathways for ecosystem

99 accounting, particularly for the monitoring of status and trends in ecosystem

100 conditions and ES across space and time. The large potential of RS for monitoring

101 and mapping ecosystem services and biodiversity is already widely recognized (Cord

102 et al., 2017; Cord et al., 2015; Pettorelli et al., 2016; Skidmore et al., 2015; Tallis et

103 al., 2012). The integration of RS in ES models is, however, less elaborated compared

104 to ES assessments without RS data. Three main gaps for ES monitoring can be

105 identified: i) Land use and land cover are still the most common RS information used

106 in ES models (e.g. InVEST (Sharp et al., 2016), ARIES (Villa et al., 2014)) (de

107 Araujo Barbosa et al., 2015; Lavorel et al., 2017), often resulting in underestimated

108 intra-class heterogeneity in ES supply due to the assumption of the same biophysical

109 values per land cover class (Eigenbrod et al., 2010). Some recent studies started

110 extracting the spatial explicitness of RS data to overcome this problem and consider

111 spatial heterogeneity of ES in their mapping approaches (Braun et al., 2017; Remme

112 et al., 2014; Schröter et al., 2014; Strauch and Volk, 2013). Nevertheless, there

113 remains a lack of quantitative approaches that link ES to ecosystem processes at

114 larger scales (Lavorel et al., 2017). ii) Many studies neglect the advantage of large

115 temporal coverage by RS products. Nearly 30 % of ES studies using Earth

116 observation data, are based upon monotemporal imagery and 56 % of the studies

117 covered only 10 years or less (de Araujo Barbosa et al., 2015). iii) A particular lack is

118 related to RS based assessments of multiple ES across space and time.

119 With this study we make a contribution to a requested paradigm shift in ES

120 assessment from purely mapping to spatially explicit monitoring of ES (Cord et al.,

121 2017; Cord et al., 2015; Karp et al., 2015; Tallis et al., 2012). In this study, we aim at

122 demonstrating the contribution of RS to quantitative and spatially explicit ES

123 monitoring for sustainable development and natural resource management. This is

124 demonstrated by investigating spatio-temporal trends in potential supply and flow of

125 ES in Switzerland between 2004 and 2014 using the ecosystem accounting

126 framework. We applied mechanistic models in combination with RS data to estimate

127 three regulating services, i.e. CO_2 regulation (CO_2 R), soil erosion prevention (SEP),

128 air quality regulation (AQR), as well as the cultural service recreational hiking (RH).

129 We use obtained ES to assess spatio-temporal changes in ES potential supply and

130 flow and to quantify ES trade-offs and synergies in Switzerland between 2004 and

131 2014.

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133

134 **2. Material and methods**

135 **2.1 Study area**

136 Switzerland is located in the center of Europe with an area of approximately

137 4.1 million ha and an altitudinal range from 196 m to 4634m above sea level (a.s.l.).

138 The country can be divided into four biogeographical regions: Jura, Swiss Midlands,

139 Central Alps, and Southern Alps (Figure 1). Land use and land cover are

140 characterized by urban and settled area covering 7.5 % of the surface area, agriculture

141 (35.8 %), wooded areas (31.3%), surface water (4.3 %), and remaining natural

142 environment (21.0 %) (Swiss Federal Statistical Office, 2016). During the last 25

143 years, Swiss landscape has constantly changed due to urban expansion particularly in

144 the Swiss Midlands (Jaeger and Schwick, 2014), and due to land abandonment in

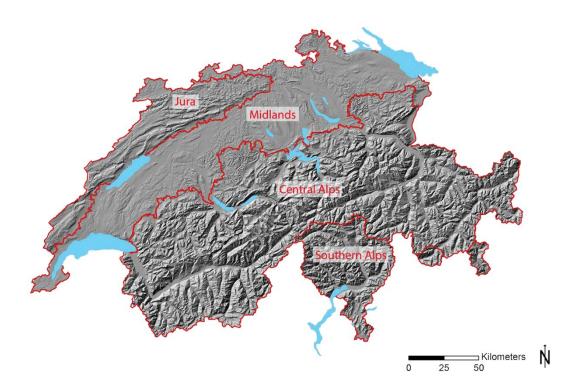145 Alpine areas followed by expansion of wooded areas (Gellrich et al., 2007).

146

147 Figure 1: The study area Switzerland with its different geographical regions. A digital

148 elevation model is used as background (courtesy of Swisstopo).

149

150 **2.2 Remote sensing data**

151 Several products derived from data of the Moderate-resolution Imaging

152 Spectroradiometer (MODIS) and the Defense Meteorological Satellite Program

153 Operational Linescan System (DMSP-OLS) were used to assess the various ES and

154 their spatio-temporal changes.

155   We utilized the MODIS products "Land cover" (MCD12Q1) (Friedl et al., 2010),

156   "NDVI" (Normalized Difference Vegetation Index) (MOD13A1) (Didan, 2015),

157   "LAI" (Leaf Area Index) (MOD15A2H) (Myneni et al., 2015), and "NPP" (Net

158   Primary Production) (MOD17A3H) (Running et al., 2015), all of them belonging to

159   product version #006 except for the "land cover" product that belongs to version

160   #055. The data have a spatial resolution of 500 m, a temporal resolution of 16 days

161   (16 day-composites) and cover the time period from 2004 until 2014

162   (cf., https://lpdaac.usgs.gov/dataset_discovery/modis/modis_products_table).

163   Additionally, we used a time series of the DMSP-OLS nighttime product "stable

164   lights" (version #4) with a global spatial resolution of 0.0083° from 2005 to 2013

165   (https://www.ngdc.noaa.gov/eog/dmsp/downloadV4composites.html).   The   product

166   contains light emissions from cities, towns, and other sites with persistent lighting.

167   Temporary light emissions such as fires and background noise are excluded from the

168   product. We resampled the data set to 500 m spatial resolution using bilinear

169   interpolation.

170

171   **2.3 Ecosystem services models**

172   Following SEEA EEA (European Commission et al., 2013), ES are contributions of

173   ecosystems to human benefits. The aim of ecosystem accounting is to measure ES in a

174   manner that facilitates integration with national accounts (Hein et al., 2015). In this

175   context, the SEEA EEA framework suggests the quantification of ecosystem assets to

176   particularly determine ES potential supply and in combination with the use by people,

177   ES flow (European Commission et al., 2013). Potential supply and flow differ for

178   provisioning, regulating and cultural ES. While there is often a spatial match for most

179   provisioning services between ES potential supply and flow related to resource

180   extraction, potential supply of regulating services covers sometimes larger areas than

181   ES flow. Soil erosion prevention of a meadow, for example, provides both ES

182   potential supply and flow as it is used for farming. However, the same potential

183   supply provided by an alpine grassland in an inaccessible area results in no ES flow,

184   as the ES potential supply is not used by people. Similarly, cultural ecosystem

185   services often provide a high potential supply in services, such as aesthetic beauty or

186   recreation, but the, partly conscious, lack of infrastructure to access untouched nature

187   results in low ES flow.

188   We selected four ES according to four criteria and mapped their potential supply and

189   flow between 2004 and 2014. The selection criteria include that ES should (i) cover

190   different Earth spheres (e.g. biosphere, atmosphere and pedosphere), (ii) be relevant

191   to the well-being of Swiss inhabitants, (iii) contain a RS input, which allows regular

192   and spatially explicit monitoring of the respective ES, and (iv) require additional *in*

193   *situ*, modeled or literature data that were available at the appropriate spatial and

194   temporal resolution.

