Article

Where do they come from? Flow connectivity detects landscape bottlenecks

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Abstract

In this paper, bottleneck flow connectivity is first introduced. A landscape bottleneck is defined here as the portion of an arbitrary study area which inevitably tunnels a specimen towards the point where it has been detected *in situ*. In other words, a bottleneck delimits the portion of the study area which forces the specimen to pass through the detected point of presence with, at most, a tolerance distance equal to an *a priori* defined uncertainty. There is one precise reason for the introduction of bottleneck flow connectivity: when a specimen is detected through in situ observations or GPS devices, it should be possible to derive the portion of the landscape where it can come from. In fact, the detected specimen is usually just one individual of an entire population that is moving somewhere in the landscape. Hence, such specimen can work as a tracker of the whole population if we have the proper methodological tools to turn its detected position into a map where the landscape bottleneck of the detected location is delineated. In case of a species of conservation interest, the application of bottleneck flow connectivity is useful for the individuation and then the conservation of such population. In case of an exotic undesired species, bottleneck flow connectivity can help individuate the location of the population that should be eradicated, starting from few field observations. An applicative example for wolf in the Ceno Valley (Italy) is provided. Bottleneck flow connectivity has thus interesting implications both for the conservation of species of interest, but also for the management of undesired exotic species.

Keywords backward simulations; biotic bottlenecks; biotic flows; dynamical GIS; exotic species; flow connectivity; gene flow; landscape connectivity; species dispersal.

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1 Introduction

Flow connectivity (FC hereafter) is a novel approach to species dispersal modelling, first introduced in 2013 (Ferrarini, 2013). Its name is due to the fact that it resembles in some way the motion characteristic of fluids over a surface. In fact, FC predicts species dispersal by minimizing at each time step the potential energy due to fictional gravity force over a frictional 3D landscape. To achieve this, FC controls 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 in FC is clear: 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). Since higher frictional values are represented by higher elevations in a 3D frictional landscape, the metaphor of water flowing down from higher elevations towards lower ones, following a fictional gravity force, is clear. 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, 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 do this, it builds up the optimized frictional landscape so that the predicted biotic flow corresponds to the one detected *in situ*.

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).

When compared to least cost (LC) modelling (Dijkstra, 1959), four main differences emerged (Ferrarini, 2014c). 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). Instead, FC has opposite properties.

FC makes use of this approach also to trace biotic dispersals backward by reverting the timeline of species dispersal (Ferrarini 2014d). 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.

Climatic Flow Connectivity (Ferrarini, 2015) has also been introduced in order to take into account the climate change into the simulations of species dispersal.

In this paper, I add a further potentiality to FC: the skill to detect landscape bottlenecks, i.e. the whole set of landscape points from which a specimen could come from, once that it has been detected in particular point of the landscape. Landscape bottleneck could also be thought as the spatial funnel that inevitably leads the specimen toward the point where it has been detected.

This could bear important implications for both the conservation of species of interest and the management of undesired exotic species.

2 Bottleneck 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,

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

Flow connectivity (FC) modelling starts with the assignment of true-to-life coefficients to L_s.

True-to-life coefficients for $\varphi(L)$ can be calculated in FC as depicted in Ferrarini (2014b), where I defined *P* as the predicted path for the species over the fictional landscape L_s, and P^* the real path followed by the species (as detected by GPS data-loggers or *in situ* observations). The bias *B* between *P* and P^* is hence calculated as

$$B = \mathrm{mod}(\int P dx - \int P^* dx) \tag{5}$$

where the function *mod* indicates the module of the difference.

It follows that

$$B = \begin{cases} \int P dx - \int P^* dx & \text{where } P > P^* \\ \int P^* dx - \int P dx & \text{where } P^* > P \end{cases} \tag{6}$$

Now, true-to-life coefficients for landscape friction can be calculated by optimizing *B* as follows:

set B to 0 (7)

or, at least,

minimize B (8)

The optimization of $\varphi(L)$ can be properly achieved using genetic algorithms (Holland, 1975).

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)

$$\frac{\delta S(x, y, t)}{\delta t} = \nabla \cdot S = \frac{\delta S}{\delta x} + \frac{\delta S}{\delta y} \tag{9}$$

with initial conditions S_0 at time T_0. See Ferrarini (2013) for further details.

