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# Incorporating climatic change into ecological connectivity: Climatic Flow Connectivity

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## Abstract

There’s an urgent need of theoretical and methodological tools to predict how much and how climate change will impact animal movements. In fact, conservation planning aimed to facilitate species movement in the face of climate change strictly requires realistic predictions of where species will likely move to reach suitable climates, and through which suitable routes such biotic shifts will happen. Climatic Flow Connectivity is introduced here with such purpose. Climatic Flow Connectivity calculates 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. So doing, 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. Climatic Flow Connectivity 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 climatic) movement plus the statistics of the movement (inertial and climatic) efforts.

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

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## 1 Introduction

While many species have already reacted to the recent climatic change (Parmesan et al., 1999; Pounds et al., 2006), climatic change will soon impose further distributional shifts to many others (Thomas et al., 2004; Thuiller et al., 2005; Huntley et al., 2008). Conservation planning aimed to facilitate species movements strictly requires realistic predictions of where species will likely move to reach suitable climates, and through which suitable routes such biotic shifts will happen (Heller and Zavaleta, 2009; Ferrarini et al., 2014a).

Flow connectivity (FC hereafter) is a novel approach to species dispersal and biotic flow modelling (Ferrarini 2013), whose name is due to the fact that it resembles in some way the motion characteristic of fluids over a surface. 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 tries to move from the portions of the landscape with high frictional values (i.e., low suitability) towards points with low frictional ones (i.e., high suitability). Thus, FC makes use of a clear directionality for predicting dispersal paths. Directionality is also used in FC to detect landscape barriers and facilities to biotic flows (Ferrarini, 2014b).

FC does not assume the knowledge about the destination points of dispersal paths. One or multiple starting points are only required. The rationale behind this choice is that FC assumes a biocentric viewpoint, in that it does not presume to know in advance the destination points of species dispersals (Ferrarini, 2013).

FC assigns realistic resistance values to each land cover type by making null the bias between the predicted dispersal and the detected one (Ferrarini, 2014c). To this aim, it builds up the optimized frictional landscape so that the predicted biotic flow corresponds to the one detected *in situ*.

When compared to least cost (LC) modelling (Dijkstra, 1959), four methodological differences emerged (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 makes use of this approach also to trace backward biotic dispersals by reverting the timeline of species dispersal (Ferrarini, 2014e). 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.

FC is also useful for the detection of landscape bottlenecks, i.e. the portions of an arbitrary study area which inevitably tunnel a specimen towards the points where it has been *in situ* detected (Ferrarini, 2015).

To date, FC has been applied only to inertial landscapes. Otherwise stated, the landscapes beneath species movements were static during the simulated biotic shift. In this paper, I introduce a further accomplishment of FC called Climatic Flow Connectivity. The goal of Climatic FC is to allow incorporate climatic changes into the dynamic simulations of biotic shifts over real landscapes (climatic landscapes, from now on).

The purpose of Climatic Flow Connectivity is clear: to provide a theoretical and methodological tool to face the challenging issue of predicting likely biotic routes induced by the climatic change.

## 2 Climatic 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. At time $T_{0,}$

$$L_0 = L(x,y,z,t_0) \tag{1}$$

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:

$$\varphi(L) = \varphi_{STR}(L) * \varphi_{FUNC}(L) \tag{2}$$

At time $T_0$,

$$\varphi_0 = \varphi(L_0) \tag{3}$$

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. At time $T_0$,

$$L_{s0} = L_s(x, y, \varphi(L_0)) \tag{4}$$

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, 2013)

$$\frac{\delta S(x, y, t)}{\delta t} = \text{div } S = \nabla \cdot S = \frac{\delta S}{\delta x} + \frac{\delta S}{\delta y} \tag{5}$$

with initial conditions $S_0$ at time $T_0$.

The symbol $\delta$ is a notation for a differential (i.e. $\partial$) or a difference (i.e. $\Delta$) partial equation depending on the kind of landscape under study. For an high-resolution frictional landscape it represents a differential operator that simulates almost continuos movements over such landscape, conversely for a low resolution landscape it describes discrete movements both in space and time.