195

196   **2.3.1 Carbon dioxide regulation (CO$_2$ R)**

197   The process of plant photosynthesis determines vegetated ecosystems as crucial for

198   the global carbon cycle: Vegetation acts as sink of atmospheric CO$_2$ and allows

199   mitigating trends and effects of rising atmospheric CO$_2$ by human activity (i.e. burn of

200   fossil fuels, land cover change, deforestation). Here, we define carbon dioxide

201   regulation (CO$_2$ R) of ecosystems as net ecosystem production (NEP) of all vegetated

202   areas (i.e. forest, agricultural and other ecosystems) to receive a spatially continuous

203   ES map. We consider neither harvest losses due to a lack of temporally and spatially

204   explicit harvest data nor carbon losses from fires, since they are very rare in

205 Switzerland. NEP (g C m^{-2} yr^{-1}) was calculated as difference of annual net primary

206 production (NPP) (g C m^{-2} yr^{-1}) and annual soil respiration (R$_S$) (g C m^{-2} yr^{-1}) as:

207 $CO_2R = NEP = NPP - R_S$, with (1)

208 $R_S = 1.250 \cdot e^{(0.05452 \cdot T_a)} \cdot \left[\frac{P}{4.259 + P} \right]$ (2)

209 Annual NPP was derived from the annual MODIS NPP (MOD17A3H) product. R$_S$

210 was estimated according to Raich et al. (2002) based on 1 km spatial mean monthly

211 air temperature (T$_a$) (°C) and mean monthly precipitation (P) (mm) data from 2004 to

212 2014 (MeteoSwiss, 2013) and was downscaled to 500 m.

213 The actual use of this ES is global and relatively indirect, so we assume that the

214 potential supply of carbon dioxide regulation directly translates into its ES flow,

215 determining ES potential supply and flow as the same.

216

217 **2.3.2 Air quality regulation (AQR)**

218 Air pollution can severely affect human health in various ways (Künzli et al., 2010;

219 Rückerl et al., 2011). One of the most important and well-documented atmospheric

220 pollutants in Switzerland is particulate matter (PM$_{10}$) (Eeftens et al., 2015). PM$_{10}$ is

221 defined as particulate matter with a diameter of less than 10 μm and is detrimental to

222 human health already at low concentrations. Vegetation has the ability to remove

223 PM$_{10}$ from the atmosphere (Manes et al., 2016) and consequently decrease human

224 health risks (Powe and Willis, 2004). We define the potential supply of air quality

225 regulation (AQR) as vertical capture of PM$_{10}$ per m^3 by an ecosystem as (adapted

226 from Nowak, 1994 and Manes et al., 2016):

227 $AQR = \sum_1^i C \cdot V_d \cdot LAI \cdot T \cdot 0.5,$ (3)

228 where i is the number of available satellite acquisition per year, C is the PM$_{10}$

229 concentration in the air (μg m^{-3}), V$_d$ is the dry deposition velocity for PM$_{10}$ (m s^{-1}),

230 LAI is the leaf area index ($m^2\ m^{-2}$), T is the time step (s) corresponding to one year,

231 and 0.5 is the suspension rate of deposited PM_{10} returning back to the atmosphere

232 (Zinke, 1967).

233 We allocated different V_d values according to different land cover types following

234 Remme et al. (2014): $0.0080\ m\ s^{-1}$ for needle-leaved forest, $0.0032\ m\ s^{-1}$ for broad-

235 leaved forest, $0.0010\ m\ s^{1}$ for grassland, cropland and other nature, and $0\ m\ s^{-1}$ for

236 water and urban infrastructure.

237 The Swiss Federal Office for the Environment (2015) provided modeled annual PM_{10}

238 concentrations for Switzerland based on 72 measurement stations resulting in a spatial

239 resolution of 200 m. For the LAI, the MODIS LAI product (MOD15A2H) was used.

240 Potential supply of air quality regulation is defined as removal of PM_{10} from the

241 atmosphere due to vegetation. ES flow is the actual use of this service, so the

242 utilization of filtered air by humans. Following Hein et al. (2016), potential ecosystem

243 service supply registers strictly what the ecosystem does, in a given biophysical

244 environment, without considering if people benefit from the service or not. Air

245 filtration leads to an actual service supply (and a benefit) if there are people living in

246 the area where pollution levels are lower because of air filtration by vegetation. If air

247 filtration leads to cleaner air in a place where no-one is living or (virtually) no-one is

248 ever visiting then it is a potential but not an actual service. Therefore, we calculated

249 the flow of AQR as its potential supply but restricted to urban (i.e. residential) areas

250 including a buffer area of 1 km following (Remme et al., 2014). In these areas people

251 live and spend most of their time, consequently consuming the ES AQR. We assume

252 that in other areas this ES flow is negligible small due to low duration of stay by

253 people.

254

2.3.3 Soil erosion prevention (SEP)

Soil erosion by water is still a main environmental problem and causes strong economic losses in agriculture by the loss of fertile topsoil (CEC, 2006). In Switzerland, the problem was widely recognized but research mainly focused on soil erosion risk (Prasuhn et al., 2013). The ES of soil erosion prevention (SEP) has not been investigated so far in Switzerland. We define the potential supply of SEP (E_{pot}) in tonnes per hectare (t ha^{-1}) according to Guerra et al. (2016) as the difference between the structural impact Y (i.e. the total soil erosion impact in absence of SEP = potential soil erosion) and the remaining impact not mitigated by this ES β (i.e. the remaining soil erosion that was not regulated by SEP) as:

$$E_{pot} = Y - \beta = Y\,(1 - C_V), \qquad \text{with} \tag{4}$$

$$Y = R \cdot K \cdot LS \tag{5}$$

Y is the structural impact (tha^{-1}), C_V is the vegetation cover (-), R is the rainfall erosivity (MJ mm ha^{-1} h^{-1}), K is the soil erodibility (t ha h ha^{-1} MJ^{-1} mm^{-1}), and LS describes the effect of topography on soil erosion (-) with L representing the impact of slope length and S quantifying the effect of slope steepness. Vegetation cover C_V was estimated as function of NDVI as suggested by Guerra et al. (2016):

$$C_V = \exp\left[-2 \cdot \frac{NDVI}{(1 - NDVI)}\right]. \tag{6}$$

Annual rainfall erosivity and soil erodibility of Switzerland were provided as spatial data with a resolution of 500 m by the Joint Research Center (JRC) European Soil Data Centre (ESDAC) (Panagos et al., 2015a; Panagos et al., 2014). We estimated the length and steepness factor according to Panagos et al. (2015b) by using a digital elevation model (DEM) of 25 m spatial resolution as input to the terrain analysis module of the SAGA (System for Automatic Geoscientific Analyses) software, which incorporates a multi flow algorithm to estimate LS (Pilesjö and Hasan, 2014). The ES

flow of soil erosion prevention (E_{flow}) was equal to its potential supply in agricultural areas and forests. In these ecosystems humans use SEP and benefit from avoided soil loss on their agricultural fields and in forests. Therefore, the flow of this ES was estimated by clipping its potential supply to agricultural areas and forest using the MODIS land cover product (MCD12Q1).

2.3.4 Recreational hiking (RH)

The Swiss landscape is well known for its nature recreation potential. Particularly hiking is a popular outdoor activity, while about 44 % of 15 to 74 years old Swiss inhabitants regularly spend time on the approximately 65'000 km long network of hiking trails in Switzerland (Bundesamt für Strassen (ASTRA) and Schweizer Wanderwege, 2015).

We estimate the potential supply of recreational hiking (RH_{pot}) using a model based on a simple ratio of hiking path density as infrastructural parameter and RS derived nighttime stable lights (NSL), a parameter describing the natural- and remoteness of a landscape, as:

$$RH_{pot} = \frac{PD}{1 + NSL},\tag{7}$$

where PD is the hiking path density as length of path per pixel (km). NSL (-) are derived from DMSP-OLS satellite data.

The flow of RH (RH_{flow}) was estimated based on its potential supply in combination with preferences of hikers derived from the Flickr data base as:

$$RH_{flow} = \frac{PD \cdot (1 + PUD)}{1 + NSL},\tag{8}$$

where PD was multiplied by PUD, the photo user days estimated per pixel (-). All variables of the equations were scaled between 0 and 1.