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 an 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 (2013), the resulting biotic flow is as follows:

$$\frac{\delta S}{\delta t} = \begin{cases} 0 \quad if \quad \frac{\delta S}{\delta x} = \frac{\delta S}{\delta y} = 0 \\ \\ 1 \quad if \quad (\frac{\delta S}{\delta x} = 1 \; and \; \frac{\delta S}{\delta y} = 0) \\ \qquad or \; (\frac{\delta S}{\delta x} = 0 \; and \; \frac{\delta S}{\delta y} = 1) \\ \qquad or \; \frac{\delta S}{\delta x} = \frac{\delta S}{\delta y} = 1 \end{cases} \tag{10}$$

Now, let's suppose that a specimen has been detected at the generic location $<x_s, y_s>$ of the real landscape *L*. FC can be reverted in order to find all the possible $S_0 = S(x, y, 0)$ so that the biotic flows starting from such binary landscapes inevitably passes through the point $<x_s, y_s>$ (i.e. $S(x_s, y_s, t_i)$ =1 at some time *i* with *i≥0*) where the species has been detected. The set of landscape points having such property is defined here as the landscape bottleneck of the detected specimen.

In order to do that, bottleneck flow connectivity makes use of a solution similar to that used by backward flow connectivity (Ferrarini, 2014d). Backward flow connectivity reverts the timeline of species dispersal, thus being able to trace backward biotic dispersals as follows

$$\frac{\delta S(x,y,t)}{\delta t_{t \to -\infty}} = \nabla \cdot S = \frac{\delta S}{\delta x} + \frac{\delta S}{\delta y} \tag{11}$$

where $t \to -\infty$ indicates that time is going backward.

Bottleneck FC is a generalization of backward FC. Instead of sending back at each simulation step the detected specimen toward only the neighbouring point with the highest level of potential energy due to the fictional gravity of the frictional landscape, it sends back the detected specimen toward all the neighbouring points with higher levels of potential energy. Thus, by definition the backward path detected by backward FC is always comprised within the biotic funnel individuated by bottleneck FC, and of which it represents the most probable biotic path.

The previous strict definition of landscape bottleneck can be relaxed by searching all the landscape points so that, starting from such points, the species will pass at a distance less or equal than a pre-defined tolerance distance *D* (e.g. 100 m) from $<x_s, y_s>$ (Fig. 1).

This relaxed definition of landscape bottleneck leads inevitably to larger landscape bottlenecks, because it incorporates a degree of uncertainty about the exact location of $<x_s, y_s>$.

