Article

Integrating landscape changes into ecological connectivity: What-if flow connectivity

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Abstract
There's an arising need for theoretical and methodological tools to predict how much and how landscape changes will impact animal movements. In fact, conservation planning in the face of landscape changes requires realistic predictions of impacts on biotic flows and species dispersals. The goal of What-if Flow Connectivity is to simulate what happens to biotic shifts over real landscapes if landscape changes happen. What-if FC calculates the spatial divergence of the biotic flow with respect to the inertial (i.e. where no landscape changes are considered) flow due to landscape changes. So doing, What-if Flow Connectivity not only predicts the most likely biotic routes imposed by landscape changes to one species, but also estimates the impact of such changes in terms of spatial divergence and differential shift effort with respect to the inertial (no landscape changes) scenario. What-if Flow Connectivity comes with the software Connectivity-Lab whose outputs are the vectors of the faunal (inertial and what-if) movements plus the statistics of the movement (inertial and what-if) efforts.

Keywords biotic flows; dynamic GIS; flow connectivity; gene flow; landscape connectivity; landscape change; landscape planning; species dispersal.

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1 Introduction

The resilience of animals to disturbing events and their fitting to long-term adaptations, like for instance climate change, depends to a great extent on their ability to move safely throughout the landscape to find food, reproduce, and migrate between habitat patches (Taylor et al., 1993). Thus, loss of connectivity can lead to population declines, loss of genetic variation and at long last species extinction.

Flow connectivity (FC hereafter) is a novel approach to species dispersal and biotic flow modelling (Ferrarini, 2013a), whose name is due to the fact that it resembles in some way the motion characteristic of water over a surface. In FC, the surface that drives the species movement is given by a 3D fictional landscape where higher elevations represents areas with elevated friction to the species due to whatever reason (unsuitable landcover, human disturbance etc), while lower altitudes represent the opposite. In FC, one or multiple starting points are only required. The rationale behind this choice is that FC assumes a complete biocentric viewpoint, in that it does not presume to know in advance the destination points of species dispersals (Ferrarini, 2013a).

FC makes use of a clear directionality for predicting dispersal paths, in fact FC predicts the movements of one species by allowing only local (pixel-based) shifts in the directions that mostly lower the friction to the species. The rationale behind this choice is that in the real world one species continuously tries to move from the portions of the landscape with high frictional values (low suitability) towards points with low frictional ones (high suitability). Directionality is also used in FC to detect landscape barriers and facilities to biotic flows (Ferrarini, 2014a). FC assigns realistic resistance values to each land cover type by making null the bias between the predicted dispersal and the detected one (Ferrarini, 2014b). To this aim, it builds up the optimized frictional landscape so that the predicted biotic flow corresponds to the one detected *in situ*.

FC makes use of a similar approach also to trace backward biotic dispersals by reverting the timeline of species dispersal (Ferrarini, 2014c). For this purpose, FC maximizes the potential energy at each step sending back the species to higher levels of potential energy due to the fictional gravity of the frictional landscape. When compared to the widely-used least cost (LC) modelling (Dijkstra, 1959), it emerged that (Ferrarini 2014d) LC modelling a) is a “from-to” approach to ecological connectivity, b) it seeks global path optimization, c) it allows for biotic paths where the biotic effort is ascending, and d) it is undirected (it does not depend on the direction of the path).

FC is also useful for the detection of landscape bottlenecks, i.e. the portions of a study area which inevitably tunnel a specimen towards the points where it has been *in situ* detected (Ferrarini, 2015a).
Climatic Flow Connectivity (Ferrarini, 2015b) has also been introduced to calculate the spatial divergence due to climate change of the biotic flow with respect to the inertial biotic flow (i.e. where no climate change is considered) over landscape. Climatic Flow Connectivity not only predicts the most likely biotic routes imposed by climatic change to one species, but also estimates the impact of climate change in terms of spatial divergence and differential shift effort with respect to the inertial (no climate change) scenario.

