1	Mapping the functional connectivity of ecosystem
2	services supply across a regional landscape
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27 Abstract

28 Sustainably managing multifunctional landscapes for production of multiple 29 ecosystem services (ES) requires thorough understanding of the interactions 30 between ES and the ecological processes that drive them. We build upon landscape connectivity theory to present a spatial approach for assessing 31 32 functional connections between multiple ES at the landscape scale. We 33 demonstrate application of the approach using existing ES supply mapping data for plant agriculture, waterflow regulation, and landscape aesthetics. The 34 35 connections we observed between these three ES revealed high-value 36 multifunctional linkages on the landscape that were not necessarily predictable 37 from supply area mapping, nor from land use or land cover data. By providing 38 spatial information on ES connectivity, our approach enables local and regional 39 environmental planning and management that takes full consideration of the 40 complex, multi-scale interactions between ecological processes, land use and 41 land cover, and ecosystem service supply on a landscape. 42 **Keywords**: ecosystem services; nature's contributions to people; multifunctional 43 landscapes; functional connectivity; environmental planning and management.

44

45 Introduction

The rapid, human-driven modification of wilderness is reshaping land cover distribution and disconnecting natural ecosystems, which has negatively impacted biodiversity and natural resources (Foley et al. 2005, Butchart et al. 2010, Foley et al. 2011). As these changes continue across the globe, everincreasing demands are being placed on landscapes to deliver nature's contributions to people, or 'ecosystem services' (ES; Carpenter et al. 2009). These juxtaposing forces highlight an urgent need for incorporating both

53 biodiversity and ES in land use planning, with recent research calling specifically 54 for consideration of landscape structure and connectivity in order to optimize 55 environmental management objectives (Mitchell et al. 2013, Ekroos et al. 2014, 56 Werling et al. 2014, Dobbs et al. 2014). The boom in ES research over the past 57 several decades has improved our understanding of the ecological drivers 58 underpinning the supply of ES, but more nuanced work is necessary to 59 meaningfully manage ES provision and their interdependencies at the landscape 60 scale (Kremen 2005, Tscharntke et al. 2005, Nicholson et al. 2009, Daily et al. 61 2009). Specifically, the supply of an ES is typically mapped within fixed areas 62 (e.g., Tallis et al. 2008) without considering the potential relevance of ecological 63 process flux across the landscape for supporting ES provisioning (e.g., Mitchell 64 et al. 2013) and multi-ES relationships. By failing to represent the spatial and functional connectivity between supply areas in ES assessment, we ignore 65 66 ecological processes that may be fundamental to the maintenance of ES 67 supplies, run the risk of overlooking potentially critical areas in landscape-scale 68 management, and miss opportunities for uniting divergent interest groups 69 around the concept of multifunctional landscapes (i.e., those that provide 70 multiple ES beyond those that are primarily managed; Power 2010). To optimize 71 ES provisioning while minimizing potential negative effects on human well-being 72 in the face of increased development pressures, it is critical to understand the 73 dynamics of multi-ES supply (Lorilla et al. 2018).

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Connectivity is a key attribute of landscape resilience and of ES in general (e.g.,
Bennett et al. 2021). A connected landscape facilitates the movement of energy,
matter, organisms, seeds, pollinators, and people, thereby supporting several
ecological processes that are critical for maintaining supplies of ES (Tscharntke

79 et al. 2005, Kremen et al. 2007, Biggs et al. 2012, Mitchell et al. 2013, Pal et al. 80 2021). Conversely, a fragmented landscape exhibits decreased productivity, 81 functional robustness, ecological richness (Leibold et al. 2004, Gonzalez et al. 82 2009, Simmonds et al. 2019, Melo et al. 2019), and increased vulnerability to 83 further human modifications (Dutta et al. 2017, Xinxin et al. 2017, Liu et al. 2017, 84 Chi et al. 2018). Smaller patches of habitat, biotic and/or abiotic supplies are not 85 able to support as many species or as large populations relative to larger 86 patches (Harper et al. 2005), and loss of landscape connectivity can hinder 87 dispersal and migration of plants and animals (Fischer et al. 2007). Such 88 deleterious effects on the wealth of biodiversity and natural capital can lead to 89 declines in total ES supply and in the quantity and/or quality of flows to human 90 beneficiaries (Mitchell et al. 2015, Pal et al. 2021). Pal et al. (2021) showed 91 specifically that fragmentation, and not just diminishment of ES supply areas, 92 contributed to significant declines in ES values over time. Landscape 93 fragmentation impacts the supply of ES through altering the distribution and 94 movement of the ecological elements, structures and processes underpinning 95 the maintenance of natural capital (Mitchell et al. 2015). Mitchell et al. (2015) 96 discuss how loss of connectivity can be a driver of interactions between multiple 97 ES and can impact both the size and location of ES flows (Bagstad et al. 2013). 98 Among key policy principles identified for enhancing ES resilience to 99 disturbances and environmental changes is managing for connectivity among 100 ES-related resources, species, and human actors, with specific focus on the 101 strength and structure of these connections (Biggs et al. 2012). All this points to 102 the importance of planning for connectivity in multifunctional landscapes 103 (Phillips et al. 2015), while considering the potential for complex ecological

process-based interactions among services, to successfully manage for thedelivery of multiple ES (Dee et al. 2017).

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107 In simple terms, planning for landscape connectivity typically focuses on habitat 108 patches and movement corridors, whereas ES planning focuses on the areas of 109 the landscape with the capacity to produce the services humans need to survive 110 and thrive (Taylor et al. 1993, Egoh et al. 2008). Recent work calling explicitly for 111 incorporating ES into connectivity research has taken the perspective of 112 assessing how the characteristics of landscape connectivity (i.e., how a 113 landscape promotes or hinders movement of matter and organisms), along with 114 composition (i.e., quantities of land use and land cover, or 'LULC', types), and 115 configuration (i.e., spatial pattern of LULC), might directly or indirectly impact ES 116 provision and related ecological processes (Debinski and Holt 2000, Fahrig 117 2003, Gonzales et al. 2009, Mitchell et al. 2013). For example, adequate 118 arrangement of adjacent natural habitat areas in agricultural landscapes can aid 119 the movement of pollinators and pest predators to croplands, and thus promote 120 delivery of these services (Priess et al. 2007, Ricketts et al. 2008, Fleischner 121 1994, Tscharntke and Brandl 2004; Kremen et al. 2007, Tallis and Polasky 2009, 122 Power 2010, Lonsdorf et al. 2011). Habitat loss, fragmentation, and 123 management strategies detrimental to related connectivity can have the 124 opposite effect on pollinators (e.g., Kremen et al. 2002, Potts et al. 2010, 125 Mitchell et al. 2013)., whereas increased connectivity in croplands can facilitate 126 pest dispersal (Margosian et al. 2009). In terms of abiotic flows, connections 127 between upstream and downstream freshwater sources can be important for 128 maintaining quantity and quality of drinking water (Dodds and Oakes 2008, 129 Bangash et al. 2013), and maintenance of the natural hydrologic regime

130 stabilizes base flows and reduces flooding, thereby promoting waterflow 131 regulation (Poff et al. 1997). Viewing the attributes of structural and functional 132 connectivity in these ways, i.e., from the perspective of ES, helps to move 133 beyond the idea of managing for spatially discrete ES supply areas and toward 134 garnering better understanding of how we might manipulate certain connectivity 135 elements (e.g., habitat patch area, isolation distance, movement corridors) to 136 more effectively manage a landscape for individual ES (Mitchell et al. 2013). The 137 above examples highlight that the ecological processes underpinning the 138 supplies of certain ES directly influence the supplies of others, both when 139 services co-occur in space and, sometimes, when they are produced in separate 140 areas. Drivers behind multi-ES interactions, and the importance of such 141 processes, are sometimes discussed in ES interaction research (e.g., Li et al. 142 2017, Alemu et al. 2020) but, to our knowledge, have not been explicitly 143 delineated on the landscape in the context of multi-ES assessments. To truly 144 understand the relevance of landscape connectivity to ES, we must ask: what 145 and where are the mechanisms responsible for maintaining these connections 146 and, consequently, supporting the production of multiple ES? 147

148 Since the seminal global appraisal of ecosystems and the ES they provide (MEA 149 2005), research that assesses the interactions between multiple services has 150 increased exponentially (Agudelo et al. 2020; Appendix 1). However, research in 151 this discipline commonly only considers services that co-occur in space (e.g., 152 Queiroz et al. 2015), and assumes positively or negatively correlated ES to 153 represent synergistic production or trade-offs, respectively (Tomscha and Gergel 154 2016, Agudelo et al. 2020). Such assessments are typically based on correlation 155 coefficients of indicators aggregated within a geographic unit (e.g., watershed,

156 municipality) or randomly sampled across a region (Anderson et al. 2009, Qin et 157 al. 2015, Qiu and Turner 2015). These approaches to not directly evaluate 158 interactions based on underlying ecological process theory nor do they allow for 159 spatially discrete relationships to occur, i.e., they do not explicitly incorporate 160 the mechanisms responsible for ES interactions, and they ignore how ES 161 occurring in one area might have direct or indirect influence on ES in other 162 areas. It has also been shown that simple spatial correlation analyses between pairs of ES are not necessarily a good predictor of how relationships between ES 163 164 change over time (Mitchell et al. 2020), and that their interactions can vary 165 across the LULC types found in heterogeneous landscapes (Li et al. 2017); thus, 166 a better understanding of the processes that underpin the spatial patterns of ES 167 is needed to improve the sustainable management of multifunctional landscapes 168 (Mitchell et al. 2020). Recent research has visualized the spatial connectivity between ES supply areas by modelling the movement potential of species 169 170 through high guality habitat corridors as a proxy for how biodiversity flow in 171 general supports ES provisioning across the landscape (Peng et al. 2018). Still, 172 this does not represent different functional connections between ES supply, and 173 how the provisioning of one type of ES directly or indirectly effects the 174 provisioning of another across a landscape. Further, a recent systematic review 175 of studies that model interactions among multiple ES between 2005 and 2019 176 found that the vast majority of studies were conducted locally while relatively 177 few studies were done at the regional scale (Agudelo et al. 2020). However, 178 focus at the regional level may be most appropriate for reconciling the common 179 scale mismatches between biophysical and socio-economic elements involved in 180 sustainable ES management (e.g., Dalgaard et al. 2003, Cumming et al. 2006, 181 Satake et al. 2008, Ingram et al. 2008), while minimizing practical issues with

empirical mapping related to data gaps and indicator variability in areas larger than this (Verberg and Chen 2000; but see de Groot et al. (2010) for examples of variability in ecological scale relevance for specific ES). However, as this relates to *interactions* between different ES, small-scale observations may be masked at larger scales (Raudsepp-Hearne and Peterson 2016); therefore, incorporating local, grid-level data and analyses is important for providing meaningful information to planners (Haase et al. 2012).