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

$$\frac{\delta S}{\delta t} = \begin{cases} 0 \quad if \quad \dfrac{\delta S}{\delta x} = \dfrac{\delta S}{\delta y} = 0 \\ \\ 1 \quad if \quad (\dfrac{\delta S}{\delta x} = 1 \; and \; \dfrac{\delta S}{\delta y} = 0) \\ \qquad or \; (\dfrac{\delta S}{\delta x} = 0 \; and \; \dfrac{\delta S}{\delta y} = 1) \\ \qquad or \; \dfrac{\delta S}{\delta x} = \dfrac{\delta S}{\delta y} = 1 \end{cases} \tag{6}$$

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

$$\frac{\delta S(x, y, t)}{\delta t} = \nabla \cdot S = 0 \tag{7}$$

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

$$E = \int_P L_s(x, y, \varphi(L))dp = \iint_P L_{s0} dxdy \tag{8}$$

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. *E* is thus the result of a local (pixel-by-pixel) path optimization.

The impact (spatial variation) imposed by climatic change to the inertial biotic flow *P* must hence be calculated as

$$\frac{\delta \frac{\delta S(x,y,t)}{\delta t}}{\delta \vec{C}} = \frac{\delta^2 S(x,y,t)}{\delta \vec{C}\ \delta t} \tag{9}$$

where the symbol $\delta$ is again a notation for a differential (i.e. $\partial$ ) or a difference (i.e. Δ) partial equation depending on the kind of available data, while $\vec{C}$ is the vector of climatic change (e.g., change in average summer T°, change in total winter rainfalls etc.).

If we consider that the climate change vector $\vec{C}$ has *n* components $<c_1 \ldots c_n>$, eq. (9) becomes

$$\frac{\delta \frac{\delta S(x,y,t)}{\delta t}}{\delta \vec{C}} = \frac{\delta^{n+1} S(x,y,t)}{\delta c_1 \delta c_2 ... \delta c_n\ \delta t} \tag{10}$$

The most common case is that the climatic change is given as a discrete change (e.g., projections to 2030, 2050 and 2070) while the landscape is given with an accurate high-resolution map. In this case, it follows that the impact on biotic flows due to the climatic change must be calculated as

$$\frac{\delta \frac{\delta S(x,y,t)}{\delta t}}{\delta \vec{C}} = \frac{\delta^2 S(x,y,t)}{\Delta \vec{C}\ \partial t} = \frac{\Delta^n \partial S(x,y,t)}{\Delta c_1 \Delta c_2 ... \Delta c_n \partial t} \tag{11}$$

which is a *n+1* 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 climatic change must be calculated as

$$\frac{\delta \frac{\delta S(x,y,t)}{\delta t}}{\delta \vec{C}} = \frac{\delta^2 S(x,y,t)}{\Delta \vec{C}\ \partial t} = \frac{\Delta^{n+1} S(x,y,t)}{\Delta c_1 \Delta c_2 ... \Delta c_n \Delta t} \tag{12}$$

which is a *n+1* degree, partial difference equation to be solved into a GIS.

The path induced by the climatic change is defined here as “climatic path” $P_c$ as opposed to the inertial path *P* which is the path predicted to be followed by the species under actual climatic conditions. The climatic impact on the movement effort for going through such climatic path is computed as

$$\Delta E = E_P - E_{P_c} = \int_P L_s(x,y,\varphi(L))dp - \int_{P_c} L_s(x,y,\varphi(L))dp \tag{13}$$

where the symbol *dp* is an elementary path length with *dx* and *dy* components, *P* is the inertial path, $P_c$ is the climatic path, $L_s$ is the landscape friction.

Otherwise stated, Climatic Flow Connectivity calculates the spatial divergence due to climate change of the climatic biotic flow with respect to the inertial biotic flow over the inertial landscape (Fig. 1). So doing, Climatic Flow Connectivity not only predicts the most likely biotic routes imposed by the climatic change to one species, but also estimates such impact in terms of spatial divergence and differential shift effort with respect to the inertial (no climate change) scenario.

In order to apply Climatic Flow Connectivity to real landscapes, I have incorporated the previous equations into the software Connectivity Lab (Ferrarini, 2013b). The outputs of Connectivity Lab are the vectors of faunal (inertial and climatic) movements plus the statistics (*txt* format) of flow (inertial and climatic) efforts.