In this paper, I introduce a further potentiality of FC called What-if Flow Connectivity. The goal of What-if FC is to simulate what happens to biotic shifts over real landscapes if landscape changes happen. So doing, What-if Flow provides a theoretical and methodological tool to face the challenging issue of predicting landscape change impacts on biodiversity conservation.

2 What-if Flow Connectivity: Mathematical Formulation

Let $L(x,y,z,t)$ be a real 3D landscape at generic time *t*, where $L \in [1,...,n]$. In other words, *L* is a generic (categorical) landcover (or land-use) map with *n* classes.

Let $\varphi(L)$ be the landscape friction (i.e. how much each land parcel is unfavourable) to the species under study. In other words, $\varphi(L)$ is a function that associates a friction value to each pixel of *L*.

Landscape friction has 2 components, i.e. the structural and the functional one, and the overall friction should be equal to their product (not the sum) since they’re interactive:

$$\varphi(L) = \varphi_{STR}(L) * \varphi_{FUNC}(L) \quad (1)$$

Let $L_s(x, y, \varphi(L))$ be a landscape where, for each pixel, the *z*-value is equal to the friction for the species under study. In other words, L_s is a 3D fictional landscape with the same coordinates and geographic projection as *L*, but with pixel-by-pixel friction values in place of real *z*-values. Higher elevations represents areas with elevated friction to the species due to whatever reason (unsuitable landcover, human disturbance etc), while lower altitudes represent the opposite.

Let $S(x, y, t)$ be a binary landscape with the same coordinates and geographic projection as L_s and *L*, but with binary values at each pixel representing species presence/absence at generic time *t*. FC simulates the biotic flow over the frictional landscape L_s as follows (Ferrarini, 2013a)

$$\frac{\delta S(x,y,t)}{\delta t} = \operatorname{div} S = \nabla \cdot S = \frac{\delta S}{\delta x} + \frac{\delta S}{\delta y} \tag{2}$$

with initial conditions S_0 at time T_0. The symbol δ is a notation for a differential (i.e. ∂) or a difference (i.e. Δ) partial equation depending on the kind of landscape under study.

For a high-resolution frictional landscape it represents a differential operator that simulates almost continuous movements over such landscape, conversely for a low resolution landscape it describes discrete movements both in space and time.

As showed in Ferrarini (2013a), the resulting biotic flow comes as follows:

$$\frac{\delta S}{\delta t} = \begin{cases} 0 \quad if \quad \frac{\delta S}{\delta x} = \frac{\delta S}{\delta y} = 0 \\ 1 \quad if \quad (\frac{\delta S}{\delta x} = 1 \; and \; \frac{\delta S}{\delta y} = 0) \\ \qquad\quad or \; (\frac{\delta S}{\delta x} = 0 \; and \; \frac{\delta S}{\delta y} = 1) \\ \qquad\quad or \; \frac{\delta S}{\delta x} = \frac{\delta S}{\delta y} = 1 \end{cases} \tag{3}$$

FC assumes that species dispersal ends at a stability point, if exists, where:

$$\frac{\delta S(x,y,t)}{\delta t} = \nabla \cdot S = 0 \tag{4}$$

Now, if we define *P* as the predicted path for the species over the fictional landscape L_s, and under the hypothesis that L_s remains equal to L_{S0} due to the short time-period considered (inertial landscape), the species effort (i.e., work) *E* for going through such path can be computed as:

$$E = \int_P L_s(x, y, \varphi(L))dp = \iint_P L_{s0} dxdy \quad (5)$$

where the symbol *dp* may be intuitively interpreted as an elementary path length with *dx* and *dy* components. FC assumes a greedy, local effort-minimization for the species dispersal that do not necessarily corresponds to the global minimization.

Now, let's assume that the real landscape $L(x, y, z, t)$ is changed by a human (e.g., road building) or natural (e.g., a landslide) event. The impact (spatial variation) imposed by such landscape change to the inertial biotic (vectorial) flow *P* must hence be calculated as

$$\frac{\delta \vec{P}}{\delta L(x, y, z, t)} = \frac{\delta \frac{\delta S(x, y, t)}{\delta t}}{\delta L_s(x, y, \varphi(L))} \quad (6)$$

where the symbol δ is again a notation for a differential (i.e. ∂) or a difference (i.e. Δ) partial equation depending on the kind of available data.

