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Modeling hydrochory effects on the Tunisian island populations of *Pancratium maritimum* L. using colored Petri nets

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ABSTRACT

Hydrochory, the seed dispersal by water, is a strategy used by many aquatic and some terrestrial plants to move into areas appropriate for establishment. In this paper we model the hydrochory effects on the Tunisian island populations of *Pancratium maritimum* L. using colored Petri nets. Nineteen Tunisian coastal sites were considered including fourteen mainland and five island sites. The model was simulated for 400 thousand Atlantic Tunisian Current cycles (years). Snapshots of the island population's genetic makeup were taken for 50, 200 and 400 thousand years. The evolution of the obtained dendrograms showed a clear divide between the northern and southern island populations according to their estimated genetic make-up for the considered simulation durations.

Hydrochory is not only with important ecological consequences, such as maintaining the populations of *P. maritimum* but also it may move species into areas appropriate for establishment. In this context, *in situ* and *ex situ* conservation measures of *P. maritimum* populations should be adopted very fast.

1. Introduction

Seed dispersal is regarded as a key process in the spatial genetic structure and the survival of plant populations (Shimamura et al., 2007). Seeds are dispersed in many different ways: by wind, animals, water, fire and ballistic mechanism (Jongejans and Schippers, 1999).

Plants which grow beside or in water often use rainwash, streams or irrigation channels, rivers and ocean tide or currents to disperse their seeds (Schneider and Sharitz, 1988). Hydrochory (seed dispersal by water) is shown as an important mean for maintaining and extending the populations of plants (Nilsson et al., 2010). The majority of plant species can be dispersed in fresh water, whereas the proportion of species of seed plants adapted to sea water dispersal is very low. These seeds are waterproof and can have air-filled tissue or other structures to increase their buoyancy for long periods of time (Armstrong, 2005).

2. Objectives

Our previous paper detailed the level and apportionment of genetic diversity and population structure at allozyme loci and floral essential oils for the Tunisian *Pancratium maritimum* L. in mainland and island habitats (Sanaa et al., 2014). This species is a monocotyledon plant belonging to the family of Amaryllidaceae (Medrano et al., 1999). Plants from this family are known to synthesize a particular type of bioactive compounds, named Amaryllidaceae alkaloids, responsible for valuable medicinal properties (Berkov et al., 2004).

P. maritimum is distributed in the Mediterranean, the Atlantic, the Black and Caspian seas (De Castro et al., 2012). The status of *P. maritimum* in Lebanon is vulnerable. In Italy, France, Spain and Crete, populations of this plant have significantly decreased in number and size and the species is considered endangered by overcollection, urbanization and tourism development (Zahreddine et al., 2004).

In Tunisia, the genetic analysis at isozyme loci among the island and mainland populations of *P. maritimum* revealed that island populations are strictly clustered each other or to mainland populations. The model of population grouping is hypothesized to be related to the dispersal of seeds by seawater and wind

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Table 1
Location of *Pancratium maritimum* populations analysed.

Populations	Population code	Degradation level	Latitude (N)	Longitude (E)	Geographic region
Mainland					
Tabarka	M_1	++	36°57′40.19″	8°44′59.63″	Coral coast
Cap Serrat	M_2	+++	37°12′48.09″	9°14′29.57″	Coral coast
Bizerte	M_3	++	37°18′37.68″	9°51′24.24″	Gulf of Tunis
Jarzouna	M_4	+	37°14′46.27″	9°56′30.75″	Gulf of Tunis
Sidi Ali elMekki	M_5	+	37° 5′35.37″	10°12′1.10″	Gulf of Tunis
Borj Sedria	M_6	+	36°43′40.58″	10°20′44.96″	Gulf of Tunis
Oued Laabid	M_7	++	36°40′35.63″	10°56′21.04″	Gulf of Tunis
Sidi Daoued	M_8	+	37° 3′45.51″	11° 0′9.60″	Gulf of Hammamet
Dar Allouch	M_9	+	36°59′15.67″	11° 4′49.36″	Gulf of Hammamet
Chott Ezzouhour	M_{10}	++	36°52′18.64″	10°36′36.36″	Gulf of Hammamet
Monastir	M_{11}	++	35°43′0.33″	10°49′6.47″	Gulf of Hammamet
Mahdia	M_{12}	+	35°30′48.29″	11° 3′0.91″	Gulf of Hammamet
Chaffar	M_{13}	++	34°31′30.57″	10°33′39.19″	Gulf of Gabes
Zarzis	M_{14}	++	33°35′27.02″	11° 5′0.28″	Gulf of Gabes
Islands					
Galite	I_{15}	+++	37°31′4.67″	8°55′28.12″	Coral Coast
Zembra	I_{16}	+++	37° 7′5.19″	10°48′31.41″	Gulf of Tunis
Kuriat	I_{17}	+++	35°46′6.35″	11° 0′42.53″	Gulf of Hammamet
Karkennah	I_{18}	+	34°42′3.77″	11° 8′18.48″	Gulf of Gabes
Djerba	I_{19}	+	33°46′21.33″	11° 2′14.76″	Gulf of Gabes

+++: population highly distributed; ++: site partially lost to development; +: degraded site.