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190 In spite of the growing knowledge around the complex interactions and feedbacks between ES and the related suite of biotic and abiotic mechanisms 191 192 and the cruciality of incorporating this into decision-making (Qiu and Turner 193 2013, Dee et al. 2017), spatial modelling of the diverse functional connections 194 between multiple ES (e.g., Cui et al. 2012, Kolosz et al. 2018, Agudelo et al. 2020) from several broad ES categories at the regional scale remains limited 195 196 (Field et al. 2017). Several approaches used in ecological connectivity studies to 197 identify potential spatial linkages across a landscape are promising in their 198 applicability multi-ES assessment. These include euclidean distances (Cressie et 199 al. 1993), least-cost path analysis (LCP; Larkin et al. 2004), least-cost corridor 200 (LCC; Singleton et al. 2002), circuit theory (McRae & Beier 2007), graph theory 201 (Pinto & Keitt 2009), and network flow models (Phillips et al. 2008). All these 202 approaches are potentially amenable to assessment of multi-ES interactions but, 203 to date, we know of no studies that have applied such methods to map the 204 process-driven interactions between the supplies of multiple ES in a regional 205 context (Peng et al. 2018). Further, studies that have incorporated both 206 landscape connectivity and ES concepts typically only focus on a single ES, are 207 skewed toward specific types of provisioning (e.g., food) and regulating (e.g.,

208 pollination) services, and, to our knowledge, have not yet tested cultural services209 (Mitchell et al. 2013).

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211 We present an approach to address the above research gaps, building on 212 existing ES mapping and modelling and rooted in landscape connectivity 213 theory, to demonstrate how the functional relationships between multiple ES 214 can be represented in the context of connectivity planning across a regional heterogeneous landscape. We demonstrate our approach using existing grid-215 216 level data from a case study landscape in the southern interior of British 217 Columbia, Canada, by mapping and assessing the connectivity between ES from 218 three broad categories: provisioning (plant food agriculture), regulating 219 (waterflow regulation), and cultural (landscape aesthetics; MEA 2005). Using 220 these, we conceptualize ES supply areas as structural components, and the 221 functional process links between these areas as configuration elements within a 222 landscape connectivity framework. We base our approach on existing, and 223 relatively straightforward, spatially co-occurring ES interaction and LCP corridor 224 methods to present a first step toward representing functional connectivity 225 between multiple ES. Our multi-step approach has three specific objectives: (1) 226 to define the ecological process-based connectivity mechanisms between 227 different types of ES supply; (2) to spatially map and quantify these connections 228 while accounting for LULC heterogeneity; (3) to compare coverages of supply 229 areas and functional connections across different types of LULC.

230

231 Materials and methods

232 Our case study area spans the Okanagan region in British Columbia (BC),

233 Canada, which we use to demonstrate a multi-ES connectivity mapping

234 approach for informing landscape planning (Fig. 1). It is located in the south-235 central interior of BC, is Canada's biodiversity hotspot and one of North 236 America's most endangered semi-arid ecoregions (Warman et al. 2004, Kerr and 237 Cihlar 2004), has a highly diverse assemblage of land use types (see Caslys 238 2013), and covers 21,580 km² from ~276 to 2,774 masl. General LULC types in 239 the region include, in decreasing order of area: forests (16,281 km²), grasslands 240 (1,482 km²), natural parks (2,403 km²; NB: contains several of the other listed LULC categories), shrubs (1,349 km²), agricultural (842 km²), lakes (599 km²), 241 242 urban residential (220 km²), rural residential (220 km²), wetlands (182 km²), 243 rock/rubble (161 km²), exposed land (113 km²), manicured parks (45 km²), rivers 244 (38 km²), commercial (23 km²), industrial (23 km²), urban institutional (16 km²), 245 and reservoirs (6 km²; Field et al. 2017). The ES-related resources in the region 246 are governed by over 80 institutions at federal, provincial, regional district, First 247 Nations, and municipal levels. Our study area has strong engagement of 248 regional government and non-government stakeholders, and an increasing 249 demand for region-wide collaboration in land use planning to accommodate 250 rapid rates of land development in response to a high rate of human population 251 growth (Neale et al. 2007, Caslys 2013).



Figure 1. Location of the case study landscape in southern interior 'Okanagan' region of British Columbia, Canada. Major waterbodies, elevation (masl), and the most populous cities and towns in Okanagan regional districts are indicated.

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We obtained spatial data for these ES from existing maps produced for our 258 259 study area (Fig. 2; Field et al. 2017, Field 2021). Based on these data, we first 260 established and valued supply area polygons - defined as spatially identifiable 261 regions of higher-than-average-value supply potential - which serve as source 262 and destination patches in a connectivity network (Appendix 1). We then 263 developed a methodology to establish and value functional linkages, or 264 connectivity, between supply areas. Functional connections were of two broad types: (1) overlapping links, which were areas where the supplies of two different 265

types of ES occur in the same place, and there is an underlying process-based connection between them; and (2) *topographic* links, which were mapped based on the ecological processes that functionally connect the supplies of two ES areas separated in space. Lastly, we compared the coverage of top-value ES supplies and their linkages on the major LULC types found in the region.

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Figure 2. Maps showing the original, full-extent of distribution and weighting for

ES supply areas in the case study landscape, including (a) plant food agriculture,

(b) waterflow regulation, and (c) landscape aesthetics (Field et al. 2017).

276

277 Mapping and valuing ES supply patches

278 To spatially partition the landscape into ES supply areas and establish the links

between them, we developed a rationale based on interdisciplinary methods for

assessing complex and connected natural systems (Bialonski et al. 2010). From

the perspective of the landscapes' capacity to provide ES, we defined

subsystems as discrete areas with the greatest potential for providing ES supply,

- 283 while the functional interdependencies between such areas were represented by
- spatial connections (also referred to herein as 'links' or 'corridors'). We
- 285 delineated ES supply areas based on approaches used in landscape connectivity
- and ES mapping studies: spatial polygons that represent high-value supply ES

287 patch boundaries (e.g., Bangash et al. 2013); and the aggregation of 288 immediately adjacent clusters of high-value supply spatial grid cells (e.g., 289 Gardner 1999, Urban et al. 2009, Qiu and Turner 2013; Field and Parrott 2017). 290 Any areas either lacking the potential for ES supply, or below a high-value 291 supply threshold (details below), were represented as the landscape matrix 292 through which ecological process-based connections between supply areas 293 could flow (Field and Parrott 2017). In reality, such spatial interaction networks 294 are dynamic through time (Boesing et al. 2020), though here we consider a static 295 snapshot of the present state of ES supply in our study region in an effort to 296 clearly illustrate real-world application of a novel approach for mapping the 297 ecological relationships underpinning multiple types of ES supply. 298 299 For the purposes of demonstrating our concept, we used existing data on the 300 spatial distribution of the 'supply' of three ES: (1) plant agriculture ('PA' herein; 301 provisioning = products obtained from ecosystems); (2) waterflow regulation 302 ('WF'; regulating = abiotic and biotic processes that moderate natural 303 phenomena); and landscape aesthetics ('LA'; cultural = non-material 304 characteristics that benefit human well-being; MEA 2005). Supply area maps 305 were created using tools centred on ecological composition (biotic and abiotic 306 elements), structure (e.g., topography, LULC distribution; Wallace 2007), 307 processes (e.g., water infiltration, nutrient cycle, energy cycle; Lyons et al. 2005), 308 and/or actual ES, and created primarily using existing and/or publicly available 309 data. All data were resampled to ~29 m x 29 m grid cells; therefore, ES models 310 accounted for fine-scale heterogeneity of parameters across the landscape. We 311 summarize the methods used for mapping the three (3) ES used in our study in 312 Appendix 2 (Field 2021). Additional details are outlined in Field et al. (2017).

313



314

315 Figure 3. Schematic and definitions for ES supply areas and functional

316 connections in the case study landscape.

317

318 Studies that consider multiple ES have found that the distribution of at least one 319 ES may be ubiquitous across a regional landscape (e.g., Queiroz et al. 2015), 320 and/or isolated supply areas may be present within a non-ES-provisioning matrix 321 (e.g., Qiu and Turner 2013; Fig. 2). Both situations were true for our landscape 322 based on the ES selected, so for the purposes of creating supply areas, we 323 chose to only retain areas with supply values above a top 50% threshold. This 324 was because two of the ES types we selected, WF and LA, had near-ubiquitous 325 spatial coverage with values ranging from very low to very high, and because 326 management applications often are most interested in maintaining the highest-327 value provisioning areas (e.g., Turner et al. 2007). For PA, we subset the top 50%-valued polygons from the original mapping; for WF and LA, we subset the 328

top 50%-valued raster cells of each of the regional ES maps, then converted these cells to single-part polygons based on aggregating adjacent cells within a diagonal raster cell width (~29 m). Note that, due to the large file size of the WF data, the above was run separately for each sub-basin (n = 118) in our study area (see Appendix 3 for details). Aggregated areas became supply area polygons, and were valued based on the summed raster values therein, then normalized on a unit-less scale from 1 to 10000.

336

337 Establishing functional connections between ES supplies

338 We define ES connectivity as areas on the landscape where one ES supply area 339 influences the provisioning of another via underlying ecological processes. We 340 identified spatial interactions between ES supply areas either as those that are 341 connected through their overlap in space, or those that transverse the landscape 342 through the relatively low value (i.e., sub-50% threshold) ES matrix. For these 343 two cases respectively, we applied spatial overlay analysis (e.g., Qiu and Turner 344 2013), or identified flows using a stepwise procedure involving least-cost path 345 (LCP) analyses akin to those applied in wildlife connectivity studies based on 346 species movement and habitat attributes (Urban et al. 2009). Movement of 347 organisms and matter across a landscape is often specifically defined in a single 348 direction as a result of biophysical (e.g., waterflow, topography) or biological 349 (e.g., movement from source to destination areas) realities, with multiple link 350 types representing qualitatively unique flows that exist between patches (Zhang 351 et al. 2007, Urban et al. 2009). For example, an area on the landscape producing 352 multiple ES supply types may have functional links between ES of the same type 353 in different locations, between different ES types in the same location, or with 354 different ES types in different locations (Fig. 4).



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Figure 4. Conceptual schematic showing the functional connections between WF (purple), PA (green) and LA (orange) supply areas on a subset area of the case study landscape. All eight link types (topographic and overlapping) represented in our case study approach are differentiated by colour-coding, and weighted by thickness gradient. ES supply areas and links are nested within a non- or low-value landscape matrix (white area). Adapted from Ernstson et al. (2010) and Field and Parrott (2017).