304   We estimated PUD by applying the recreation model of InVEST (Sharp et al., 2016),

305   a widely used open source ecosystem service toolbox. The model calculates the

306   distribution of photo-user-days (PUD) for recreation based on geo-tagged

307   photographs posted on the photo-sharing website Flickr (www.flickr.com) (see

308   Appendix A.1 Figure A.1.1). This results in a proxy for visitation frequency and

309   preferences of hiking trails (Keeler et al., 2015; Wood et al., 2013). We defined April

310   to October as core hiking season and summarized PUD during these months. We

311   normalized PUD by the average PUD per year to account for the increasing use of

312   Flickr data during our investigation period. As Flickr data were first available in 2005,

313   RH was computed from 2005 to 2013.

314 Table 1: Overview of investigated ecosystem services (ES), their potential supply (= P) and flow (= F) as well as their remote sensing inputs.

315 The transformations were applied to provide comparability for the trade-off and synergy analysis.

Section	ES	ES potential supply	ES flow	Remote sensing input	Transformation	
					P	F
	CO_2 regulation (CO_2 R)	Sequestered CO_2 [$kgCm^{-2}yr^{-1}$]	Same as potential supply	MODIS: Land cover (MCD12Q1), net primary production (MOD17A3H)	$x^{0.5}$	$x^{0.5}$
Regulating	Air quality regulation (AQR)	PM_{10} removal [$\mu g\ m^{-2}$]	PM_{10} removal [$\mu g\ m^{-2}$] in urban areas	MODIS: Leaf area index (LAI) (MOD15A2H)	$x^{0.25}$	$x^{0.25}$
	Soil erosion prevention (SEP)	Potential soil erosion [$t\ ha^{-1}$]	Potential soil erosion [$t\ ha^{-1}$] in agricultural areas	MODIS: NDVI (MOD13A1), Digital elevation model	$x^{0.2}$	$x^{0.2}$
Cultural	Recreational hiking (RH)	Density of hiking paths combined with nighttime stable lights as natural-/remoteness parameter [-]	Recreational hiking potential weighted with visitation preference [-]	DMSP-OLS: Nighttime stable lights	$x^{0.6}$	$x^{0.15}$

15

2.4 Spatial and temporal analysis of ecosystem services

Annual spatial maps of retrieved ES were used to quantify the temporal variability of each ES in Switzerland and its four regions (Figure 1). Therefore, we calculated the annual mean value of ES potential supply and flow per biogeographical region and represented results as time series.

Trends of ES between 2004 and 2014 were analyzed for all ES and spatially represented. We applied a linear regression analysis per pixel; slopes above zero indicated an increase of the respective ES over time and values below zero showed a decreasing ES trend. Results were represented in a map and were later utilized to calculate average ES trends for Switzerland and each Swiss region.

Additionally, annual total ES potential supply and flow of Switzerland were calculated and stratified by four ecosystem types, namely forest, grassland, agriculture and urban. Ecosystem types were selected from raster-based CORINE land cover 2006 (250 m; (Steinmeier, 2013) and resampled to 500 m spatial resolution based on majority count of the pixel and its nearest neighbours. We selected this classification to stratify the different ecosystem types during the investigation period, since land use change per year in Switzerland is negligibly small with approximately 1 % (Swiss Federal Statistical Office, 2016).

Annual spatial maps of ES per year were used to estimate ES relationships and their temporal change during the investigation period. We identified ES synergies and trade-offs among ES potential supply and flow for all pair-wise combinations of ES by calculating annual Pearson correlation coefficients. A synergy between two ES occurs if a high value of one ES correspond to a high value of another ES (Bennett et al., 2009). In this case, the Pearson correlation coefficient is larger than 0. A trade-off between two ES occurs if a certain ES value corresponds to an opposite value of

341 another ES (Rodriguez et al., 2006), resulting in a Pearson correlation coefficient

342 smaller than 0. Annual maps of Pearson correlation coefficients per ES pair

343 combination were calculated at national and regional scale and visualized as time

344 series.

345 Temporal ES synergies and trade-offs were analyzed for all ES pair combinations and

346 spatially represented. A temporal synergy between two ES occurs if both ES fluctuate

347 in synchrony (e.g. both increase) over time, while a temporal trade-off is defined by

348 opposite temporal trends of two ES (e.g. one increases while the other decreases). We

349 computed temporal synergies and trade-offs using the Pearson correlation coefficient

350 to describe the relationship between two ES time series per pixel. Positive correlations

351 represented temporal synergies between two ES, while negative correlations

352 represented temporal trade-offs. Preprocessing steps of the correlation analysis

353 included a transformation (Table 1) and a standardization of each ES (i.e. mean of

354 zero, standard deviation of one), since the variables must have a linear relationship

355 and be normally distributed. The best transformation was selected by checking

356 quantile-quantile plots. Resulting Pearson correlation coefficients per ES pair are

357 presented in a map.

358

359 **3. Results**

360 **3.1 Spatial and temporal trends in ecosystem services**

361 The temporal analysis of ES in Switzerland revealed changes in yearly averages of

362 both ES potential supply and flow (Figure 2). Temporal fluctuations were

363 synchronous between the different Swiss regions. However, temporal variability

364 within a region could be of similar magnitude to differences between regions, e.g. for

365 CO_2 R and AQR (Figure 2a, d, e). In contrast, temporal fluctuations of SEP and RH

within a region were smaller compared to differences between regions (Figure 2b, c, f, g). ES potential supply and flow showed slightly differing changes during the investigated period.

CO_2 R displayed ES values for Jura and Swiss Midlands above the national average, while Central and Southern Alps had lower values compared to the national average (Figure 2a). Temporal CO_2 R pattern are consistent across all regions with a decrease in the service since 2011. Temporal variations in SEP potential supply and flow per region were low relative to differences among the regions (Figure 2b, c), tough with apparently larger temporal fluctuations in the Southern Alps, where SEP was highest, approximately threefold the Swiss SEP average. AQR showed fluctuating temporal trends in ES potential supply and flow for all investigated regions characterized by an overall decrease, but with two maxima in 2007 and in 2011 (Figure 2d, e). Highest average AQR potential supply was found in Jura, followed by Swiss Midlands, Southern Alps, and Central Alps. AQR ES flow was nearly the same for all regions except for the Southern Alps, which was larger compared to the other regions. RH averages of potential supply and flow slightly decreased during in investigated period with an absolute minimum in 2010 (Figure 2f, g). ES potential supply of RH revealed the highest averages for the Central Alps and Southern Alps, followed by Jura and Swiss Midlands. In contrast, averages of ES flow were highest for the Southern Alps and remained relatively stable for Jura and Swiss Midlands within the investigation period.
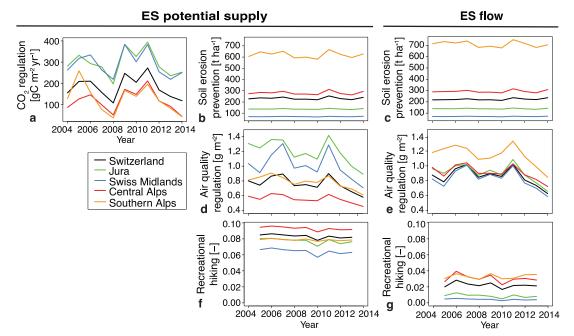
Figure 2: Average temporal change of ES potential supply (a, b, d, f) and flow (a, c, e, g) in Switzerland and its regions between 2004 and 2014: (a) carbon dioxide regulation, (b, c) soil erosion prevention, (d, e) air quality regulation, and (f, g) recreational hiking (only 2005 – 2013). ES potential supply and flow are the same for carbon dioxide regulation (a), but is only shown here once.