The most common case is that the landscape change is given as a discrete change, while the landscape is given with an accurate high-resolution map. This means that we consider the impact on biodiversity after that the event has happened. In this case, it follows that the impact on biotic flows must be calculated as

$$\frac{\delta \vec{P}}{\delta L(x, y, z, t)} = \frac{\Delta(\partial S(x, y, t))}{\Delta L_s(x, y, \varphi(L))\partial t} \quad (7)$$

which is a second degree, mixed partial difference-differential equation to be solved into a GIS.

In case that also the landscape is given as a low resolution map, the impact on biotic flows due to landscape change must be calculated as

$$\frac{\delta \vec{P}}{\delta L(x, y, z, t)} = \frac{\Delta^2 S(x, y, t)}{\Delta L_s(x, y, \varphi(L))\Delta t} \quad (8)$$

which is a second degree, partial difference equation to be solved into a GIS.

The third case, is that the landscape change is continuos (e.g., the change is running) and the landscape is given as a high resolution map. The impact on biotic flows due to landscape change must be calculated as

$$\frac{\delta \vec{P}}{\delta L(x, y, z, t)} = \frac{\partial^2 S(x, y, t)}{\partial L_s(x, y, \varphi(L))\partial t} \quad (9)$$

which is a second degree, partial differential equation to be solved into a GIS.

The path induced by the landscape change is defined here as "divergent path" P_d as opposed to the inertial path *P* which is the path predicted to be followed by the species under actual landscape conditions.

The impact on the movement effort for going through the divergent path is computed as

$$\Delta E = E_P - E_{P_d} = \int_{\vec{P}} L_s(x, y, \varphi(L))dp - \int_{\vec{P}_d} L_s(x, y, \varphi(L))dp \quad (10)$$

where the symbol *dp* is an elementary path length with *dx* and *dy* components, *P* is the inertial path, P_d is the divergent path, L_s is the landscape friction. Otherwise stated, What-if Flow Connectivity calculates the spatial divergence due to landscape change of the biotic flow with respect to the inertial biotic flow over the inertial landscape (Fig. 1). So doing, What-if FC not only predicts the most likely biotic routes imposed by the landscape changes to one species, but also estimates such impact in terms of spatial divergence and differential shift effort with respect to the inertial (no change) scenario.