363

For the three ES we considered in this study, we characterized eight (8) spatial link types by the directional, ecological process-based relationships between high-value ES supply areas. The rationale behind these connectivity mechanisms are summarized in Table 1. As connection model distribution and valuations

368 were based on the original fine-scale supply area mapping, they also accounted 369 for model parameter heterogeneity across the study area. We identified two 370 high-level types of connections: overlapping (n = 5) and topographic (n = 3). 371 Overlapping links were defined as areas where the supplies of two different 372 types of ES occur in the same location on the landscape, and there is an 373 underlying process-based connection between the two. For PA, the presence of 374 vegetation crops can contribute to WF through providing a variety of beneficial 375 ecological properties (e.g., soil texture, low-slope, high-perviousness, 376 floodplains, riparian areas, and seasonally flooded fields; Power 2010), though 377 the weight of this positive interaction may be higher if agricultural land was 378 allowed to return to a natural vegetated state (Roa-García et al. 2011). PA also 379 interacts with LA by providing farmland that is recognized as being aesthetically 380 valuable (e.g., vineyards; Wagner and White 2009, Field et al. 2017) where these 381 areas overlap. For WF, a direct positive influence stems from the spatial 382 confluence of high-value WF areas on PA and LA supply areas through the 383 maintenance of underlying hydrological processes where they co-occur (e.g., De 384 Laney 1995, Nelson et al. 2009, Seavy et al. 2009). In the other direction, high-385 value terrestrial LA supply areas can be linked to WF areas through supportive 386 ecological functions (e.g., pervious and water-retaining vegetated landscapes, 387 floodplains in populated areas; Boyd and Banzhaff 2007, Van der Ploeg et al. 388 2010, Berkel and Verburg 2012, Carpenter et al. 2015; Table 1). We used the 389 high-value ES supply area maps (Fig. 5b-c,d) to identify areas where each pair of 390 ES overlapped (directionally) based on the above theory using a GIS-based clip 391 procedure (see Appendix 4 for step-by-step details; Field 2021). The resulting 392 single-part polygons of overlapping links represented the ecological processes 393 connections between spatially co-occurring ES types (Fig. 5e-i).

394

395 Table 1. Rationale behind functional connection mechanisms, directionality, and

396 weighting between top-value ES supply areas.

			Supply Areas		
	linked from \rightarrow	Link Type	Plant Agriculture (PA)	Waterflow Regulation (WF)	Landscape Aesthetics (LA)
	linked to 👃		supply area weight: potential PA crop area (ha)	supply area weight: summed WF model value	supply area weight: area (ha) x LA model value
	Plant Agriculture	Overlap		WF regulation on PA croplands	Other direction
			None	link weight: summed WF model supply area values within PA supply area	
		Topographic		WF regulation downslope	None
				link weight: summed WF model values along LCP pathway from WF to PA supply area	
	Waterflow Regulation	Overlap	PA croplands providing WF regulation		LA areas providing WF regulation
Supply			link weight: all summed WF model values within entire PA supply area	None	<i>link weight</i> : summed WF model values within LA supply area
Areas		Regulation Topographic		WF regulation downslope	
			Other direction	link weight: summed WF model values along LCP pathway from WF1 to WF2 supply area	Other direction
	Landscape Aesthetics	Overlap	PA cropland providing LA	WF regulation on LA areas	
			link weight: summed LA model values within PA supply area	link weight: summed WF model supply area values within LA supply area	None
		ics Topographic	None	WF regulation downslope	
				link weight: summed WF model values along LCP pathway from WF to LA supply area	

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Figure 5. Distribution and weighting of top-50%-valued ES supply areas and
functional connections on the case study landscape. Insets show (a) all top-value
supply areas and links; top-value supply areas for (b) plant food agriculture (PA),
(c) waterflow regulation (WF), and (d) landscape aesthetics (LA); overlapping
connections from (e) LA to WF, (f) PA to LA, (g) PA to WF, (h) WF to LA, and (i)

WF to PA; and topographic connections from (j) WF to WF, (k) WF to PA, and (l)WF to LA.

407

408 Topographic links were based on the ecological processes that functionally 409 connect the supplies of two spatially separated ES areas across the landscape. 410 Based on the three ES we considered, topographic connections always originate at a WF supply area, and represent the influence of upslope water regulation on 411 412 the maintenance of the natural hydrologic processes that help support PA (e.g., 413 crop growth and nutrient retention; De Laney 1995, Nelson et al. 2009), WF 414 (e.g., natural baseline flow regulation; Nelson et al. 2009), and LA (e.g., 415 maintenance of hydrology-dependent vegetation and aquatic features deemed 416 to have high aesthetic value) supplies in downslope areas. We developed a 417 stepwise procedure to create topographic links between ES supply areas. First, a 418 separate least cost path (LCP) analysis was run for each WF supply area polygon 419 to identify link corridors between these and other ES supply areas (Fig 6a). LCP 420 analysis is a common method of mapping directional ecological corridors in 421 landscape connectivity research, where the movement of an organism (or abiotic 422 unit) is simulated across a resistance (cost) surface from a start to a destination 423 point, and the lowest-accumulated resistance becomes the most likely path it 424 will follow across a landscape (Beier et al. 2009). LCP can also be effectively 425 used for hydrological flow models, where the algorithm seeks to minimize 426 cumulative elevation along its path (e.g., Melles et al. 2011). The starting WF 427 supply area polygon centroid was used as the 'origin' point for each associated 428 LCP analysis. A single LCP 'goal' point was determined for each sub-basin by 429 identifying the basin stream outlet (FLNRO 2017); the LCP goal point 430 coordinates were identified as the intersect of this stream line feature and the

431 valley-bottom line feature of the associated major watershed (Appendix 3; Field 432 2021). If multiple outlets were present in a sub-basin (e.g., Okanagan sub-basin 433 'w11213'), the furthest downstream outlet line feature was used. LCP transition 434 functions were built based on the assumption of downslope waterflow over a 435 DEM surface, and allowed for connecting to a 16-cell neighbourhood to avoid 436 paths being terminated based only on a single depression cell (van Etten 2017). 437 Following this, we executed various procedures to produce topographic 438 corridors between pairs of supply areas, which we summarize in Figure 6. This, 439 along with approaches used to address other analytical nuances, are also 440 discussed in Appendix 4.

441



442

Figure 6. Schematic outlining steps for the creation of topographic ES corridors 443 444 from each origin ES supply area to downslope supply areas. (a) An initial line 445 feature resulting from a least cost path (LCP) analysis, i.e., from the origin to the 446 goal point, amalgamated with a line from the goal point to a downstream 447 influential landscape feature (ILF). (b) Types of LCP segment deletions 448 addressed, including (red) segments overlapped by ES supply area polygons, (i) 449 segments from origin points external to origin ES polygon, and (ii) segments 450 flowing between two areas of an intersected (i.e., non-origin) ES supply area. (c)

Resulting ES flow corridors after deletions, including feedbacks to origin ES
supply area (4), flows to downslope ES supply areas (1) and (3), and flows to
downstream ILF areas (2).

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We then identified influential landscape features (ILFs) as additional WF 455 456 polygons downstream of each sub-basin in the valley-bottom and associated 457 with wetlands, floodplains, riparian areas, and/or seasonally flooded fields, 458 which are functionally linked to upstream hydrological regulation. We connected 459 ILFs to each upstream sub-basin outlet point, and individually merged these 460 sub-basin lines with the LCPs for each WF supply area within that sub-basin (Fig. 461 6). Additionally, if a sub-basin flowed into a lake or reservoir, all ILF polygons 462 immediately adjacent to that waterbody were included in the list of 463 'downstream' supply areas. Lastly, because the DEM raster resolution was 464 approximately 20 m, some LCPs flowed outside sub-basin boundaries between 465 the origin polygon (typically those close to a sub-basin boundary) and the goal 466 point. Any nodes outside the sub-basin of interest that were overlapped by such LCPs were not considered to be true 'intersections' 'and such line segments 467 468 were therefore excluded from within sub-basin links. However, such LCPs were 469 still able to become connected to downstream ILFs.

470

471 Assigning value to the functional connectivity between ES

472 In addition to spatially identifying connections between pairs of ES, we

473 quantified the weight of these connections based on assumptions around the

- 474 functional relationships between ES (e.g., Urban et al. 2009). We based
- 475 valuations on the original ES provisioning maps, which assigned each raster cell
- in the map an ES value equivalent to results of the underlying models (Appendix

477 2; Field 2021; Field et al. 2017), and on the following assumptions. Since some 478 of the ecological characteristics of both PA and AE areas can support the 479 maintenance of WF supply, and high-value WF lands maintain the hydrological 480 characteristics that help support PA provision and AE, we assumed that the 481 value of these connections would approximate the available WF capacity. 482 Therefore, the overlapping links between WF and PA, and between WF and LA, 483 were weighted by the summed WF raster values therein. The plant food-484 providing agricultural areas of the Okanagan are prized by some for their beauty 485 (Wagner and White 2009; though this subjective evaluation is complicated, see 486 Wagner 2008), and we assumed the level of this significance to be equivalent to 487 the underlying LA model value; therefore, such overlap links were 488 unidirectionally weighted from PA to LA by the summed LA raster values therein. 489 We assumed the contribution of upslope, high-value WF lands to the hydrologic 490 maintenance of intersected downslope PA, WF and LA areas to be equivalent to 491 the amount of flow regulation provided by landscape where water flows 492 between these areas. Therefore, we quantified the weight of these unidirectional 493 links by the cumulative value of all WF raster cells on the original map (i.e., not 494 just top 50%; Fig X B original ES maps) traversed along corridors. All link 495 weights were obtained by extracting summed raster cell values coincident with 496 overlap link areas or with topographic link segments, then normalized on a unit-497 less scale from 1 to 10000. Additionally, raster overlay analysis was conducted, 498 wherein cell values were summed across all eight link types to produce a 499 weighted distribution map of all multi-ES connections for our entire study 500 region. We acknowledge that alternative ecological process models could be 501 used to produce more nuanced or accurate measures of link weightings (e.g., 502 Cadotte et al. 2011). However, we chose to base our link quantification on high-

- 503 level and readily calculable assumptions in an effort to provide simple,
- 504 replicable, and easily-communicated metrics to inform applied decision-making
- 505 for corridor, conservation, and protected area placement.
- 506
- 507 Comparison with regional LULC

508 To compare the spatial coverage of supply areas and their linkages, and to aid

in our assessment of potential uses of ES connectivity results for on-the-ground

510 planning and management, we calculated the proportion of several high-level

- 511 LULC categories intersected by each of the high-value supply areas and eight
- 512 link types identified in the above analyses. We selected several LULC categories
- 513 to provide both local and regional decision-makers additional information about

514 where on the landscape ES connectivity is distributed, including forests,

515 grasslands, shrubs, parks, aquatic areas, wetlands, rock and exposed land,

agriculture, residential, and urban areas. We calculated the total area (ha and %)

- 517 of LULC types covered by each link type, and the proportions of study area total
- 518 LULC covered by each link.
- 519

520 ArcMap 10.7.1 (ESRI 2011) and R (version 3.6.2; R Development Core Team

521 2017) packages sp 1.4-5 (Pebesma and Bivand 2005, Bivand et al. 2013), sf

522 0.9-8 (Pebesma 2018), rgdal 1.5-23 (Bivand et al. 2015), raster 3.4-5 (Hijmans

523 and van Etten 2012), rgeos 0.5-5 (Bivand et al. 2017), maptools 1.1-1 (Lewin-

524 Koh et al. 2012), and stringr 1.4.0 (Wickham 2010) were used to build, assess

- 525 and visualize the ES connectivity map. LCP analyses and subsequent stepwise
- 526 link refinement were run using R package gdistance 1.3-6 (van Etten 2017).
- 527 For transparency and reproducibility, data, R scripts and further details on our

- 528 methodological procedures are available on the Open Science Framework (OSF;
- 529 Field 2021; Appendix 5); limitations are discussed in Appendix 6.
- 530

