Recolonisation of USA: Slime Mould on 3D Terrains

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Abstract *P. polycephalum* imitates development of man-made transport networks of a country when configuration of nutrients represents major urban areas. We employ this feature of the slime mould to imitate Mexican migration to USA, which is the World's largest migration system. In laboratory experiments with 3D Nylon terrains of USA we analyse development of migratory routes from Mexico-USA border to ten urban areas with high concentration of Mexican migrants. From results of laboratory experiments we extract topologies of migratory routes, and highlight a role of elevations in shaping the human movement networks.

1 Introduction

When inoculated in an environment with scattered sources of nutrients the slime mould spans the nutrients with a network of protoplasmic tubes resembling human-made transport networks. Previously, we have conducted a large-scale experimental study to uncover analogies between biological and human-made transport networks and to project behavioural traits of biological networks onto development of vehicular transport networks, see collection of results in [1]. Using living slime mould we imitated major road networks in Africa, Australia, Belgium, Brazil, Canada, China, Germany, Iberia, Italy, Malaysia, Mexico, The Netherlands, UK, and USA. We found that for all regions studied [1], networks of protoplasmic tubes grown by plasmodium match, at least partly, the networks of man-made transport routes. The shape of a country and the exact spatial distribution of urban areas, represented by sources of nutrients, may play a key role in determining the exact structure of the plasmodium network.

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Being encouraged by results of imitating the transport networks with slime mould we decided to undertake an analog modelling of human migration. The analog modelling devices built of the slime mould imitates large-scale migration of humans via analogical propagation and foraging of living slime mould. We used Mexican migration to the USA as benchmark task the Physarum analog modeller.

A migration from Mexico to the USA is the largest people-flow system in the World [2]. Every third of Mexicans has been in USA at some stage of their life. The scale of migration is unprecedented. Over eighty percent of migrants are undocumented migrants (there are about 6.2 million of undocumented Mexican migrants amongst estimated 11 millions of all undocumented migrants in the US) [3]. There are several reasons for the migration. First reason is that culture of migration is deeply rooted in Mexican society [4]. Second is that even despite one and a half century passed after Treaty of Guadalupe Hidalgo there remains a high degree of 'internal' migration to North Mexican territories detached in the result of the Treaty. Three more reasons for the migration are highlighted in [5]: market consolidation, social capital formation (people related to USA migrated are more likely to migrate), and human capital formation (if some has previous experience of migration he will more likely to migrate again).

The migrations shapes economical and social structures of the USA and thus investigation of migratory patterns becomes an issue of great importance. A range of theoretical and analytical models are developed. The models provide a predictive analysis of migration [6, 7], statistical estimates [8, 9], evaluate integral patterns of migration [10, 11]. Such models make a priceless contribution towards deciding on what measures of controlling migration should be taken, e.g. intensity of a border control might affect migration levels [12] and duration of circular migrants staying in the USA [13]. Most models of Mexican migrations deal rather with integral numbers of migrants, sometimes attributed to particulars states, however neither of models published considered spatial geographic routes of migration.

We apply our experience on bio-physical imitation routes [1] to imitate Mexican migration [14].We go a step further experimentally, comparing to our previous works,—we take into account configuration of elevations and grow slime mould on a 3D terrain of the USA. We discuss functioning of the Physarum analog modeller, which consists of a living slime mould, 3D plastic model of USA and source of nutrients. Usage of 3D terrain in laboratory experiment bring the analogous modelling closer to reality. The slime mould reacts to 3D topography because *P. polycephalum* is gravisensitive and positively geotropic [15, 16]. Plasmodium shows morphological geopolarity [17]: the ectoplasmic wall of a slime mould tube to earth. We expected that being placed on a 3D terrain with a source of nutrients slime mould propagates towards the source of nutrients and navigates around elevations due to positive geotropism and relatively lower humidity of the elevations. The results were originally published in [14], here we present an updated overview.

2 Methods

Terrain of USA used in our experiments is 20 cm wide, 10.8 cm long and 5 cm high. 3D terrain of USA was ordered in http://www.printablegeography.com/. The terrain was produced as follows. The elevation data are downloaded from DIVA-GIS (http://www.diva-gis.org/gdata), original source is CGIAR (http://srtm.csi.cgiar.org/). The data are projected with Mercator, and the terrain is printed using Selective Laser Sintered PA 2200 with Nylon 12. To highlight a role of 3D terrain in defining migratory patterns we conducted experiments on a flat agar plate shaped as USA. Solution of 2 % Aldrich Select Agar was poured in 12 cm square Petri dishes, allowed to cool and then shaped of USA were cut out. We have conducted 14 experiments on flat agar plates and 12 experiments on 3D terrain. It takes slime 3–5 days to colonise all source of nutrients on flat agar, and 5–10 days to colonise the nutrients on 3D terrain. We have placed oat flakes, to act as sources of nutrients and attractants, in the sites of the 3D terrain and flat agar plate corresponding to the following areas (Fig. 1):