(Sanaa and Ben Fadhel, 2010). In fact, the seedling period is from late September to early December which coincides with rough sea conditions. Such conditions might lead to the washing off of the newly released seeds that are typically very light and easily transported by sea waves (Keren and Evenari, 1974). Furthermore, hydrographic observations over Tunisian coast reported that during winter, the surface Modified Atlantic Water (MAW) flows from the western Mediterranean sea along the Algerian coast and bifurcates at the Sardinia channel level: one branch continues in the Tyrrhenian sea while the other branch, called as the Atlantic Tunisian Current (ATC), strongly flows along the Tunisian coast from the Tunis Gulf to the shallow Gulf of Gabes (Astraldi et al., 2002).

Computational modelling is progressively used to get insights into the functioning of complex biological systems (Sharov, 1991). In this context, Petri nets (PNs) have emerged as a useful tool among the different methods employed for the simulation and analysis of ecological and biological processes and to analyze different modes of evolution (Heiner et al., 2004). Colored Petri nets (CPNs) are an extension of the classical Petri nets where only one type of tokens is defined. As a graphical language, CPNs have shown their suitability to model a plethora of discrete event systems, and to represent sequential and parallel systems with clarity and without distraction due to anachronisms of the representation (Jensen et al., 2007).

In this paper, we propose a colored Petri net-based framework for modeling, simulating and analyzing hydrochory at isozymes loci for *P. maritimum* in Tunisia.

3. Materials and methods

3.1. Surveyed populations

We assessed five island and fourteen mainland populations of *P. maritimum* (Table 1). The habitat of *P. maritimum* in the close proximity of the sea is marked by direct exposure to breezes and salt water droplets carried by the wind, strong radiation and high air humidity. The underdeveloped state of the Cap Serrat region (M_1) and the uninhabited island populations of (I_{15}, I_{16} and I_{17}; Galite, Zembra and Kuriat, respectively) is such that the populations of *P. maritimum* are highly and well distributed. The inhabited Karkennah island and the well-known touristic island of Djerba (I_{18} and I_{19}, respectively) populations in addition to many mainland populations are characterized by their small size, growing in destroyed habitats and replaced with beach resorts and large commercial and industrial installations.

3.2. Atlantic Tunisian Current

The Modified Atlantic Water (MAW) is transported by the Algerian Current (AC) which, approaching the Straits of Sicily, splits in two branches (Fig. 1). The branch passing the region of the Straits of Sicily constitutes an energetic and meandering stream known as the Atlantic Ionian Stream (AIS), while the southern branch, called the Atlantic Tunisian Current (ATC), flows along the Tunisian shelf break (Robinson et al., 1996). Both branches are distinguished by a strong seasonal variability in terms of path and hydrological features. The ATC signature is weaker in summer, while it is well developed during the winter season (Manzella et al., 1990).

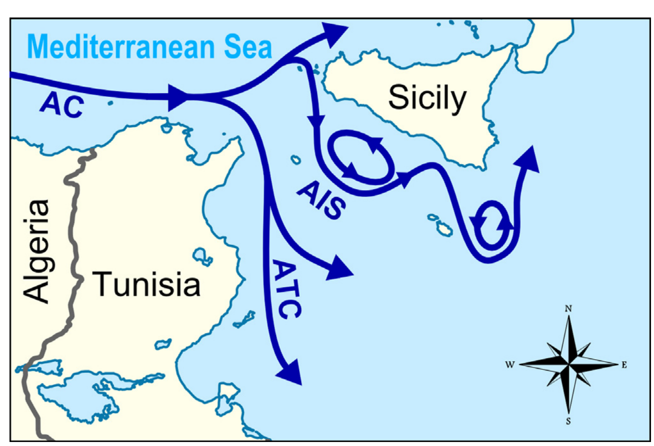

Fig. 1. Scheme of the AC, AIS and ATC paths according to Astraldi et al. (2002) and Lermusiaux and Robinson (2001).
AC: Algerian Current, AIS: Atlantic Ionian Stream, ATC: Atlantic Tunisian Current.