531 Results

532 Distribution and values of ES supply areas

533 The top-valued 50% supply areas were distributed north-to-south across our 534 study region (Fig. 5b-d). Plant foods are grown primarily in valley bottom areas 535 in the Okanagan, and thus PA supply areas (n = 1,497) were concentrated in 536 lower-elevation and population-dense regions with similar coverage to the 537 original PA map (distribution of specific crop types detailed in Field et al. 2017). 538 The highest-value PA supply areas were coincident with the largest farm parcels, 539 present in the agriculture-rich areas of the south, north and east-central 540 Okanagan. Given the extensive coverage of their original model results, top-541 value supply areas for both WF (n = 7,350) and LA (n = 5,262) were distributed 542 fairly evenly across the entire study area. The highest-value WF supplies were 543 associated with stream riparian areas in larger, partially-protected sub-basins of 544 the southwest, and with riparian and wetland complexes in the central- and 545 north-east. Our results suggest that the highest-value LA supplies were 546 associated with large areas of upland forests, rivers, lakes, and protected 547 parkland in the southwest and northeast, with relatively lower cumulative LA 548 values in the more heavily-populated valley bottom. It is worth noting that, as 549 our method of delineating distinct LA supply areas was based on the 550 amalgamation of immediately adjacent raster cells, there were several large LA 551 supply areas that may or may not be subjectively interpreted by human 552 consumers as part of a single supply area. Issues with inherent subjectivity 553 around LA mapping and assessment are common (e.g., van Zanten et al. 2016,

554 see also Daniel et al. 2012), and this could lead to variable results in strength 555 and physical location of cultural supply areas and their inter- and intra-ES 556 linkages. Even nuances within a single cultural ES valuation method can lead to 557 complex results; for example, tourist's aesthetic appreciation of landscape 558 features can differ from that of residents (Beza 2010). That said, the goal of this 559 study is not to present the most accurate spatial representation of ES and their 560 connections, but rather is to demonstrate a connectivity-based approach to 561 evaluating multi-ES relationships. The original LA value distribution map is 562 reproduced in Fig. 2c (Field et al. 2017).

563

564 Distribution and values of functional connections between ES supplies 565 The spatial distribution and value of connections between overlapping ES were predictable based on the extents of supply area mapping and on the functional 566 theory we applied to link weighting. Bi-directional overlap links between WF and 567 568 LA (n = 9,363 in each direction) were distributed across the entire study area (Fig. 569 5e,h). The highest-value links from LA to WF were associated with stream and lake riparian areas in both populated and remote valleys in the north, with 570 571 riparian and wetland complexes in the central-east, and with remote stream and 572 river riparian areas in the southwest. Similarly, the highest-value links from WF to 573 LA were present in stream and river riparian areas in the southwest, and with 574 stream riparian and wetland complexes in the central-east. For overlapping 575 connections from PA to LA (n = 174), link distribution was sparse throughout the 576 valley bottom and limited to croplands with high aesthetic value; primarily 577 associated with vineyards and orchards (Fig. 5f). In terms of bi-directional 578 overlap connections, the majority of PA supply areas were connected with WF 579 regulation areas throughout the valley bottoms (WF to PA n = 1,220; PA to WF n

580 = 1,320), with highly-weighted links typically associated with cultivated lands,

581 fields, crop transitions, vineyards, and orchards near to (or containing) riparian,

582 floodplain, and/or wetland areas (Fig. 5g,i).

583

Topographic links from high-value WF supplies to other ES supply areas 584 585 revealed corridors variable in length and weight flowing across the landscape, 586 sometimes linking ES supplies ~200 kms apart (Fig. 3). Between pairs of spatially isolated WF areas, corridors (n = 484,602) approximated the location of 587 588 watercourses (FLNRO 2017), as was expected due to the elevation-based LCP 589 resistance surface used to simulate surface waterflow. The highest-value WF-WF 590 corridors were observed through the large central Okanagan Lake system and 591 several of its relatively low-order tributaries; in high-order valley-bottom rivers, 592 streams and lakes in the southwest; and in the larger valley-bottom rivers of the 593 northeast. These observations resulted from connections between WF supply 594 areas and the ILFs that are prevalent next to valley-bottom aquatic areas. 595 Flowing from WF to LA supply areas, corridors were scattered throughout the 596 study area (n = 2,864), with the majority of links associated with the more 597 populated valley-bottom areas in the central Okanagan basin (Appendix 3), and 598 with the highest-value links in higher-order streams where sub-basins contained 599 larger numbers of WF supply areas upstream of one or several LA supply areas. 600 Connections to PA were only possible where farmlands were present within the 601 sub-basin of the associated WF supply area, or downstream where farms were 602 within ILF zones. Therefore, such corridors were concentrated in sub-basins 603 along the central valley-bottom (n = 5,256), with particularly high weights in a 604 northern agricultural valley used primarily for growing cereals and vegetables, in 605 the largest sub-basin in the central Okanagan watershed primarily farmed for

berries and tree fruits, and in a southern basin known for vineyards, tree fruits
and vegetables. A general trend we observed for all topographic links was the
co-occurrence of higher-value corridors with larger rivers and streams, rather
than being associated with smaller headwater streams. This was a result of the
culmination of overlapping corridors from several headwater WF areas in the
lower-elevation stream valleys that had the largest number of supply areas for
the related ES pair type.

613

614 When all link types were included on a map of accumulated weights, it 615 highlighted expansive networks of high-value functional connectivity corridors 616 between all three ES types and distributed across the entire landscape (Fig. 7). 617 The highest-value link areas were found in low- and mid-elevation riparian areas 618 across the landscape; in a mid-elevation wetland complex of the eastern-central 619 region; in riparian and surface waterflow corridors associated with a large 620 eastern-central sub-basin; and generally in areas where several (or all) of the 621 eight link types co-occurred. Notably, the accumulation map revealed that 622 several of the highest-value areas were not coincident with the highest-value on 623 any of the individual link-type maps (Fig. 5), and were sometimes in relatively 624 remote, higher-elevation areas.

625



626

627 Figure 7. Distribution and weighting of link values amalgamated across all eight

628 (8) overlapping and topographic link types across the case study landscape.

629

630 Spatial coverage of supply area and linkages across LULC types

631 The distribution of ES supply areas and links were only in part determined by the

- 632 underlying LULC types included in the original model parameters. In decreasing
- 633 order of coverage of our study area (21,580 km²), the high-level LULC types are
- 634 as follows: 76.7% forest; 11.9% park (NB: overlaps with forest, grassland, shrub,
- rock and exposed categories); 6.8% grassland; 5.8% shrub; 3.7% agriculture;
- 636 3.0% waterbodies (lakes, rivers, reservoirs); 1.6% residential; 1.3% rock and

637 exposed land; 0.8% wetland; 0.3% urban; and 0.1% unknown (Appendix 7). For 638 the subset top-50% ES areas, almost all PA supplies were, unsurprisingly, on agricultural lands (~100.0%), but only covered 15.8% of all croplands in the 639 640 region. Both WF and LA supplies were found mainly on forested lands (78.7% 641 and 93.0%, respectively) and within parks (14.0% and 13.1%, respectively). 642 Distribution of top-valued WF supplies covered large portions of most LULC types in the study area (19.7% to 50.6%; NB: 0% aquatic), including 99.6% of all 643 644 mapped wetlands. Top-valued LA supplies spanned the majority of aquatic 645 (98.8%), forested (81.9%), park (74.4%), and wetland (69.1%) LULC types (Fig. 646 8a-c).



647

648 Figure 8. Proportion of major LULC types present within the extent of ES supply

and link areas in the case study landscape. LULC types assessed are colour-

650 coded and include forests, agriculture, rocks/exposed areas, residential areas,

651 shrubs, grasslands, urban areas, water, wetlands, and areas with unknown use

and/or cover. Insets show proportions in coxcombs for each top-value supply

- area, including (a) plant food agriculture (PA), (b) waterflow regulation (WF), and
- 654 (c) landscape aesthetics (LA); overlapping connections from (d) LA to WF, (e) PA
- to LA, (f) PA to WF, (g) WF to LA, and (h) WF to PA; and topographic
- 656 connections from (i) WF to WF, (j) WF to PA, and (k) WF to LA.
- 657

658 Similar trends in LULC coverage were observed for overlapping connections,

659 with links from PA to LA found mainly on agricultural lands (69.7%) and in forests

660 (28.5%). In both directions between PA and WF, connections were mainly on

agricultural lands (both 98.0%), and covered 5.8% and 5.7% of all croplands in

our study area from PA to WF and from WF to PA, respectively. In both

663 directions between WF and LA, connections were mainly on forested land

664 (90.8% and 91.1%, respectively) and in parks (14.7% and 14.6%, respectively).

665 Moreover, these links covered large portions of all wetlands, parks and forests

666 (from WF to LA 68.0%, 39.2 and 37.6%; from WF to LA 68.0%, 39.2 and 37.8%,

667 respectively) in the study region (Fig. 8d-h).

668

For topographic corridors, we found that LULC coverage was less consistent with relevant ES supply area coverages. Corridors between different WF supply areas were found mainly in forested (42.9%) and aquatic (35.2%) areas, with more minor distribution in park (7.1%), grassland (6.9%), and agricultural (5.2%) LULC types. Notably, topographic WF corridors covered 24.3% of the entire aquatic areas found in our study region. From WF to PA, corridors mainly traversed forested areas (54.1%), followed by agricultural (19.8%), park (10.7%),

- 676 grassland (10.6%), and residential (5.4%) LULC types. From WF to LA, corridors
- 677 were mainly found in forested areas (57.3%), followed by parks (14.5%),
- agriculture (12.7%), and grasslands (10.2%; Fig. 8i-k). All LULC overlay analyses
- 679 results are summarized in Appendix 8.
- 680

681 **Discussion**

- 682 We applied a novel approach to mapping and modelling the functional
- 683 connectivity between multiple types of ES across a regional landscape. By
- testing the application of this approach on three ES categories for a case study
- area, we identified and mapped eight link types connecting ES supply areas on
- the landscape. The results demonstrate the variety of ways categorically
- 687 divergent ES can exhibit interdependencies related to their production
- 688 potential, and the importance of considering these dependencies in land use
- 689 planning for ecological connectivity.
- 690

691 The case study: ES connectivity across a heterogeneous regional landscape 692 The connections we observed between ES revealed high-value multifunctional 693 linkages on the landscape that were not necessarily predictable from supply 694 area mapping. Across all link types we found heterogeneous distribution as well 695 as spatially distinct areas of markedly higher value, or 'hotspots' of connectivity, 696 relative to surrounding areas (e.g., Alemu et al. 2020). But one surprising 697 observation is that the weighted amalgamation of all eight link types uncovered 698 areas of high-value connectivity that were not present on any of the ES supply or 699 pairwise link maps. This finding points to nuances that can be discovered when 700 multiple ES and multiple linkage types are assessed together, and suggests that 701 the spatial focus of planning for optimal service provisioning may shift when

702 functional relationships between several ES are considered. Ultimately, such 703 multifunctional areas represent possible conservation priorities that, if degraded 704 or lost, may cause significant disruption of ES connectivity networks. 705 Understanding the complexity of interactions between multiple ES has been 706 highlighted as a critical challenge in planning for sustainable multifunctional 707 landscapes in the face of changing environmental conditions and management 708 interventions (Dee et al. 2017). A recent review of studies that have modelled 709 interactions between multiple ES found that a large proportion did so from the 710 perspective of co-occurring production synergies and trade-offs, but that the 711 examination of flows, and the identification and quantification of explicit 712 functional relationships remain largely unexplored (Agudelo et al. 2020). 713 Ultimately, simultaneously modelling multiple ES continues to be difficult in part 714 because of methodological inadequacies and the complexity of the ecological processes involved (Kolosz et al. 2018). Our approach provides a new framework 715 716 that can help address these challenges.