Spatial patterns of temporal trends in ES potential supply and flow were rather diverse (Figure 3, significant trends see Appendix A.2). Nearly nationwide, CO_2 R showed decreasing trends (Figure 3a). Highest negative trends were located in the Southern Alps, while partly increasing trends were detected in the western and eastern Central Alps. SEP potential supply and flow remained relatively stable in large areas of Switzerland between 2004 and 2014, with spatially scattered increasing trends in the Central Alps and Southern Alps (Figure 3b, e).
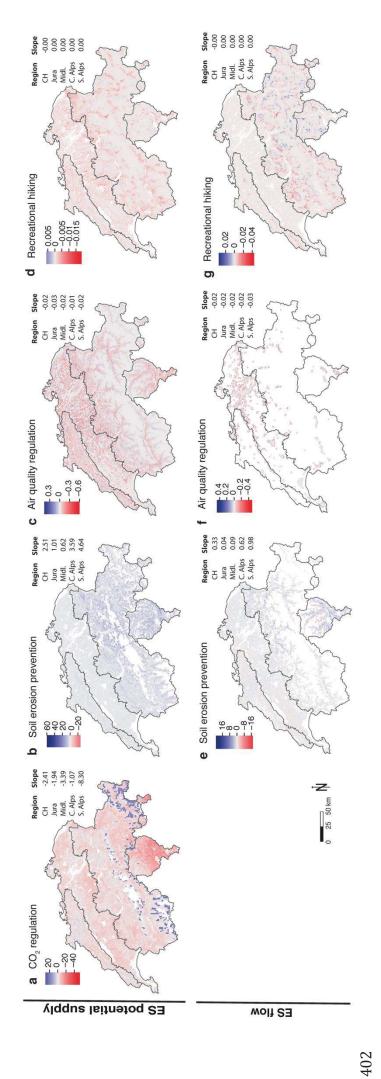
Figure 3: Temporal trends in ecosystem service potential supply (a-d) and flow (a, e-g) during 2004 and 2014: (a) Carbon dioxide regulation, (b, e) soil erosion prevention, (c, f) air quality regulation, and (d, g) recreational hiking (only 2005 – 2013). ES potential supply and flow are the same for carbon dioxide regulation (a), but is only shown once here.

20

Temporal trends of AQR revealed spatial heterogeneity with mainly decreasing trends for AQR potential supply in the Jura, Swiss Midlands and in valleys of the Central and Southern Alps (Figure 3c). AQR flow showed stable trends in urban areas with decreasing trends at their borders (Figure 3f). RH potential supply remained stable in most parts of Switzerland with some spatially scattered decreasing trends all-over Switzerland (Figure 3d). RH flow showed no trends in the Jura and the Swiss Midlands, but revealed some fluctuating spatial pattern of increasing and decreasing trends in the Central and Southern Alps (Figure 3g).

Swiss annual total ES potential supply and flow revealed the same relative importance of ecosystem types for all investigated ES (Figure 4). In general, forest was the most important ecosystem type to provide ES potential supply and flow, followed by agricultural areas, grasslands and urban areas. The strongest changes between ES potential supply and flow were found for grasslands with reduced contributions for SEP and AQR (Figure 4b-c, d-e) and urban areas with increased contributions for AQR (Figure 4d-e). The temporal variability in ES potential supply and flow revealed slight changes for all ecosystem types during the investigation period (Figure 5). Forest and agriculture were characterized by the strongest variability in ES potential supply and flow. Furthermore, forests displayed relatively strong temporal variability in CO_2 R and RH flow and urban vegetation in potential supply and flow of AQR.
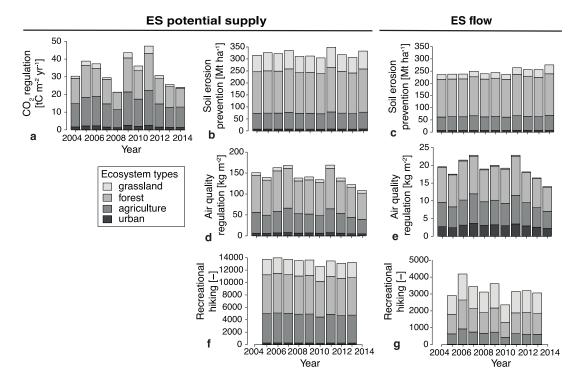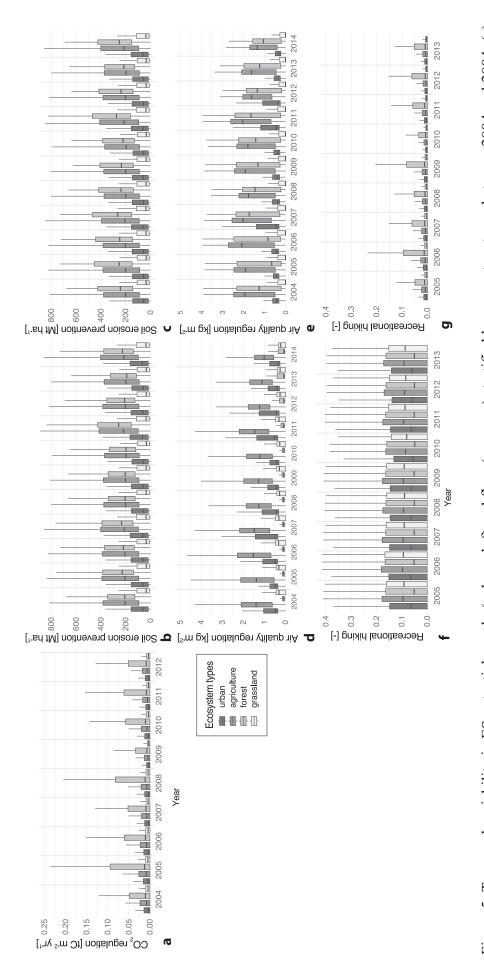
Figure 4: Annual total Swiss ES potential supply (a, b, d, f) and flow (a, c, e, g) stratified by ecosystem types between 2004 and 2014: (a) carbon dioxide regulation, (b, c) soil erosion prevention, (d, e) air quality regulation, and (f, g) recreational hiking (only 2005 – 2013). ES potential supply and flow are the same for carbon dioxide regulation (a), but is only shown here once.

3.2 Spatial and temporal ecosystem service trade-offs and synergies

Retrieved annual spatial maps of ES were used to estimate at an annual base ES synergies and trade-offs for all pair-wise combinations of ES and their temporal changes during the investigation period (Figure 6). In general, identified patterns fluctuated over time and substantially differed across regions. Swiss-wide synergies were identified between ES potential supply of CO_2 R-SEP ($R_{mean} = 0.15$), CO_2 R-RH ($R_{mean} = 0.05$), SEP-AQR ($R_{mean} = 0.02$), SEP-RH ($R_{mean} = 0.17$), AQR-RH ($R_{mean} = 0.02$). Only one trade-off was found for CO_2 R-AQR ($R_{mean} = -0.70$). ES flow showed the same patterns of synergies and trade-offs.

442

443   Figure 5: Temporal variability in ES potential supply (a, b, c, d, f) and flow (a, c, e, g) stratified by ecosystem types between 2004 and 2004: (a)

444   carbon dioxide regulation, (b, c) soil erosion prevention, (d, e) air quality regulation, and (f, g) recreational hiking (only 2005 – 2013). ES

445   potential supply and flow are the same for carbon dioxide regulation (a), but is only shown here once.

23

The analysis of ES relationships at national and regional scale revealed two patterns.

Firstly, regional and altitudinal differences in synergies and trade-offs of both ES potential supply and flow became evident. Several ES combinations revealed a split in Jura and Swiss Midlands versus Central and Southern Alps and in low and high elevations, respectively (e.g. ES flow of CO_2 R-RH and ES potential supply of CO_2 R-AQR) (Figure 6).

Secondly, ES relationships were depending on spatial scale. Pearson correlation coefficients were e.g. positive for ES potential supply of CO_2 R and SEP at national scale representing a synergy, but they were negative at regional scale resulting in trade-offs. Similar patterns were identified for ES potential supply of CO_2 R-RH and AQR-RH.
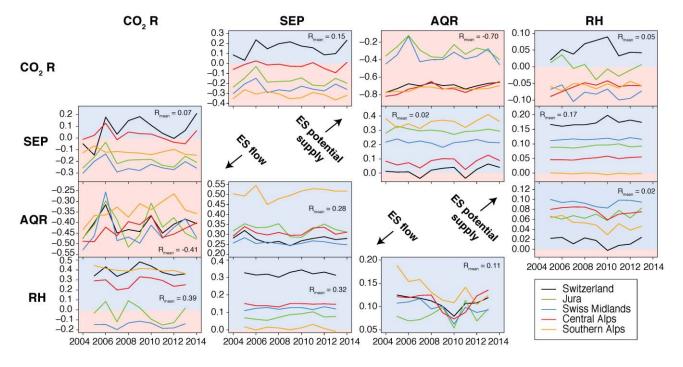

Figure 6: Annual Pearson correlation coefficients of ecosystem service potential supply (upper right corner) and flow (lower left corner) combinations between 2004 and 2014. R_{mean} is the Swiss mean correlation coefficient of two ecosystem services during the investigation period. Blue background colour indicates positive correlations, while red represents negative correlations.