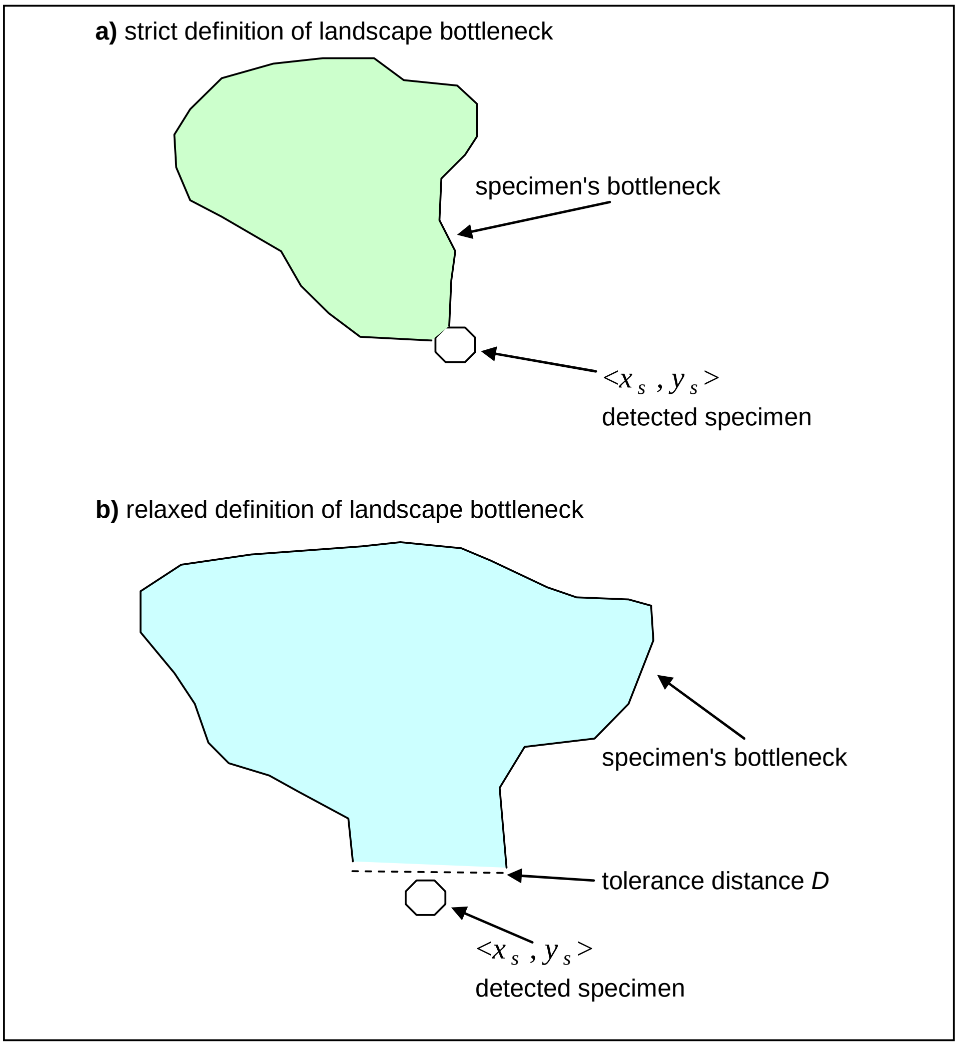

Fig. 1 Conceptual representation of a) strict and b) relaxed definitions of a landscape bottleneck.

In order to detect biotic bottlenecks of real landscapes, I have incorporated bottleneck FC into the software Connectivity Lab (Ferrarini, 2013b).

3 An Applicative Example

The Ceno valley is a 35,038 ha wide valley situated in the Province of Parma, Northern Italy. It has been mapped at 1:25,000 scale (Ferrarini, 2005; Ferrarini, et al. 2010) using the CORINE Biotopes classification system. The landscape structure of the Ceno Valley has been widely analysed (Ferrarini and Tomaselli, 2010; Ferrarini, 2011; Ferrarini, 2012a; Ferrarini, 2012b). From an ecological viewpoint, the most interesting event recently registered is the shift of wolf populations from the montane belt to the lowland one. Several populations have been recently observed *in situ* by life-watchers, environmental associations and local administrations.

I have applied here bottleneck FC to a portion of the Ceno valley above 1000 m a.s.l. close to the municipality of Bardi (Fig. 2). The area is a square of about 20 km * 20 km. Optimized friction values $\varphi(L)$ to wolf presence are borrowed from Ferrarini (2012c).