1. New York area: New York, Philadelphia, Baltimore, Washington;
2. Jacksonville area: Jacksonville, FL;
3. Chicago area: Chicago, Detroit, Indianapolis, Columbus, Columbus, Louisville;
4. Dallas area: Dallas, Fort Worth;
5. Houston area: Houston, San Antonio, Austin;
6. Denver area: Denver,
7. Albuquerque area: Albuquerque, Santa Fe;
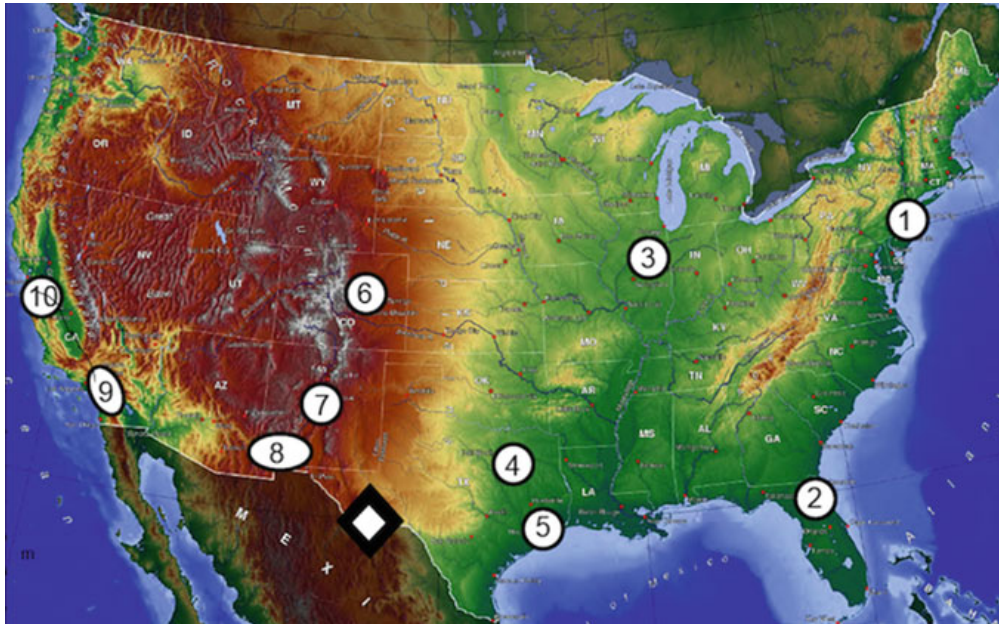
Fig. 1 Configuration of attractor-sites. Site of plasmodium inoculation is shown by rhomb
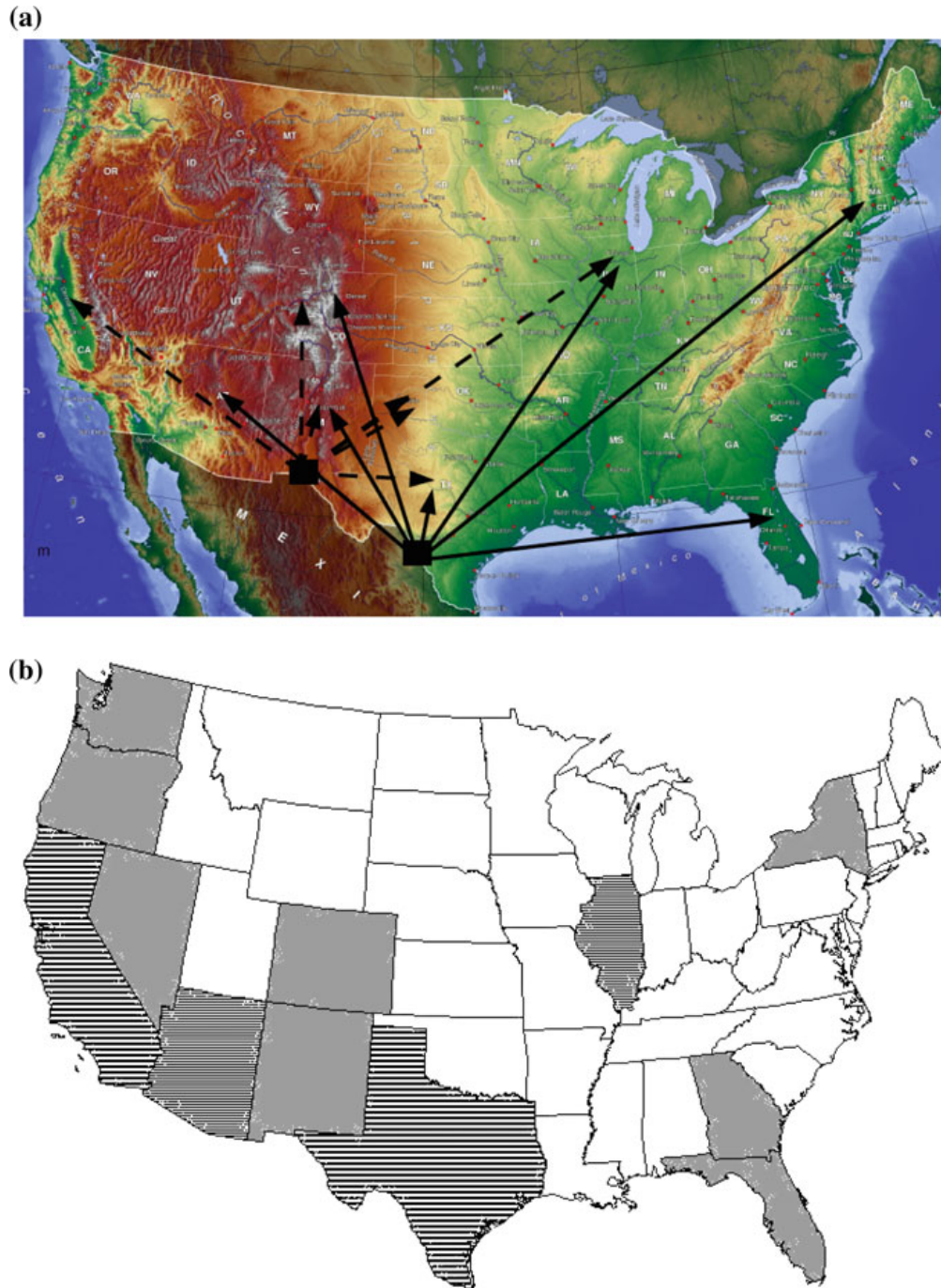
Fig. 2 Migration basics. **a** Scheme of major migration routes from Ciudad Juárez, and Nuevo Laredo, generalised from maps [18]. **b** Scheme of state proportion of Mexican born population in the USA, *stripes* 21–37 %, *fine stripes* 3–7 %, *grey* 1–3 %, modified from [19]