717

718 From initiation points within WF supply areas, our modelling revealed several 719 functional connections that operate over both short and long distances. Some of 720 these topographic corridors extended over 200 km within the boundaries of our 721 study area and, based on the underlying ecological process theory, also extend 722 across the Canada-USA border to wetlands, riparian areas, seasonally-flooded 723 agricultural fields, service supply areas along the extent of the Columbia River to 724 the Pacific coast confluence between Washington and Oregon states, more than 725 1,100 km downstream from the originating supply areas in our study region. 726 Similar long-range connectivity may be observed for other water-related ES 727 (e.g., water provisioning, water quality), as both mean-annual water volume and

728 water quality have been found to be heavily influenced by first-order headwater 729 catchments, even in watersheds with large high-order rivers (Alexander et al. 730 2007, Freeman et al. 2007). Additionally, WF exhibits close- and long-range 731 interactions with many other ES not modelled in our study. For example, water 732 extraction and damming to take advantage of freshwater provisioning supplies 733 alters natural hydrological regimes (e.g., Jackson et al. 2001); afforestation 734 reduces peak and maintains base flows (e.g., Zhang et al. 2007, Power 2010), whereas deforestation destabilizes flows (Mäler et al. 2013); areas providing WF 735 736 supply help to decrease pollution, flood-related turbidity, and residence time of 737 chemicals in lakes (Burmil et al. 1999, Blackstock et al. 2001, Jackson et al. 2001, 738 Bennett et al. 2009); certain pollination services can be facilitated by moving 739 water (Biesmeijer et al. 2003); and some recreational activities are dependent on 740 the maintenance of waterflow (e.g., fishing, kayaking; Burmil et al. 1999). Based 741 on our observations of the potential for both short- and long-range functional 742 connectivity, ES planning for other water-related services should also consider 743 the potential impacts of management interventions on related services areas 744 and management jurisdictions downstream.

745

746 Our study demonstrates that functional connections between ES often span 747 several LULC categories, and that trends in dominant cover types may be 748 unexpected relative to those associated with related supply areas. Certain areas or cover types are sometimes considered 'hotspots 'for ES production, i.e., 749 750 provide several different, often high-value, ES (e.g., Qiu and Turner 2013). For 751 example, wetlands provide flood and flow control, storm protection, erosion 752 control, groundwater supply, water guality maintenance, nutrient waste disposal, habitat to support fishing and hunting, natural materials, biodiversity, micro-753

754 climate stabilization, carbon sequestration, recreation, and aesthetic value 755 (Brander et al. 2006). Agricultural lands can provide many ES beyond food for 756 humans, such as habitat and food for pollinators, biological pest control (e.g., 757 Loos et al. 2019), and tourism (e.g., Wagner and White 2009). We assessed the 758 potential for LULC-associated connectivity hotspots in our region using LULC 759 comparisons. Forested lands clearly stand out as being important for the 760 regulating and cultural ES we investigated. Forests are often identified as hubs 761 for maintaining regulating and cultural ES, including surface water quality, soil 762 retention, carbon storage, and recreation (Matson et al. 1997, Brauman et al. 763 2007, Qiu and Turner 2013). Notably, although parks make up only 11.9% of the 764 study area, they represent important landscapes for WF and LA supply and 765 overlapping connectivity, and as flow corridors between all ES types we 766 investigated. Both the above observations are likely driven by the suite of 767 ecological processes present in complex forest, grassland and shrub ecosystems 768 (e.g., vegetation-mediated infiltration, Mills and Fey 2004), and the contribution 769 of wildlands and parks to aesthetics (Thompson 1995). From the perspective of 770 functional connectivity, our study suggests a need to expand upon the ES 771 'hotspot' notion by considering that other LULC types beyond those associated 772 with supply areas may be serving as critical corridors for interdependent ES. A 773 clearly delineated example of this is the ecological process links between 774 terrestrial and aquatic ecosystems. Areas of land adjacent to waterbodies are 775 known to provide various regulation services in addition to WF, including 776 erosion and water quality regulation through soil- and vegetation-mediated 777 retention and filtration (Mills and Fey 2004). Whereas the model parameters we 778 applied for WF preclude supply area coverage within any aquatic areas, the 779 LULC proportions we observed within upland and downslope WF corridors

780 transversed 24.4% of all surface waterbodies in the region and demonstrated 781 that aquatic areas represent some of the most high-value linkages between 782 different production areas for this ES. In addition, croplands proportionally 783 represent the third-largest cover type in the corridors between upland WF and 784 downslope LA supplies, with the majority of these corridors found in riparian 785 zones, or on farms adjacent to wetlands and waterbodies. The synergistic 786 association of WF and PA supply areas has been observed in other ES 787 interaction studies (e.g., Qiu and Turner 2013), and stems from crops', especially 788 deep-rooted perennials, ability to provide a variety of hydrological benefits 789 including increased water infiltration and recharge, reduced runoff, and 790 mitigation of peak flows (Dabney 1998, Tilman et al. 2002, Brauman et al. 2007, 791 Power 2010). These observations have implications for ecosystem- and habitat-792 based management programs as LULC types are often imposed as boundaries 793 for interventions and/or institutions (e.g., BC Ministry of Agriculture). Especially 794 in heterogeneous regional landscapes, our results point to potential for 795 increased need for cross-jurisdictional collaboration when planning for functional 796 connectivity in the optimization of multiple ES.

797

798 Ecological degradation and climate change-induced aridity is increasing across 799 the globe. This has detrimental impacts on the structure and function of dryland 800 ecosystems, which are characteristics strongly related to the ability of these 801 systems to produce essential ES (Middleton and Sternberg 2013, Huang et al. 802 2015). The high interconnectivity of natural biotic and abiotic attributes can lead 803 to cascading changes. Single ecological attributes can have negative impacts on several others (Schlesinger et al. 1990, Reynolds et al. 2007, Maestre et al. 804 805 2016); can exhibit sudden non-linear responses to increased aridity; and can
806 cross sequential, multi-phase thresholds of ecosystem change. This can further 807 be complicated by interactions with topographic- and land use-related factors. 808 Climate forecasts predict that up to 28.6% of current drylands will cross one of 809 the three sequential aridity-induced degradation thresholds by 2100, broadly 810 characterized by vegetation decline, soil disruption, and systemic breakdown 811 (Berdugo et al. 2020). This is relevant to our study region as it comprises the 812 northern extent of the semi-arid North American Great Basin ecoregion, with 813 high-elevation mountains flanking its eastern and western boundaries. This 814 topography leads to the Okanagan region's function as a critical movement 815 corridor for north-south species migrations (Transboundary Connectivity Group 816 2016), and it likely exhibits similar pinch-point connectivity dynamics for 817 topography-influenced ES, as we observed for the WF corridors modelled our 818 study. The potential for imminent and irreversible degradation of ecological 819 processes in dryland systems calls attention to the desperate need for 820 understanding potential implications of these effects on multiple ES and their 821 interdependencies. Our study is a jumping-off point for a more thorough 822 evaluation of future aridity risks to ES relationships in the Okanagan and other 823 dryland regions.

824

The conceptual shift: from correlative interactions to functional connectivity
Designing landscapes for optimizing delivery of ES, while minimizing ecosystem
degradation, requires thorough understanding of the interactions between
multiple services and the ecological processes that drive them (Fu et al. 2013,
Agudelo et al. 2020). Key guiding paradigms for this, and indeed landscape
ecology in general, are to understand the relationships between spatial patterns
and ecological processes, and to consider not only individual components (e.g.,

a single ES or supply area) but their combined effects (Wallace 2007, Nassauer
and Opdam 2008, Fu et al. 2013). Viewing ES in terms of their spatial
interconnectivity is especially relevant to regulating and supporting services that
are known to be connected to the supply of many others; e.g., water flow is
essential to the production of water for drinking, irrigation, and industry; plant
and animal food production; regulating microclimates; and, as we exemplify in
this study, landscape aesthetics (Fu et al. 2013).

839

840 Areas of ES supply are not necessarily spatially congruent with the discrete 841 structural components traditionally considered in landscape connectivity 842 frameworks (e.g., habitat patches, specific LULC types); therefore, linkages 843 between ES are also unlikely to be coincident with these components (e.g., 844 movement of organisms and matter; Brooks 2003). For example, the global 845 benefit of carbon storage and sequestration depends only on the quantity of 846 natural landcover, and not the spatial arrangement of patches (Mitchell et al. 847 2015). Although protected areas and intact habitat patches are important spaces 848 for some of the plants, animals, and abiotic ecosystem components responsible 849 for providing ES, provisioning and flows are not bound by human-defined 850 reserve areas, and many ES are produced completely by and interact with one-851 another in human-modified landscapes (Schröter et al. 2019). Further, 852 connectivity of certain ES will be limited by distance thresholds and/or human or 853 ecological barriers to the flow of ecological processes. For example, crop 854 production can benefit from interspersion of natural habitat throughout 855 agricultural landscapes, which can increase pollination and pest control services 856 delivery from species that can only move limited distances from their habitat 857 patches (Tscharntke et al. 2005). There may be spatial congruency between

858 existing wildlife movement corridors and certain regulating services, especially 859 those that depend on the movement of organisms for their delivery, e.g., 860 pollinators, disease control, pests and their predators, seed dispersal; Kremen et 861 al. 2007), which suggests that there may be opportunities for win-win 862 conservation initiatives for wildlife and ES together. Our approach can be used 863 to explore this possibility, and to explicitly map and assesses the mechanisms 864 behind distance-threshold-mediated and cross-landscape ES interactions in 865 general. Outcomes of such work can be readily incorporated into connectivity-866 based management for these and other complex interactions that operate 867 across heterogeneous landscapes.

868

869 Our approach reveals cross-landscape connectivity processes that represent 870 important drivers of ES production, and are undetectable with traditional 871 approaches for identifying ES synergies and trade-offs (e.g., Qui and Turner 872 2013, Su and Fu 2013, Tomscha and Gergel 2016). It can be used to represent 873 several different types of functional connections, e.g., between different ES that 874 occupy the same space, and abiotic movement from one ES supply area to 875 another across the landscape. Identification of links between spatially co-876 occurring supply areas is similar to a representation of paired ES 'interactions', a 877 concept for identifying synergies and trade-offs among services, as well as 878 identifying groups of services that repeatedly occur together across a landscape 879 (i.e., 'ES bundles'; Bennett et al. 2009). Co-occurring ES typically arise as a result 880 of common drivers or direct interactions among ES. For example, fertilization 881 can drive-up crop yield while simultaneously decreasing water quality. Such 882 services can interact through the same underlying ecological function (e.g., 883 forests can have high recreational and aesthetic value and also provide water

884 flow regulation). Further, ES in the same 'neighbourhood 'can interact with one 885 another (e.g., pollinator habitat adjacent to crop lands can increase crop 886 productivity; Cord et al. 2019). Our methods take a closer look at the concept of 887 ES interactions by explicitly representing the mechanisms behind the cooccurrence ES in the delineation and valuation of these areas (Bennett et al. 888 889 2009). Investigation of interaction mechanisms with respect to multi-ES 890 assessment has been highlighted as a crucial step toward providing more 891 rigorous information to inform the management of multifunctional landscapes 892 (Alemu et al. 2020), and our study is one of the few to provide this information 893 at the regional scale (Agudelo et al. 2020).