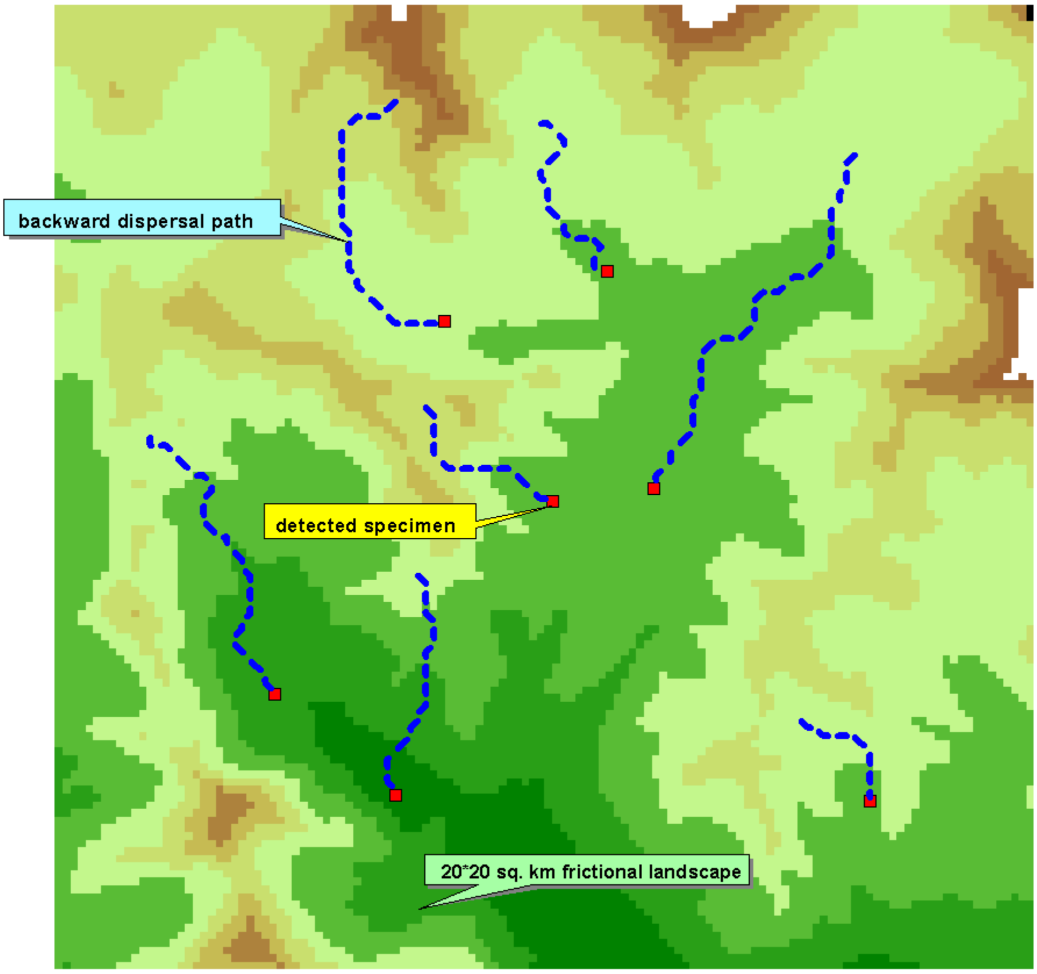

Fig. 2 The frictional landscape *Ls* has been built for wolf upon a portion (20 km * 20 km) of the Ceno valley (province of Parma, Italy) that represents here the real landscape *L(x,y,z,t)*. Red squares represent sites where the species is simulated to be present (S_0=1; detected specimen). Blue scattered lines represent back-in-time dispersal paths calculated via backward flow connectivity using the software Connectivity-Lab (Ferrarini, 2013b).

Bottleneck FC provides the results depicted in Fig. 3. Cyan polygons represent the calculated landscape bottlenecks of the detected specimens (red squares). It can be seen that, using a tolerance distance *D* equal to 0 meters, five out of seven points have a landscape bottleneck that only correspond to their backward paths. This means that the landscape friction for wolf around these points is so steep that only sharp biotic paths can lead to the detected points. Instead, two points have a large bottleneck even with a null tolerance distance *D*. The two detected bottlenecks have areal extensions of 742.3 and 461.5 hectares respectively.

I have then repeated the bottleneck simulations using a tolerance *D* equal to 100 meters (Fig. 4) for each point of specimen presence. In this case, each specimen has its non-null bottleneck that also comprises the backward simulation path.