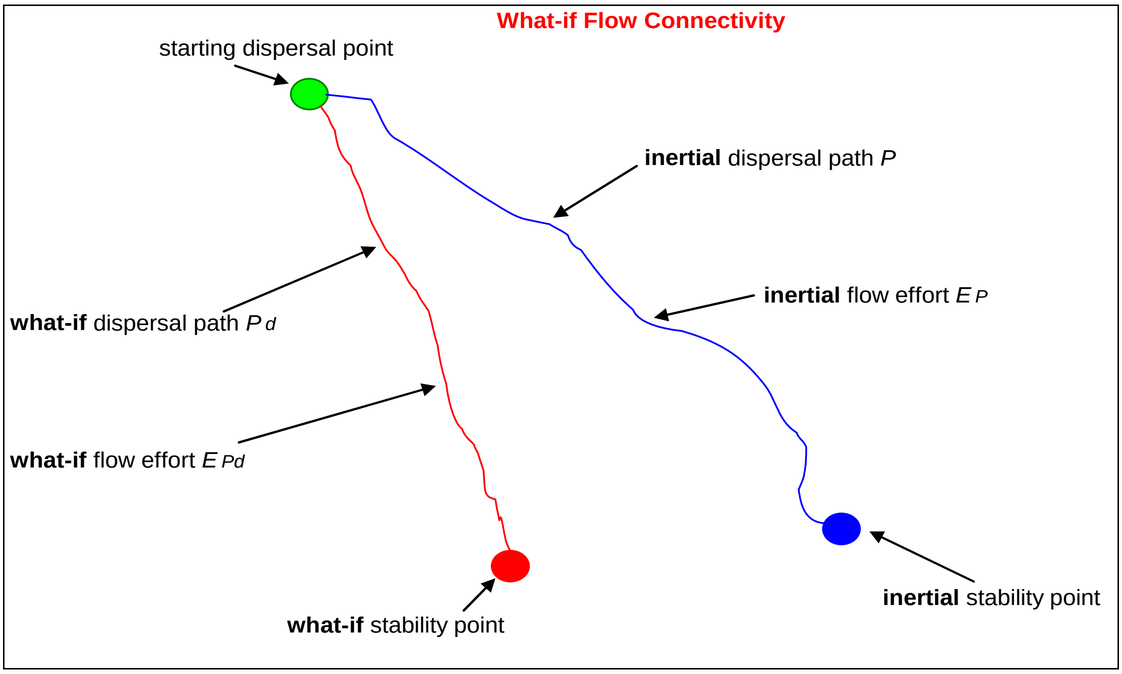

Fig. 1 Schematic diagram of the concepts exposed above: a) inertial dispersal path, b) inertial flow effort, c) inertial stability point, d) what-if dispersal path, e) what-if flow effort, f) what-if stability point.

In order to apply What-if FC to real landscapes, I have incorporated the previous equations into the software Connectivity-Lab (Fig. 2; Ferrarini, 2013b). The outputs of Connectivity Lab are the vectors of faunal (inertial and what-if) movements plus the statistics (txt format) of flow (inertial and what-if) efforts. The most recent version of Connectivity-Lab is 7.0 as of January 2015.

3 Conclusions

There's an arising need of theoretical and methodological tools to predict how, and how much, landscape changes will impact animal movements over landscape. In fact, conservation planning in the face of landscape changes requires realistic predictions where species will likely move after that the landscape has changed, and through which suitable routes such divergent biotic shifts will happen.

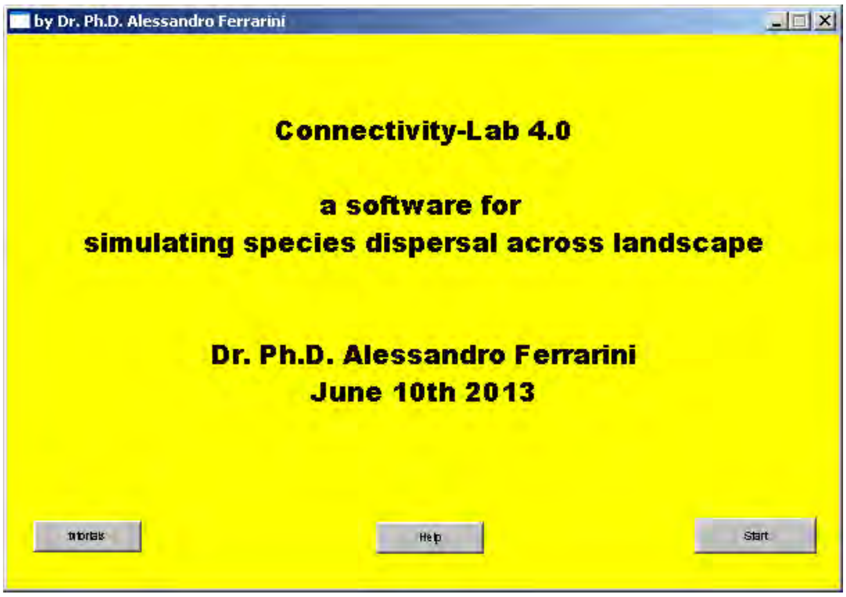

Fig. 2 Splash screen of the software Connectivity-Lab (Ferrarini, 2013b). The most recent version is 7.0 as of January 2015.

What-if Flow Connectivity has been introduced here with such purpose. It takes advantage of the previously introduced Flow Connectivity, and it comes with the software Connectivity Lab whose outputs are the vectors of the faunal (inertial and what-if) movements plus the statistics of the movement (inertial and what-if) efforts.

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