24

Pixel-wise correlations of time series of ES pairs revealed a spatially heterogeneous mix of temporal synergies (positive correlation) and trade-offs (negative correlations) (Figure 7). Mainly temporal trade-offs were found for CO_2 R-AQR potential supply and flow across Switzerland. CO_2 R-SEP potential supply partly showed synergies in the Swiss Midlands and Southern Alps, but trade-offs in the Jura and the Central Alps. In contrast, ES flow displayed partly opposite patterns. A spatially heterogeneous mix of synergies and trade-offs characterized CO_2 R-RH, SEP-RH, AQR-RH, and SEP-AQR all-over Switzerland for both ES potential supply and flow.
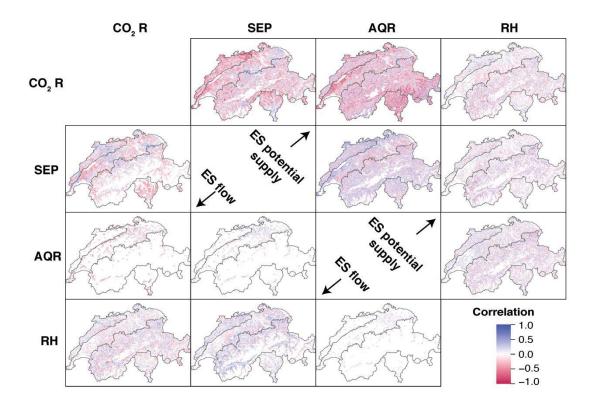

Figure 7: Pair-wise spatial correlations of ES time series from 2004 to 2014. Correlations between ES potential supplies are located in the upper right corner, between ES flow in the lower left corner. Correlations > 0 represent synergies and < 0 are trade-offs. Note that correlations with recreational hiking (RH) refer to the time period 2005 to 2013.

25

4. Discussion

4.1 Spatial and temporal pattern in potential supply and flow of ecosystem services

We observed a declining trend of CO_2 R between 2004 and 2014 across regions in Switzerland. Considering the stimulating effect of increasing atmospheric CO_2 concentration for photosynthesis (Kirschbaum, 2011) and a general increase of biomass in Switzerland (de Jong et al., 2013), this result seems contradicting. We defined CO_2 R as equivalent to NEP that was approximated by MODIS NPP and modeled soil respiration. MODIS NPP was lower in 2013 and 2014 compared to the years before, since we used a simple linear model to describe the trend, the two relatively low NPP values likely impact the calculated trend and partly explain the observed decline in CO_2 R. The use of liner models to estimate ES trends could influence the results of all ES, since these models are sensitive to extreme values, in particular when a relatively short time period of 10 years was investigated. Further, increasing temperatures between 2004 and 2014 also contributed to the decreasing trend of CO_2 net uptake, because of its enhancing effect on soil respiration (Bond-Lamberty and Thomson, 2010; Reichstein and Beer, 2008). Inaccuracies in modeled soil respiration could render another explanation eventually causing the decreasing trend of CO_2 R: Schröter et al. (2014) applied a similar approach for mapping the annual carbon storage in a study area in Norway. The authors restricted their analysis to forested areas, while arguing that modeled soil respiration highly exceeded actual NPP in other ecosystems, where a neutral carbon balance can be assumed. This seems to indicate a problem to model soil respiration spatially explicit based on the approach of Raich et al. (2002). Some ecosystems, in particular with sparse vegetation such as grasslands in alpine areas, seem particularly sensitive to correct soil respiration

estimations. In contrast to such underestimations, the influence of agricultural areas to CO_2 R was partly overestimated, since carbon losses due to harvest removal were not considered. Apart of the general decline in CO_2 R, we also observed increasing CO_2 R trends in the Central Alps. These could originate from land abandonment in Alpine areas followed by expansion of wooded areas (Gellrich et al., 2007). Wooded areas enable higher CO_2 uptake (Bolliger et al., 2008), hence, increasing CO_2 R during the investigated period. An alternative to our approach of estimating CO_2 R is the measurement of change in carbon stocks, in particular in forests. This can be achieved e.g. by measuring over time the increment in standing biomass in a forest using light detection and ranging (LiDAR) (Babcock et al., 2016).

Swiss-wide SEP remained relatively stable during the investigation period. Only few areas in the Central and Southern Alps showed increasing trends of SEP. Compared to the study of Guerra et al. (2016), who developed and exemplified the SEP model for a Mediterranean test case, our estimates of SEP are lower. This difference can be explained by different climatic conditions, soil characteristics and agricultural practices. Furthermore, Switzerland has had several legal frameworks to protect soils, for example the Soil Pollution Ordinance from 1986 and the voluntary agri-environmental scheme as part of the agricultural legislation since 1993. 98% of Swiss farmers participate in this agri-environmental scheme and receive direct monetary support if ecological standards are fulfilled (Prasuhn et al., 2013). Therefore, the contribution of agricultural ecosystems to annual total SEP was relatively high with approximately 20 % after forests as main contributor. Since the legal frameworks have already existed for approximately 25 years, ES trends in our investigation period were very small. Nevertheless, obtained results of SEP reveal the huge service

528 ecosystems provide and confirm the success of Swiss legislation to effectively protect

529 soils against soil erosion.

530 Analysis of AQR potential supply and flow showed a decreasing trend. This,

531 however, does not imply something negative or a decreasing capability of ecosystems

532 for AQR: The applied AQR model highly depends on actual PM_{10} concentrations.

533 Since PM_{10} concentrations decreased during the investigation period, the actual

534 service diminished as well, indicating a positive effect for human well-being. It is

535 important to notice the inverse relationship between the trend in AQR and the effect

536 for human well-being. This negative relationship is different compared to the other ES

537 and could cause confusion when interpreting results or discussing further trajectories

538 of environmental protection. Our average AQR values per year for Switzerland are in

539 the range of other studies (Manes et al., 2016; Remme et al., 2014). The Swiss

540 Midlands displayed the most heterogeneous picture with small-scale changes in AQR

541 trends due to high particulate matter emissions by industry, traffic, heating systems of

542 private households, and agriculture on the one hand and scattered green space in

543 urban areas on the other hand. Urban vegetation had a higher contribution to AQR

544 flow than potential supply indicating the benefits of urban green space for aerosol

545 removal and contributing to the small-scale spatial variability in ES potential supply

546 and flow.

547 Trends in RH revealed stagnation in large parts of Switzerland. A decreasing trend of

548 RH was found in some Alpine valleys and along lakes, suggesting decreasing

549 recreational potential in these areas. We argue that this finding is mainly caused by

550 the strategy and underlying data used to calculate RH, which does not lead to a clear

551 indicator yet. Increasing nighttime light emissions, for example, represent less

552 natural- and remoteness of the landscape compared to the years before. A decreasing

amount of Flickr data at these locations suggests declining visitation rates, however the direct link of Flickr data to visitation rates is missing and requires additional research in the future. While the night-light data represent a reliable quantitative measure, the use of Flickr data is problematic. When using Flickr data, one has to account for temporal and spatial biases. A temporally increasing bias is caused by the fact that the website was created in 2004 and has shown a strong increase in users since then. A spatial bias is due to an uneven and clustered distribution of social media data (Li et al., 2013; Wood et al., 2013). Additionally, only a limited amount of hikers take geotagged photographs and share them on Flickr, causing a preference in the used RH model towards a specific group of hikers using Flickr: Social media users are typically younger, better educated, and wealthier than average (Li et al., 2013). However, female hikers in Switzerland represent a nearly equal share between 15 to 74 years, while the proportion of male hikers increases with age (Bundesamt für Strassen (ASTRA) and Schweizer Wanderwege, 2015). Therefore, a large part of older hikers and their preferred hiking areas are likely not represented in the Flickr data, and hence in this analysis. Nevertheless, our results of RH indicated that even though the RH potential supply was the highest in forest and agricultural ecosystems, ES flow took mainly place in grasslands and forests. This represents a preference for alpine and natural landscapes instead of agricultural ecosystems and a realistic picture of hiking preferences in Switzerland (Bundesamt für Strassen (ASTRA) and Schweizer Wanderwege, 2015). In general, the use of social media data for analyzing people's preferences for recreation in combination with RS-based estimates of natural- and remoteness of a landscape offers many opportunities for more detailed investigations, in particular when neglecting the temporal component of Flickr data (Levin et al., 2015). Examples are the identification of nature elements that attract

578   people or whether changes in ecosystems will modify visitation rates. In the future,

579   estimations of recreation based on Flickr data can provide a more comprehensive

580   picture by analyzing not only the photo user days, but as well the semantics attached

581   to the geotagged photos and the content of the photo. This can provide a better inside

582   about the executed activity (e.g. hiking, mountain biking, go for a walk etc.) and the

583   landscape preferences (e.g. view, lake side, waterfall, alpine grassland etc.).