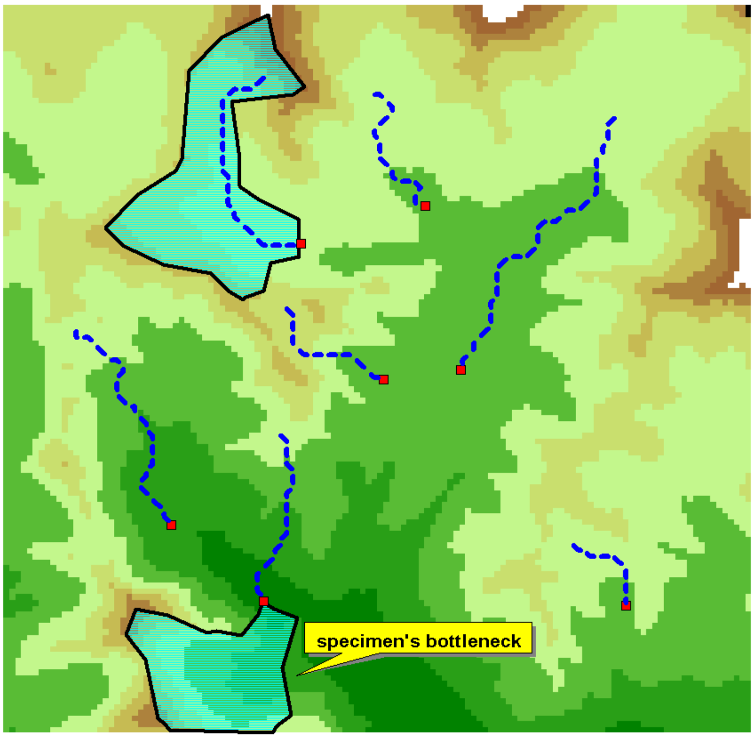

Fig. 3 For each detected specimen (S_0=1; red squares), landscape bottlenecks (cyan polygons) have been detected via bottleneck flow connectivity. Blue scattered lines represent back-in-time dispersal paths calculated via backward flow connectivity. A bottleneck delimits the portion of the study area which forces the specimen to pass through the detected presence with, at most, a tolerance distance equal to an *a priori* uncertainty. In this case, such tolerance distance has been set equal to 0 m (i.e., no uncertainty about the localization of the specimens).

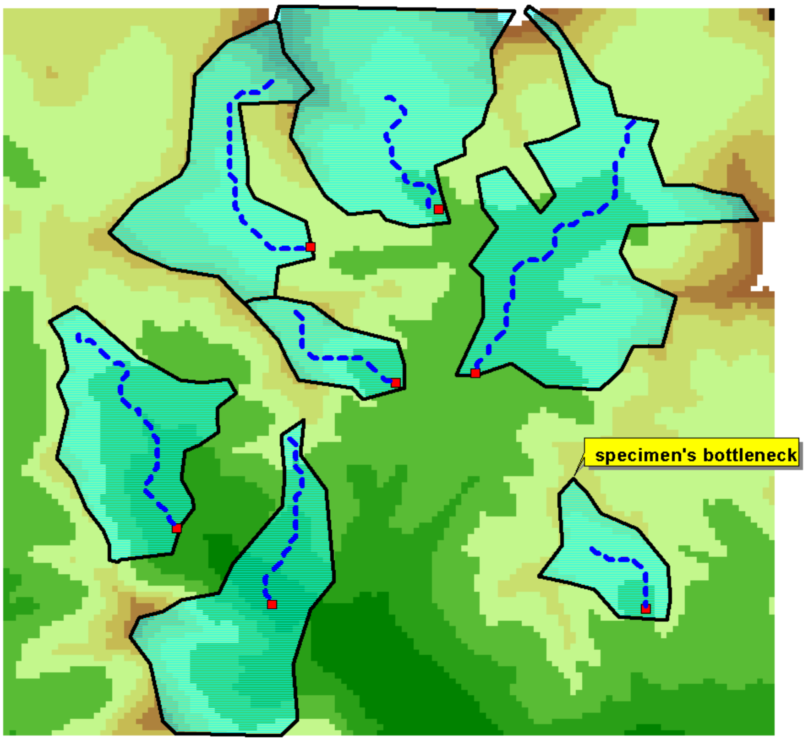

Fig. 4 For each specimen (S_0=1; red squares), landscape bottlenecks (cyan polygons) have been calculated via bottleneck flow connectivity. Blue scattered lines represent back-in-time dispersal paths as calculated via backward flow connectivity. In this case, the tolerance distance *D* has been set equal to 100 m (i.e., heavy uncertainty about the localization of the specimens).

Of course simulations can be repeated using any tolerance distance *D*. Clearly, the most realistic tolerance distance should be equal to the average accuracy error of the GPS instrument used to detect the specimens. Today, many GPS devices have sub-metric accuracy, so the tolerance distance for bottleneck FC can be set to 1 meter. In case of field observations, the uncertainty about the exact location of the specimens could be much higher, in the order of 100 m or even more as simulated in Fig. 4.

4 Conclusions

In this paper, bottleneck flow connectivity has been first introduced. Bottleneck flow connectivity is a generalization of backward flow connectivity.

There one precise reason for the introduction of bottleneck FC: when a specimen is detected through field observations or GPS devices, it should be possible to derive the portion of the landscape where it comes from. In fact, the detected specimen is probably just one individual of an entire population that is moving somewhere in the landscape. Hence, such specimen can work as a tracker of the whole population if we have the right methodological tools to turn its detected position into a map where the landscape bottleneck of such location is delimitated. In case of a species of conservation interest, the application of bottleneck FC is useful for the individuation and then the conservation of such population. In case of an exotic undesired species, starting from few field observations bottleneck FC can help individuate the population that should be eradicated. Thus, bottleneck FC has interesting implications both for the conservation of species of interest, but also for the management of undesired exotic species.

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