894

895 Practical implications

896 Landscape planning typically involves considering the spatial layout of different, 897 often incompatible, land use types that ultimately influence connectivity (Phalan 898 et al. 2011). From an ecological connectivity perspective, such guidelines may 899 include the maintenance of biodiversity to support ecosystem function, and thereby ES production and resilience, by including an assemblage of native 900 901 habitat patches, corridors, stepping stones, and sensitive habitat buffers within a 902 structurally complex matrix, with more focused management strategies for 903 species and/or functional groups (Fischer et al. 2006). Notwithstanding that 904 biodiversity can have complex, non-linear relationships with ES production (Fu et 905 al. 2013) and is not necessarily directly related to multifunctionality (Birkhoffer et 906 al. 2018), one drawback of this approach is that a disconnect emerges between 907 the general maintenance of ecological connectivity and the benefits realized by 908 humans. Recent conceptual frameworks have called for research that uncovers a 909 more nuanced understanding of how landscape structure impacts the provision

910 of *multiple* ES, how abiotic flows impact ES provision, and which services are 911 more influenced by landscape connectivity (e.g., Mitchell et al. 2013, Mitchell et 912 al. 2015). However, by not explicitly considering how ecological processes result 913 in the production of ES and how these ecological processes are connected (Fu 914 et al. 2013), there is risk of spatial incongruence between traditional connectivity 915 planning priority areas and actual ES supply and flows across the landscape. Our 916 approach helps to address this risk by enabling spatially explicit identification of 917 high-value multi-ES links across the landscape, which can be overlaid and 918 compared with other connectivity priorities (e.g., wildlife corridors).

919

920 Opportunities for future work

921 Our case study maps and quantifies relationships between ES at a snapshot in 922 time. However, modifications of natural landcover can change the number, size, 923 shape, isolation, and distribution of ecological patches across the landscape and 924 their proximity to human beneficiaries, all of which may lead to positive, 925 negative or neutral impacts on ES supply and flow (Mitchell et al. 2015). For 926 example, agricultural intensification tends to negatively impact large pollinators 927 more than small ones, the former of which are more efficient crop pollinators 928 (Suding et al. 2008). Both types of pollinators could be represented in a multi-ES 929 network, and potential impacts of land use change could be addressed using 930 modelling of future scenarios (e.g., Redhead et al. 2020). In the face of climate 931 change, increases in dryland aridity causes grasslands and savannahs to 932 metamorphose into shrublands as the latter grow better in sandy, nutrient-poor 933 soils (D'Odorico and Okin 2012, Phillips et al. 2019). In our study area 934 specifically, such a shift would have implications for ES coverage and value 935 through the dependency of model variables on underlying vegetation

936 characteristics (Field et al. 2017), and thus influence future ES production and 937 connectivity. The ultimate impacts of landscape changes on ES are dependent 938 on the structure and quantity of such changes, and on the biophysical process, 939 ecosystem functions, species, and human activities driving the ES supply of 940 interest, as well as the flows to and demands of human beneficiaries (Mitchell et 941 al. 2015). Even if human development does not greatly diminish the quantity of 942 natural landcover, it can still have far-reaching impacts on ES supply. For 943 example, the prolific damming of the majority of major river systems has 944 reduced the flow of water and the use of these systems as corridors for human 945 movement, and changed natural patterns of water provisioning, water quality 946 regulation, and recreation opportunities (Loomis 2002, Whittaker and Shelby 947 2002, Nilsson et al. 2005). Further, it has been shown that spatial correlations 948 between pairs of ES can exhibit inter-annual variability (e.g., Renard et al. 2015, 949 Li et al. 2017), and that snapshots in time are not good predictors of how their 950 relationships may change over time (e.g., Mitchell et al. 2020). Future studies 951 could use the ES connectivity framework presented here to assess how changes 952 in LULC ultimately have cascading impacts on multiple ES across a landscape 953 (Bagstad et al. 2013, Grêt-Regamey et al. 2017, Rieb et al. 2017), which can 954 practically be achieved by incorporating seasonal and inter-annual variations in 955 ES supply, demand and functional connectivity (e.g., increases in fresh water 956 provisioning during dry months; Field and Parrott 2017). The application of our 957 framework along with scenario modelling and/or historical data could help us to 958 move beyond examining how natural and anthropogenic drivers of change 959 impact local provisioning of an individual ES or trade-offs between multiple ES 960 (e.g., Li et al. 2017, Schroter et al. 2019), to how such isolated drivers might 961 have far-reaching, cumulative impacts at multiple spatial and temporal scales.

962

963 We acknowledge that several other methods exist for identifying and evaluating 964 corridors across a landscape, including least cost corridors (Singleton et al. 965 2002), circuit theory (McRae and Beier 2007, McRae et al. 2008), graph theory 966 (Fall et al. 2007, Pinto and Keith 2009, Rayfield et al. 2011), networks (Phillips et 967 al. 2008; Parks et al. 2013), and deterministic eight models (Mark 1984). We 968 chose to employ only LCP analysis mainly because the topographic ES flows in 969 our study all originated at WF supply areas, corridors all were to represent the 970 ecological process of water flowing downslope, and because LCP has been 971 shown to be a valid method for approximating drainage networks while being 972 capable of overcoming issues around topographic depressions (Melles et al. 973 2011). Therefore, a DEM-driven model representing water moving downslope 974 was deemed the most appropriate for these types of ES connections in our 975 study region. Further, our aim was to provide relatively simple representations of 976 corridors between supply areas to support the primary goal of this paper, i.e., to 977 demonstrate a novel approach for conceptualizing how the provisioning of ES 978 are functionally connected across a landscape. It is important to highlight that 979 our method of valuing topographic links corresponds to the accumulated 980 weights of relevant ecological processes along the entire length of a corridor. 981 We do not attempt to quantify the potential strength of contribution the 982 upstream supply area exerts on an individual downstream supply area (i.e., 983 contribution to maintaining the downstream area's potential for producing 984 baseline service supply). A promising area of future research for addressing the 985 latter distinction will be through the use of network theoretic methods 986 (discussed below), which can employ patch (e.g., supply area or 'node') and link 987 valuations, as well as viewing these in the context of the entire network, to

calculate metrics of the overall influence of an individual patch (e.g., Field and
Parrott 2017). In summary, future research could compare and validate
alternative spatial corridor mapping and valuing approaches (e.g., Melles et al.
2011) for predicting process-based movement between WF and other ES types.

992

993 Landscape connectivity studies have assumed that larger ecological patches are 994 more robust and valuable to a network (e.g., Pal et al. 2021). However, 995 especially for multiple ES that span a variety of habitat types, for those 996 influenced by below-ground processes (e.g., soil texture - WF, Brauman et al. 997 2007; sub-surface carbon stock - climate regulation, Friess 2016), and for those 998 dependent on landscape features that are typically independent of 'patch' 999 arrangement (e.g., topography - WF, Crossman et al. 2013), additional methods 1000 should be explored to identify alternative methods of delineating and valuing 1001 patches for ES connectivity. Spatial network (graph) theory has been used to 1002 assess the movement of individual ES across the landscape (e.g., Janssen et al. 1003 2006, Fortuna et al. 2006, Heckmann and Schwanghart 2013, Phillips 2013, 1004 Peron et al. 2014) but, although it has been called for (e.g., Bohan et al. 2013, 1005 Hines 2015, Quintessence Consortium et al. 2016, Dee et al. 2017), studies on 1006 real-world networks with different types of linkages between multiple types of 1007 ES, especially relating to all the broad categories of provisioning, regulating and 1008 cultural services, are still lacking (Field and Parrott 2017). In spatial network analysis, landscape components (e.g., habitat patches) are represented as 1009 1010 'nodes', and connections (e.g., habitat corridors, species dispersal) form the 1011 'links' between them. Once built, network metrics can be used to evaluate a 1012 variety of characteristics including the strength of connectivity, most likely flow 1013 routes, relative contribution of individual nodes to overall connectivity, flow

1014 efficiency, node and link vulnerability to disturbances, etc. (e.g., Urban et al., 2009; Heckmann et al., 2015). Network analyses have been applied to well-1015 1016 described species-specific mutualistic interactions as they relate to indicators of 1017 ES supply (e.g., pollinator and seed-disperser relationships with plants, Gilarranz 1018 et al. 2011). A recent single ES and species-specific case study on the 1019 relationship between river red gum tree and periodic flooding (i.e., WF) used a 1020 conceptual network framework based on the functional drivers and feedbacks 1021 between abiotic, biotic, and social system components to guide management of 1022 the system (Dee et al. 2017). However, we know of no study that has considered 1023 combined biotic and abiotic contributors, both of which are necessary to build 1024 an accurate picture of ES supply across real world landscapes. Our approach 1025 provides a framework for network-based ES assessment by spatially representing 1026 interactions and feedbacks between multiple services from three broad 1027 categories. It is also amenable to situations where there are several distinct link 1028 mechanisms (i.e., multiplex network; Horvát and Zweig 2012), resulting in 1029 positive and negative interactions between the same ES types, all of which can 1030 be analyzed in a spatial network framework. For example, links between plant 1031 agriculture and water quality regulation areas could be driven both by positive 1032 unidirectional flows from (especially perennial) croplands providing water 1033 filtration services, and by negative unidirectional flows from croplands that use 1034 fertilizers and/or pesticides. The next step will be to use spatial network analyses 1035 to assess our multi-ES framework from the perspective of supply area 'nodes' 1036 and ES connection 'links', which will allow for the incorporation of both 1037 gualitative and guantitative social-ecological data and the evaluation of metrics 1038 related to functionality of supply areas, their connections, and the entire ES 1039 network (e.g., Field and Parrott 2017).

1040

1041 Conclusions

1042 Our study provides a new approach for the assessment of multiple ES and 1043 provides important information on the spatial interconnectivity of a variety of 1044 divergent types of ES across a diverse temperate landscape in southern interior 1045 British Columbia. We are confident that providing a tool for visualization of 1046 multiple ES will help address several ongoing challenges: increase awareness and understanding of how dependent humans are on nature; highlight a need 1047 1048 to maintain landscape connectivity to support ecological functioning; advance 1049 the interdisciplinary science around the ES concept; and help move toward 1050 incorporating this science into management of natural capital (Guerry et al. 1051 2015). As the ES concept continues to be developed and refined, considering 1052 how ES operate within the context of interconnected, complex social-ecological 1053 systems will help improve our ability to meaningfully incorporate multiple ES 1054 into decision-making and planning at the landscape scale. Overall, our methods 1055 not only allow for the explicit incorporation of the current knowledge of the 1056 ecological processes driving linkages between multiple ES, but they also 1057 provide decision makers mapping tools that show where these connections 1058 occur on the landscape and how valuable they are to ES production potential. 1059 Thus, our approach can help quide planners in predicting how intervention(s) in 1060 specific location(s) are likely to have synergistic or antagonistic impacts on ES 1061 supply areas in other, sometimes distant places.