584

585   **4.2 Spatio-temporal pattern in ecosystem service trade-offs and synergies**

586   Identified synergies and trade-offs of different ES potential supply and flow

587   combinations were relatively stable between 2004 and 2014. Except for the

588   CO_2 R-AQR combination, representing a trade-off in our analysis, our results are in

589   agreement with findings of a European study by Jopke et al. (2015).

590   The presence of vegetation explains observed synergies between CO_2 R-SEP,

591   CO_2 R-RH, and SEP-RH as it determines CO_2 R due to CO_2 uptake by

592   photosynthesis, enhances SEP due to mitigated soil erosion by vegetation cover, and

593   is enjoyed while hiking. The trade-off between AQR-CO_2 R was caused by a

594   mismatch in areas of high PM_{10} concentrations, typically less covered with

595   vegetation, and densely vegetated areas with potentially high rates of photosynthetic

596   activity and thus CO_2 uptake. For other ES combinations including AQR (i.e.

597   AQR-SEP, and AQR-RH) slight synergies were found but it is difficult to explain

598   them mechanistically.

599   In general, research on ES trade-offs and synergies has particularly focused on trade-

600   offs between provisioning and regulating ES (Maes et al., 2012; Rodriguez et al.,

601   2006). Trade-offs within regulating or between regulating and cultural ES have not

602   yet been extensively investigated so far. Observed temporal changes of ES trade-offs

603 and synergies were relatively small, indicating robustness of the determined

604 relationships over time. This is important for sustainable decision-making in

605 agricultural management, landscape planning and conservation.

606

4.3 What can remote sensing contribute to spatio-temporal ecosystem service assessments?

607

608

609 RS-based assessments of spatio-temporal trends in ES potential supply and flow

610 provide new insights and facilitate ES research and monitoring. We could

611 demonstrate the added value of including RS data in ES assessments compared to

612 commonly applied ES mapping approaches that use land cover information as key

613 input in combination with expert knowledge (Burkhard et al., 2012; Jacobs et al.,

614 2015) and ES models that assign the same biophysical values to each land cover class

615 (Nelson and Daily, 2010). Such approaches often quantify only the change of an ES

616 providing area (Eigenbrod et al., 2010), while RS allows detailed insights into the

617 variability of ES potential supply and flows across spatial scales and time. This is

618 particularly relevant since ES potential supply and flow are similarly important

619 concerning natural capital accounting within SEEA. Further, the high spatio-temporal

620 granularity of derived ES information allows relating changes in ES to environmental

621 condition and supports the definition of appropriate spatial scales for monitoring

622 purposes of ES, their trade-offs, and synergies.

623 Suggested RS-based approaches to assess ES avoid the use of less informative proxies

624 or indicators of ES and rather rely on biophysical models to determine ES potential

625 supply and flow. Trend analyses based on multi-temporal ES monitoring directly

626 represent changes in ES, rendering another advantage compared to currently used ES

627 indicators. Shepherd et al. (2016), for example, identified ES indicators for trend

628   analyses at global scale. Only for 62 % of the investigated indicators they could find a

629   strong ability to detect trends in relevant ES. Particularly for some regulating services

630   (e.g. local climate and air quality, erosion prevention and soil fertility) and any

631   cultural service, no suitable ES potential supply indictors could be identified at all.

632   RS- based approaches can partly fill this gap for several ES.

633   Further, RS-based ES assessments foster a regular monitoring of ES at critical time

634   intervals (i.e. monthly, half-yearly or yearly). Non-RS derived ES indicators or land

635   cover-based ES maps are challenged with a regular monitoring in sufficiently short

636   intervals to capture ES changes and facilitate decision-making with temporal ES

637   assessments. Although a study by Maes et al. (2014) developed more than 300 ES

638   indicators for a European ES mapping attempt, only a small fraction of these ES

639   indicators (i.e. 15% for forests, 27% for agro-ecosystems, 13% for freshwater, 42%

640   for marine systems) can be mapped regularly in short intervals. Further, some of the

641   often used ES indicators rely on land-use data with a rather long update interval, i.e.

642   the five yearly updated CORINE Land Cover product. Further, even though RS

643   technology can provide land cover maps more regularly and accurate, direct estimates

644   of ES potential supply and flow using biophysical models can avoid the use of rather

645   static land cover classifications (Karp et al., 2015).

646   Detailed RS-based information of ES potential supply and flow, as well their trends,

647   trade-offs, and synergies facilitate research and evidences of ES changes relevant for

648   stakeholders and decision-makers. Regular spatially explicit monitoring of ES using

649   RS data can enable the evaluation whether decisions in politics, economy, and

650   conservation have a positive or negative influence on ES (Rose et al., 2015).

651

652

5. Conclusion

We conclude on the importance of RS and its versatile advantages for spatio-temporal monitoring of ES compared to indicator based mapping approaches. Particularly the analysis of spatial time series data enables the detection of ES trends and ES interactions in both time and space, eventually contributing to advance decision-making in landscape planning and conservation and to verify progress towards policy targets (e.g. Aichi Biodiversity Targets and Sustainable Development Goals). Spatial ES data can enable regular evaluations of e.g. the efficiency of agri-environmental schemes and of payments for ES.

We suggest exploiting the capability of RS data for ES assessments and implementing them at a regular base. Depending on the spatial and temporal scale as well as the spectral requirements of the ES assessment, a variety of RS sensor is available such as IKONOS, Landsat, Sentinel-2, AVHRR (Advanced Very High Resolution Radiometer), which partly enable either long (but spatially coarse) or dense (but temporally short) ES time series. The limited range of (partly) assessable ES with RS data (except for land cover), however, must be carefully taken into consideration. Nevertheless, the huge potential of RS has not yet been fully exploited, in particular, for regulating and cultural ES. Upcoming Earth observation missions will extend this potential in the future and will allow more holistic and regular monitoring of ES.