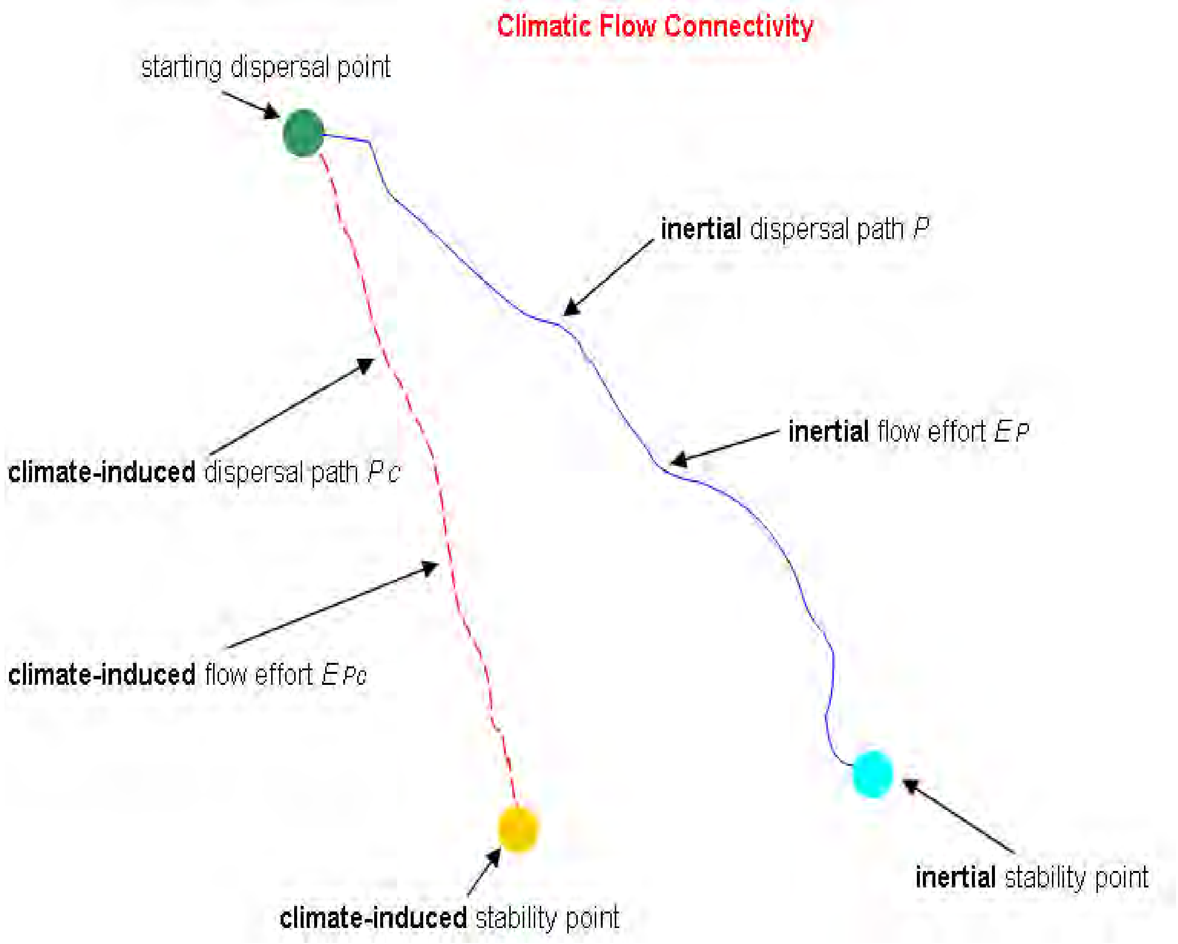

**Fig. 1** Schematic diagram of the concepts exposed above: a) inertial dispersal path, b) inertial flow effort, c) inertial stability point, d) climate-induced dispersal path, e) climate-induced flow effort, f) climate-induced stability point.

## 3 Conclusions

There's an urgent need of theoretical and methodological tools to predict how and how much climate change will impact animal movements over landscape. In fact, conservation planning aimed to facilitate species movement in the face of climate change strictly requires realistic predictions of where species will likely move to reach suitable climates, and through which suitable routes such biotic shifts will happen.

Climatic 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 climatic) movement plus the statistics of the movement (inertial and climatic) efforts.

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