1062

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- 1782
- 1783
- 1784 Appendices
- 1785 **Appendix 1**

1786 Background information

ES interactions: Other work has defined 'interactions' as value-based synergies 1787 (increase in supply quality and/or quantity of one ES results in supply increase of 1788 1789 another), trade-offs (increase in supply of one ES results in decrease of another; 1790 Bennett et al. 2009), bundles (groups of ES that co-occur repeatedly across a 1791 landscape, typically linked to co-variation in LULC types; Raudsepp-Hearne et al. 1792 2010, Lee and Lautenbach 2016), or flows (ES interactions from the perspective 1793 of beneficiaries) between ES that occur over the same space and time (Agudelo 1794 et al. 2020).

1795

1796 ES supply: We note that, although we use the term 'supply' to refer to the 1797 portion of the ES provisioning delivery chain on which we are focused, two of 1798 the ES we have selected can be conceptualized as spanning both the supply 1799 and 'flow' aspects of this chain. ES supply refers to the ecological good(s) and 1800 service(s) produced by a natural or man-made area on the landscape (Potschin 1801 et al. 2016), whereas ES flow represents human access to ES supplies, i.e., the 1802 transfer of a good and/or service from a supply to a benefit area or actor for use 1803 (Villamagna et al. 2013, Schröter et al. 2018, Schirpke et al. 2019, Vallecillo et al. 1804 2019). For agriculture and landscape aesthetics, human action is typically 1805 required for these services to actually flow to beneficiaries, e.g., produce being 1806 shipped to grocers; people venturing into nature to enjoy beautiful viewscapes. 1807 However, in the case of aesthetics, the data on which we based our mapping 1808 was informed by a viewshed analysis, which spatially quantified the potential for

1809 people to actually see areas all across the landscape, thereby incorporating an 1810 ES flow component. In the context of preventing or minimizing the impacts of 1811 flooding, waterflow regulation is provided (i.e., flows from supply to demand 1812 areas) when a supply area limits or delays the flow of water (Luck et al. 2009), 1813 which is typically a temporal dynamic dependent on seasonal temperature 1814 and/or weather patterns. Although the existing ES maps we use in this study are 1815 static spatial representations of potential supply areas, in the cases of waterflow 1816 regulation and landscape aesthetics, the distribution of potential spatial location 1817 of flows will still be captured by this mapping. Note also that ES flows are not 1818 equivalent to ES connectivity, the latter of which we are defining by the 1819 functional ecological interrelationships between different supply areas.

1820

1821 Appendix 2

1822 Original ES supply area mapping summary

1823 Below we summarize the procedures for primary- and proxy-based mapping of 1824 the three ES used in our study, originally produced by Field et al. (2017). 1825 Ecosystem attributes were mapped, and their potential contribution to ES 1826 supply quantified, based on environmental functions that are known to underpin 1827 ES production; on explicit incorporation of perceived benefits to humans; or a 1828 combination of the two methods (Fig. 3; Jakeman and Letcher 2003, Vigerstol 1829 and Aukema 2011, Field et al. 2017). Spatial data sources for original maps 1830 included LULC indicators, remote sensing image interpretation, and were 1831 supported by some field-validations. For analytical consistency, raster data for 1832 original mapping were resampled to \sim 29 m x 29 m resolution and assigned the 1833 identical spatial projection. Original maps were created using ArcMap 10.2 and

1834 10.4 (ESRI 2011), and R (R Core Team 2013). For additional details see Field et 1835 al. (2017); data are available on the Open Science Framework (OSF; Field 2021). 1836

1837 Plant food agriculture (PA) is an economically and culturally important ES in our 1838 study area (e.g., Okanagan Valley Economic Development Society 2013, Kyle 1839 2018), and its supply was mapped based on the spatial extent of all crop types 1840 used directly for human nutrition. These include tree fruits; vines and grapes; 1841 cereals and oilseeds; rotation crops; vegetables; berries; nut trees; and specialty 1842 foods, all of which are concentrated primarily in valley-bottom areas (Field et al. 1843 2017). From these data, we dissolved boundaries between adjacent Agricultural 1844 Land Use Inventory (ALUI) polygons which, in some cases, resulted in different 1845 crop types being merged into a single node (MoAg 2017). We did this to 1846 generalize the mapping of connectivity between PA as a whole, and the other 1847 ES considered in this study, as the rationale for the mechanistic connections 1848 between PA and the other ES were consistent for all crop types. This outcome 1849 fits with our method of PA supply area valuation, which is based solely on 1850 potential crop area (ha) and not on crop type.

1851

1852 The terrestrial areas that provide waterflow regulation (WF) were mapped as a

1853 function of soil texture, slope, land use and land cover (LULC)-specific

1854 perviousness, and functionally relevant ecosystem types including floodplains,

1855 riparian areas, wetlands, and seasonally flooded fields ('influential landscape

1856 features' - 'ILF' herein). WF supply areas were defined as those that sustain water

- 1857 delivery in dedicated areas, and protect against flooding and draughts, both of
- 1858 which are persistent environmental concerns in the study region (Haughian et al.
- 1859 2012). Several wetland areas were excluded from the Field et al. (2017) WF map

1860 due to the absence of soil texture data, which was one of the inputs for the 1861 waterflow infiltration model. Because wetlands are so critical to supporting WF 1862 and are relevant to connectivity mechanisms with several other ES, we added 1863 these areas back to our WF map by re-running the infiltration model under the 1864 assumption that all wetland areas without soils data have 100% saturated 1865 hydraulic conductivity, and then applying an ILF multiplier per Field et al. (2017). 1866 These resulting raster values ranged from 19 to 1200 (mean = 237.7; st.dev = 120.1), and wetlands coincident with mapped floodplains provided the highest-1867 1868 value WF supply areas in the region.

1869

1870 Lastly, landscape aesthetics (LA) supply areas were mapped based on models of 1871 perceived values of different LULC types in the region, on 'visual condition' 1872 ranging from preserved to manicured lands, and on the visibility of areas from 1873 various viewpoints across the case study region. LA supply areas spanned both 1874 terrestrial and large aquatic (i.e., lakes, rivers, manmade reservoirs) areas. We 1875 did not separate adjacent terrestrial from aquatic LA supply areas as 13 LULC 1876 (10 terrestrial; 3 aquatic) values were used as input for original LA mapping, in 1877 conjunction with two other valuation methods (i.e., tourism brochure 1878 assessment; viewshed analysis), and we aimed to keep supply area delineation 1879 methodologically as consistent as possible across different ES types (e.g., for 1880 amalgamation of immediately adjacent supply areas). 1881

1882 Appendix 3

1883 Major watersheds and sub-basins within and surrounding the case study 1884 landscape.

1885 Due to the large file size of the waterflow regulation (WF) data, supply area 1886 delineation steps were run separately for identified sub-basins (n = 118) in our 1887 case study area. To identify sub-basin catchment areas, we used BC Major 1888 Watershed, Fresh Water Atlas (FWA) Watersheds, and FWA Streams datasets 1889 (FLNRO 2017; see Field et al. 2017 for data source descriptions; datasets 1890 available at https://www.data.gov.bc.ca/). For major watersheds with significant 1891 (or complete) overlap with our study area, which would result in a large number 1892 of within-basin ES supply areas and therefore potentially lead to computational 1893 limitations, nested sub-basins were identified. These major watersheds included 1894 Kettle (west), Okanagan, Similkameen, and South Thompson rivers (Appendix B). 1895 FWA Watersheds with a common terminus into valley bottom waterbodies, 1896 verified using the FWA Streams dataset (FLNRO 2017), were merged. Several of 1897 the major watersheds (Columbia, Fraser, Kettle (east), Thompson, and 1898 Washington (Coast) rivers) overlapped with our study area primarily along its 1899 border; the overlapping portions of these watersheds were clipped and added 1900 to the sub-basin dataset (see Appendix B map). The high-value WF raster was 1901 then split by sub-basins using the nearest neighbour sampling technique and 1902 Split Raster tool in ArcMap. Each major watershed was assigned a unique 'goal' 1903 point location for LCP analyses, i.e., sub-basins within a major watershed shared 1904 the same goal point. In some cases, the mapped borders of the BC Major 1905 Watersheds and FWA Watersheds did not exhibit perfect overlap; therefore, 1906 following the high-value WF split exercise, the ArcGIS Erase tool was run by 1907 erasing the spatial extent of sub-basins from other BC Major Watersheds where 1908 they overlap. This ensured that WF supply areas were assigned to sub-basins by 1909 prioritizing the more detailed FWA Watershed dataset.



1910

1911 Appendix 3 - Figure 1. Map of major watersheds and sub-basins within and

- 1912 surrounding the case study landscape in southern interior British Columbia,
- 1913 Canada.
- 1914
- 1915 Appendix 4
- 1916 Detailed methods for building pairwise topographic corridors
- 1917 Once initial LCPs were created, segments of LCP lines were erased where they
- 1918 were overlapped by a non-origin ES supply area polygon, and resulting
- 1919 disconnected lines were made into separate line features. Next, we deleted any
1920 lines that were deemed invalid from the perspective of real-world ES 1921 connectivity. Specifically, any resulting lines that intersected with the sub-basin 1922 goal point were deleted as we were only interested in retaining connections 1923 between pairs of ES supply areas. Certain ES polygons with an irregular shape 1924 had a centroid external to their polygon coverage, which resulted in line 1925 segments that initiated at the origin polygon centroid and terminated on the 1926 origin polygon border; these were also deleted as they did not represent links 1927 between a pair of ES supply areas. Irregular shaped nodes also sometimes 1928 yielded lines that were connected between two points on the parent-polygon 1929 border. These were retained to account for real-world feedbacks that may help 1930 maintain a supply area; however, we ensured that any such lines associated with 1931 two borders of an intersected polygon (i.e., where the line segment was part of 1932 a non-origin polygon) were deleted to avoid duplication with feedback links 1933 identified when separate analyses were run with the intersected polygon (in this 1934 example) as the origin (Fig. 6b).