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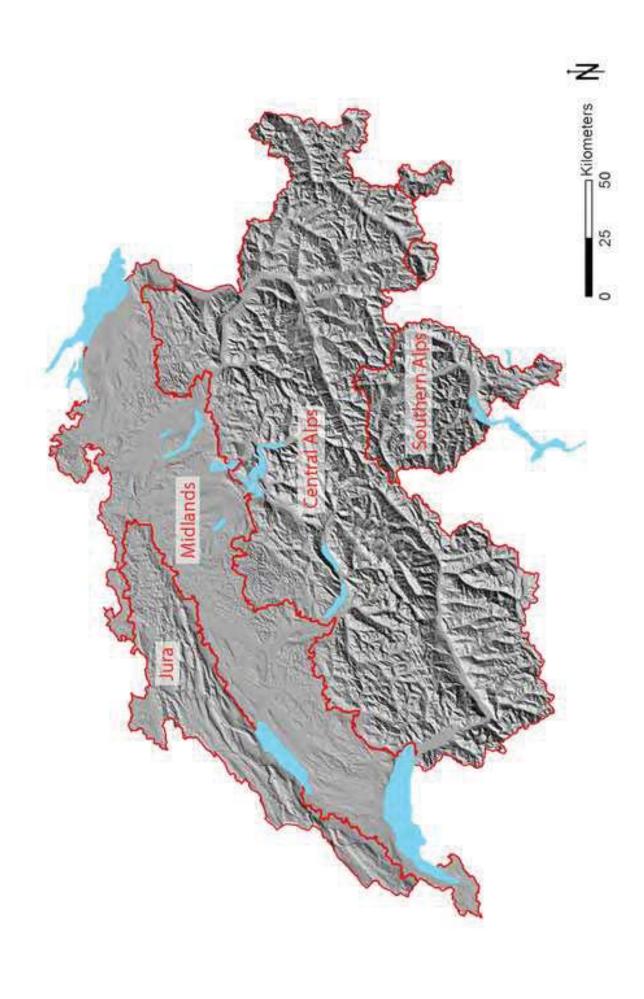
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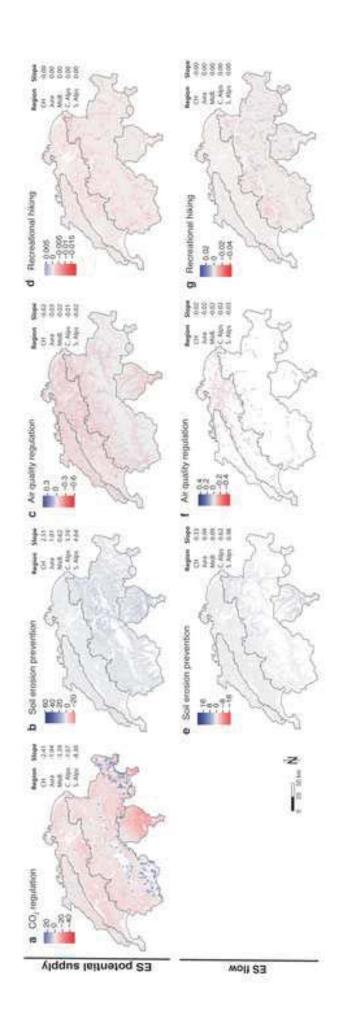929   Lull, H.W. (Eds.), Forest Hydrology. Pergamon Press, Oxford, UK, pp. 137 - 161.

930

Figure2

Figure4

ES potential supply

ES flow

a CO$_2$ regulation [tC m^{-2} yr^{-1}]

b Soil erosion prevention [Mt ha^{-1}]

c Soil erosion prevention [Mt ha^{-1}]

d Air quality regulation [kg m^{-2}]

e Air quality regulation [kg m^{-2}]

f Recreational hiking [−]

g Recreational hiking [−]

Year

Ecosystem types
grassland
forest
agriculture
urban

Figure5

a
CO_2 regulation [tC m^{-2} yr^{-1}]
0.00 0.05 0.10 0.15 0.20 0.25
2004 2005 2006 2007 2008 2009 2010 2011 2012

Ecosystem types
- urban
- agriculture
- forest
- grassland

b
Soil erosion prevention [Mt ha^{-1}]
0 200 400 600 800
2004 2005 2006 2007 2008 2009 2010 2011 2012 2013 2014

c
Soil erosion prevention [Mt ha^{-1}]
0 200 400 600 800

d
Air quality regulation [kg m^{-2}]
0 1 2 3 4 5
2004 2005 2006 2007 2008 2009 2010 2011 2012 2013 2014

e
Air quality regulation [kg m^{-2}]
0 1 2 3 4 5
2004 2005 2006 2007 2008 2009 2010 2011 2012 2013 2014

f
Recreational hiking [-]
0.0 0.1 0.2 0.3 0.4
2005 2006 2007 2008 2009 2010 2011 2012 2013
Year

g
Recreational hiking [-]
0.0 0.1 0.2 0.3 0.4
2005 2006 2007 2008 2009 2010 2011 2012 2013

Year

Figure6

Figure7

Correlation
1.0
0.5
0.0
-0.5
-1.0

ES potential supply

ES flow
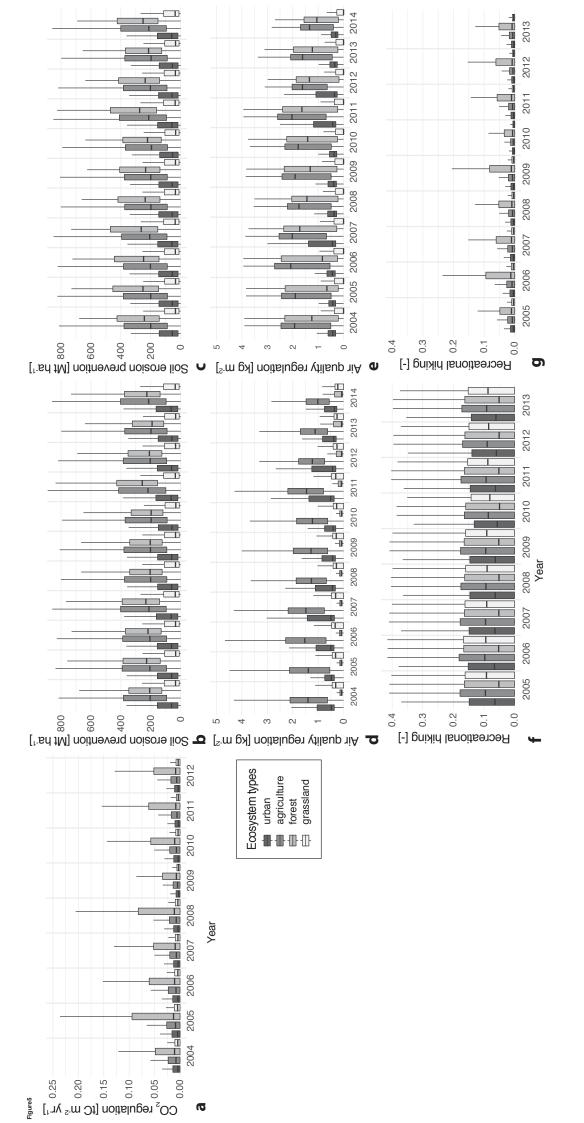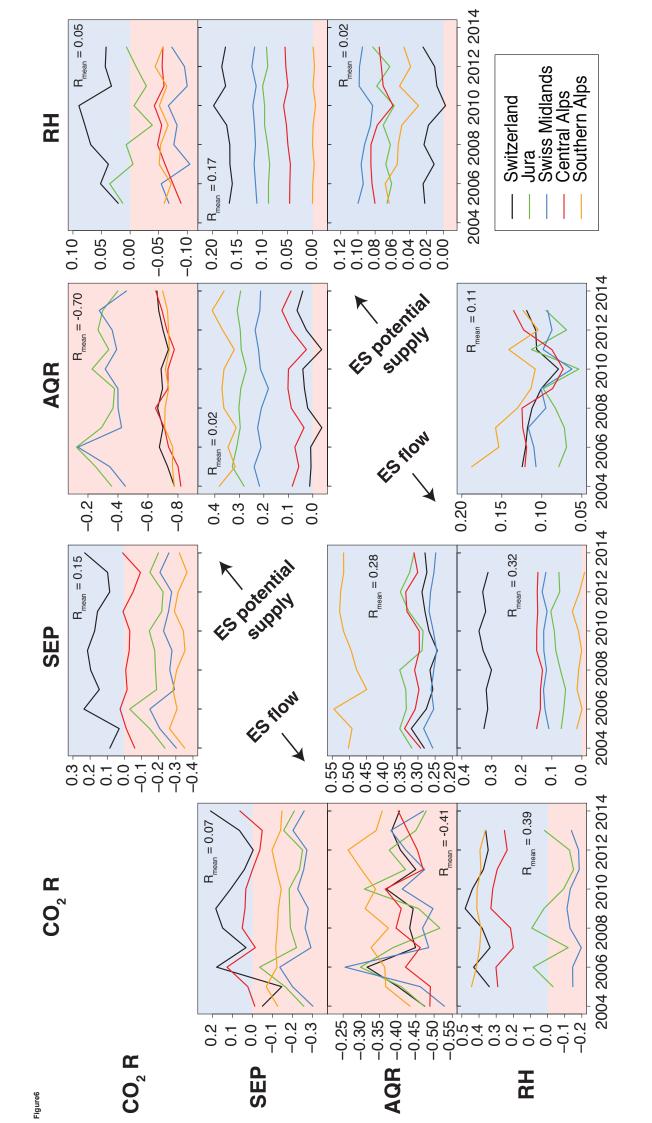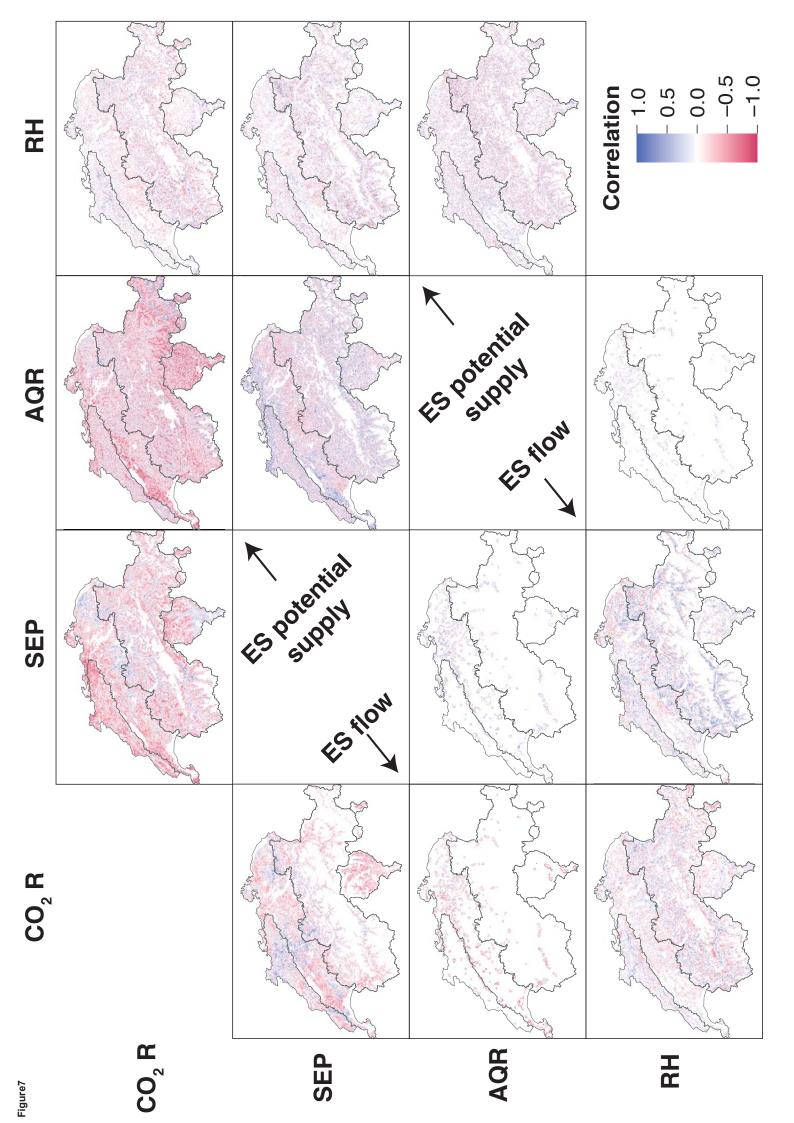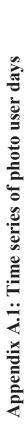
Tables

Table 1: Overview of investigated ecosystem services (ES), their potential supply (= P) and flow (= F) as well as their remote sensing inputs.

The transformations were applied to provide comparability for the trade-off and synergy analysis.

Section	ES	ES potential supply	ES flow	Remote sensing input	Transformation	
					P	F
	CO_2 regulation (CO_2 R)	Sequestered CO_2 [$kgCm^{-2}yr^{-1}$]	Same as potential supply	MODIS: Land cover (MCD12Q1), net primary production (MOD17A3H)	$x^{0.5}$	$x^{0.5}$
Regulating	Air quality regulation (AQR)	PM_{10} removal [$\mu g\ m^{-2}$]	PM_{10} removal [$\mu g\ m^{-2}$] in urban areas	MODIS: Leaf area index (LAI) (MOD15A2H)	$x^{0.25}$	$x^{0.25}$
	Soil erosion prevention (SEP)	Potential soil erosion [$t\ ha^{-1}$]	Potential soil erosion [$t\ ha^{-1}$] in agricultural areas	MODIS: NDVI (MOD13A1) Digital elevation model	$x^{0.2}$	$x^{0.2}$
Cultural	Recreational hiking	Density of hiking paths combined	Recreational hiking potential	DMSP-OLS:	$x^{0.6}$	$x^{0.15}$

(RH) with nighttime stable lights as weighted with visitation Nighttime stable lights

natural-/remoteness parameter [-] preference [-]

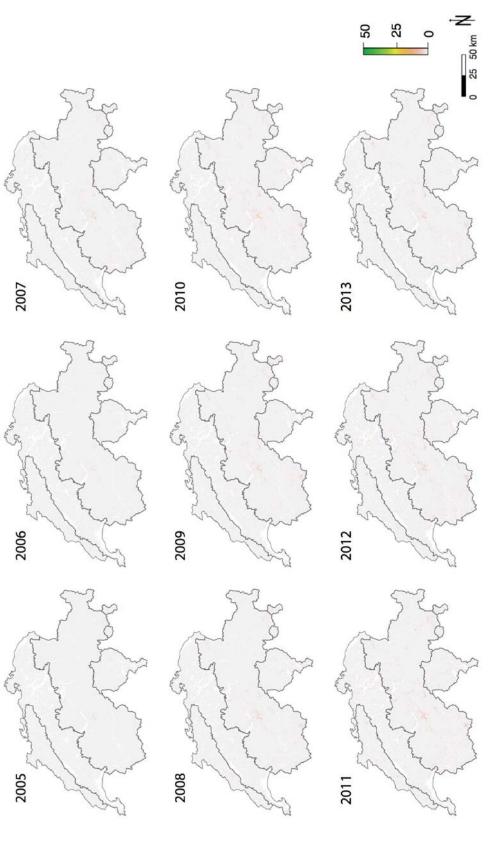**Appendix A.1: Time series of photo user days**

Figure A.1.1: Photo user days (PUD) per year from 2005 until 2013.

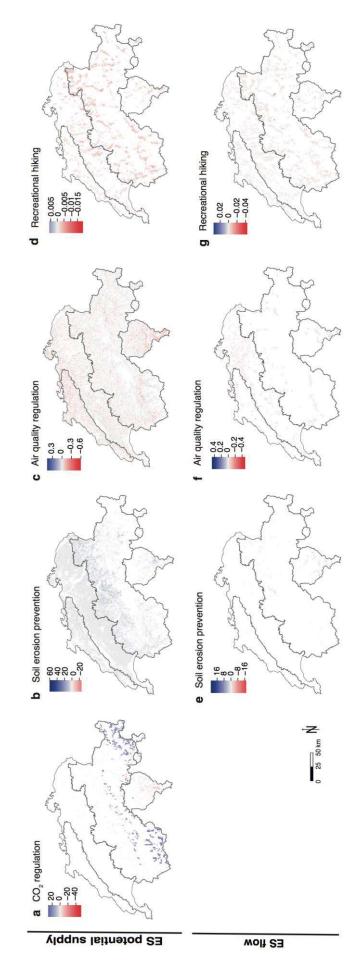# Appendix A.2: Significant ecosystem service trends

Figure A.2.1: Significant temporal trends in ecosystem service potential supply (a-d) and flow (a, e-g) during 2004 and 2014: (a) Carbon dioxide regulation, (b, e) soil erosion prevention, (c, f) air quality regulation, and (d, g) recreational hiking (only 2005 – 2013). ES potential supply and flow are the same for carbon dioxide regulation (a), but is only shown once here