1935

1936 For topographic corridor mapping we needed to address various rare analytical 1937 outcomes that became evident upon manual model validation. The LCP 1938 analyses resulted in some connections that violated landscape topography. For 1939 example, some LCPs from WF supply areas associated with relatively flat lands in 1940 the headwaters of one sub-basin (Bellevue Creek) were found to flow south to 1941 Okanagan Lake rather than flowing north as they would in reality (Appendix 2). 1942 This was due to the necessity of balancing the smallest possible raster resolution 1943 (20 m) with the overall large size of the study area for computational efficiency. 1944 As individual sub-basins were analyzed separately for topographic links, invalid 1945 linkages between sub-basins were not possible; however, we manually

1946	inspected all LCP results and removed any LCPs that violated downslope flow
1947	logic from subsequent analyses. Further, we did not incorporate certain rare
1948	spatial occurrences. These included instances of a smaller supply area inside
1949	bigger one; centroids captured by the incorrect buffer due to two or more
1950	centroids occurring close to one another; and LCP segments that resulted in
1951	feedback loops that occurred across non-origin supply areas (these loops were
1952	likely retained as feedback loops when such nodes served as LCP origins).
1953	
1954	
1955	Appendix 5
1956	R script files (available on the OSF; Field 2021).
1957	i. TOP-VALUE SUPPLY AREA NODE CREATION (file name:
1958	'nodes_waterflow_FORMAT.R')
1959	ii. OVERLAP LINK CREATION (file name: 'links(overlap)_waterflow <>
1960	plantag_MASTER_FORMAT.R')
1961	iii. SUPPLY AREA CENTROID CREATION (PREP FOR LEAST COST PATH 'LCP'
1962	ANALYSES) (file name: 'links_waterflow_ALL_centroids_FORMAT.R')
1963	iv. CREATE LCP GOAL POINTS FOR EACH SUB-BASIN/MAJOR WATERSHED
1964	(file name: 'links_waterflow_ALL_LCP goal pts_FORMAT.R')
1965	v. LEAST COST PATH 'LCP' ANALYSIS FOR TOPOGRAPHIC LINK CREATION
1966	(file name: 'links_waterflow_okanagan_LCPs_SUBBASIN_FORMAT.R')
1967	vi. TOPOGRAPHIC LINK CREATION (file name:
1968	'links_waterflow_okanagan_1_MASTER_FORMAT.R')
1969	vii. INFLUENTIAL LANDSCAPE FEATURES (ILF) LINKS (file name:
1970	'links_waterflow_okanagan_LCPs_ILF_FORMAT.R')
1971	

1972 **Appendix 6**

1973 Study limitations

1974 We identified three primary limitations of our approach. Firstly, we only included 1975 three ES in our study and comparisons. Therefore, we are limited in the 1976 generalizations we can make, especially as they pertain to the specific locations, 1977 LULC- and ecosystem-relevance of the potential for connectivity 'hotspots'. 1978 Investigating a limited number of ES is common among studies that model 1979 interactions among ES (Agudelo et al. 2020), with data limitations, complexity of 1980 socio-ecological process involved, and methodological gaps cited as barriers to 1981 inclusion of all ES (Kolosz et al. 2018). However, our choice to test only three ES 1982 was motivated by our goal to provide a straightforward case study of how each 1983 of the three broad ES categories (i.e., non 'supporting'; MEA 2005) can be 1984 represented in the same study. Our approach is easily adaptable to including an 1985 unlimited number of ES, though the complexity in representing the functional 1986 connections between them will may increase disproportionately to the number 1987 of ES included, and limited data and/or gaps in our understanding of interaction 1988 mechanisms may preclude modelling of certain pairwise relationships (Field and 1989 Parrott 2017). Secondly, we only identified synergistic interactions among the 1990 case study ES we included, but no trade-offs were represented in our case 1991 study. The presence of potential trade-offs, as well as ecosystem dis-services 1992 (e.g., competition for water and pollination among different LULC types; spread 1993 of pests and diseases; Zhang et al. 2007), is of critical importance to informing 1994 management, as the optimization of all ES on a landscape is usually not 1995 simultaneously possible (e.g., Qiu and Turner 2013). We encourage future 1996 applications of our approach to represent trade-offs and negatively-valued 1997 functional connections between ES.

1998

1999 Lastly, we do not incorporate a measurement of uncertainty into our approach. 2000 For example, we did not attempt to directly assess spatial autocorrelation of our 2001 functional connectivity models with any other, potentially influential ecological 2002 processes, as we were interested in providing straight-forward and replicable 2003 rationale for mapping linkages; however, this precluded us from being able to 2004 parse the presence of shared drivers and potential artefacts in proxy or primary 2005 data. Additionally, the location and value of the identified connectivity corridors 2006 may be driven by the assumptions of original ES mapping and the threshold (top 2007 50%) we used to delineate high-value supply areas. Several publications have 2008 suggested that incorporating uncertainty measures is necessary for producing 2009 reliable results to support decision making, and will lead to improved 2010 understanding of the system under study through identification of the most compelling findings (Seppelt et al. 2011, Hamel and Bryant 2017, Stritih et al. 2011 2012 2018). Sources of uncertainty considered in ES assessments are related to 2013 models of ecological processes; subjective choices of researchers and/or 2014 participants; and practical modelling skills and data guality (Gos and Lavorel 2015 2012, Burkhard et al. 2013, Hou et al. 2018, Wang et al. 2018). To date, only a 2016 limited number of studies on ES interactions have incorporated measures of 2017 uncertainty and/or model validation (Boerema et al. 2017, Agudelo et al. 2020). 2018 As unconfirmed results are difficult to reliably assess, they are not as useful for 2019 direct practical applications (Agudelo et al. 2020). Studies with the express 2020 purpose of providing guidance for on-the-ground multi-ES planning should 2021 therefore incorporate metrics of uncertainty and model validation procedures. 2022

2023 Appendix 7

2024 Distribution of major LULC types across the case study region.



2025

2026 Appendix 7 - Figure 1. Map of the distribution of major LULC types across the 2027 case study region.

2029 Appendix 8

2030 Summary tables of total areas and proportional coverages for major LULC

2031 types within each ES supply area and link type.

2032 Appendix 8 - Table 1. Percent of LULC overlapped by each ES supply area.

			High Value Supply Areas (Top 50%)											
		Study Area		PA			WF		LA 1456241					
LULC Type	Total area (ha)	2158001		12606			922425							
		% of study area	Area (ha)	% of supply area	% of total LULC	Area (ha)	% of supply area	% of total LULC	Area (ha)	% of supply area	% of total LULC			
Forest (incl. parks)	1654215	76.65	30.85	0.24	1.86e-03	725852.30	78.69	43.88	1354434.00	93.01	81.88			
Park	255964	11.86	4.25e-06	0	0	129588.70	14.05	50.63	190476.70	13.08	74.42			
Grassland	147610	6.84	0.12	9.80e-04	8.37e-05	72050.87	7.81	48.81	3783.53	0.26	2.56			
Shrub	124953	5.79	0	0	0	53425.76	5.79	42.76	3889.10	0.27	3.11			
Agriculture	79769	3.70	12605.44	100.00	15.80	31338.00	3.40	39.29	241.00	0.02	0.30			
Water	64272	2.98	0	0	0	0	0	0	63469.20	4.36	98.75			
Residential	34897	1.62	3.08e-04	0	0	10990.55	1.19	31.49	241.44	0.02	0.69			
Rock / exposed	27373	1.27	2.78e-04	0	0	5387.80	0.58	19.68	779.82	0.05	2.85			
Wetland	18207	0.84	9.44e-06	0	0	18128.12	1.97	99.57	12586.06	0.86	69.13			
Urban	6187	0.29	0	0	0	1918.28	0.21	31.01	27.75	1.91e-03	0.45			
Unknown	1291	0.06	1.72	0.01	0.13	473.51	0.05	36.67	52.74	3.62e-03	4.08			

2033

2034

2035 Appendix 8 - Table 2. Percent of LULC overlapped by each topographic link.

			Topographic Links												
		Study Area		WF> PA			WF -> WF		WF> LA 4695						
LULC Type	Total area (ha)	2158001		4079			44449								
		% of study area	Area (ha)	% of link area	% of total LULC	Area (ha)	% of link area	% of total LULC	Area (ha)	% of link area	% of total LULC				
Forest (incl. parks)	1654215	76.65	2205.94	54.08	0.13	19069.77	42.90	1.15	2688.56	57.26	0.16				
Park	255964	11.86	438.39	10.75	0.17	3146.14	7.08	1.23	682.44	14.54	0.27				
Grassland	147610	6.84	433.05	10.62	0.29	3065.90	6.90	2.08	477.85	10.18	0.32				
Shrub	124953	5.79	102.67	2.52	0.08	1230.22	2.77	0.98	195.80	4.17	0.16				
Agriculture	79769	3.70	807.02	19.79	1.01	2329.46	5.24	2.92	596.03	12.70	0.75				
Water	64272	2.98	127.65	3.13	0.20	15664.49	35.24	24.37	184.83	3.94	0.29				
Residential	34897	1.62	218.51	5.36	0.63	1368.65	3.08	3.92	304.98	6.50	0.87				
Rock / exposed	27373	1.27	46.70	1.14	0.17	671.99	1.51	2.45	112.70	2.40	0.41				
Wetland	18207	0.84	56.51	1.39	0.31	732.48	1.65	4.02	51.79	1.10	0.28				
Urban	6187	0.29	43.92	1.08	0.71	185.53	0.42	3.00	45.69	0.97	0.74				
Unknown	1291	0.06	1.07	0.03	0.08	2.83	0.01	0.22	1.72	0.04	0.13				

2036 2037

2038 Appendix 8 - Table 3. Percent of LULC overlapped by each overlapping links.

			Overtapping Links														
		Study Area	PA -> LA			PA -> WF			WF -> PA			WF -> LA			LA -> WF		
LULC Type	Total area (ha)	2158001	8.57024			4747.30300			4672.03900			684301			685377		
		% of study area	Area of overlap (ha)	% of link area	% of LULC area	Area (ha)	% of link area	% of total LULC	Area (ha)	% of link area	% of total LULC	Area (ha)	% of link area	% of total LULC	Area (ha)	% of link area	% of total LULC
Forest (incl. parks)	1654215	76.65	2.44	28.47	1.47e-04	31.28	0.66	1.89e-03	29.11	0.62	1.76e-03	621652.40	90.84	37.58	624572.00	91.13	37.76
Park	255964	11.86	0.37	4.31	1.44e-04	14.13	0.30	0.01	14.04	0.30	0.01	100349.60	14.66	39.20	100349.60	14.64	39.20
Grassland	147610	6.84	0.24	2.75	1.59e-04	43.72	0.92	0.03	42.58	0.91	0.03	2543.49	0.37	1.72	2543.49	0.37	1.72
Shrub	124953	5.79	0.02	0.18	1.27e-05	0.64	0.01	5.15e-04	0.64	0.01	5.15e-04	2481.88	0.36	1.99	2481.88	0.36	1.99
Agriculture	79769	3.70	5.97	69.71	0.01	4652.62	98.01	5.83	4579.59	98.02	5.74	150.98	0.02	0.19	150.98	0.02	0.19
Water	64272	2.98	0.27	3.19	4.25e-04	0.50	0.01	7.84e-04	0.50	0.01	7.84e-04	2057.04	0.30	3.20	2057.04	0.30	3.20
Residential	34897	1.62	0.01	0.08	1.86e-05	12.32	0.26	0.04	12.02	0.26	0.03	124.52	0.02	0.36	124.52	0.02	0.36
Rock / exposed	27373	1.27	0.05	0.53	1.64e-04	5.40	0.11	0.02	5.11	0.11	0.02	291.40	0.04	1.06	291.40	0.04	1.06
Wetland	18207	0.84	0.16	1.92	9.02e-04	3.83	0.08	0.02	3.82	0.08	0.02	12387.53	1.81	68.04	12387.53	1.81	68.04
Urban	6187	0.29	0	0	0	2.02	0.04	0.03	1.97	0.04	0.03	14.73	2.15e-03	0.24	14.73	2.15e-03	0.24
Linknown	1201	0.06	0	0	0	0	0	0	0	0	0	0	0	0	29.40	4 200-02	2.28

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