  8. Phoenix area: Phoenix, El Passo, Tucson;
  9. Los Angeles area: Los Angeles, San Diego;
 10. San Jose area: San Jose, San Francisco.

The attractor areas selected correspond to typical destinations of Mexican-born migrants (Fig. 1) and also reflect current distribution of Mexican population in USA (Fig. 2a). In each experiment we inoculated plasmodium between Ciudad Juárez and Nuevo Laredo. We decided to use a single inoculation site to avoid interference or even competition between plasmodium growing from several sites of inoculation. The position of inoculation site chosen in experiments allows to cover most possible routes of migration, as illustrated in Fig. 2b.

Containers with experimental setups were kept in closed yet naturally ventilated containers with water added to keep high humidity. We did not wetted the 3D terrain or covered it with agar gel: the plasmodium grown on a bare Nylon surface. The terrains were kept in darkness, at temperature 22–27 °C, except for observation and image recording. Configurations of plasmodium networks were photographed with FujiFilm FinePix 6000 camera and scanned with an Epson Perfection 4490 scanner.

3   Results

When colonising a flat substrate plasmodium is guided only by a configuration of attractant fields, generated by sources of nutrients, and possibly humidity distribution in the USA-shaped agar plates (Fig. 3). A typical scenario of colonisation is following. Plasmodium propagates from the inoculation site towards Phoenix area and either Dallas area or Houston area. After colonising Phoenix area plasmodium grows towards Albuquerque area and Los Angeles area. San Jose area is usually colonised by slime mould which propagated from Denver area or Los Angeles area, and in few trials from Albuquerque area (Fig. 3a–d). This matches well historical migration of Mexicans to Dallas or Houston areas, which are inhabited now by millions of Mexican migrants. Phoenix is a strategic point of migration to Los Angeles and Albuquerque areas.

When propagating east plasmodium grows from Dallas area or Houston area to Jacksonville area and then from Jacksonville area to New York area. Also, very characteristically, the plasmodium makes a branching while propagating from Dallas area to Jacksonville area. Typically a branching site is located south of Louisiana. East branch continues towards Jacksonville area while north branch growth towards Chicago area. In few experiments we observed grows from the branching site to New York area (Fig. 3). A protoplasmic link between New York area and Chicago area is established either by plasmodium growing from New York area to Chicago area or from Chicago area to New York area. A transport route connecting Chicago area and Denver area is usually developed by slime at the final stages of colonisation. Frequencies of routes observed in experimental laboratory trials are visualised in Fig. 3. Chicago city is one of the most important cities for Mexican migrants and
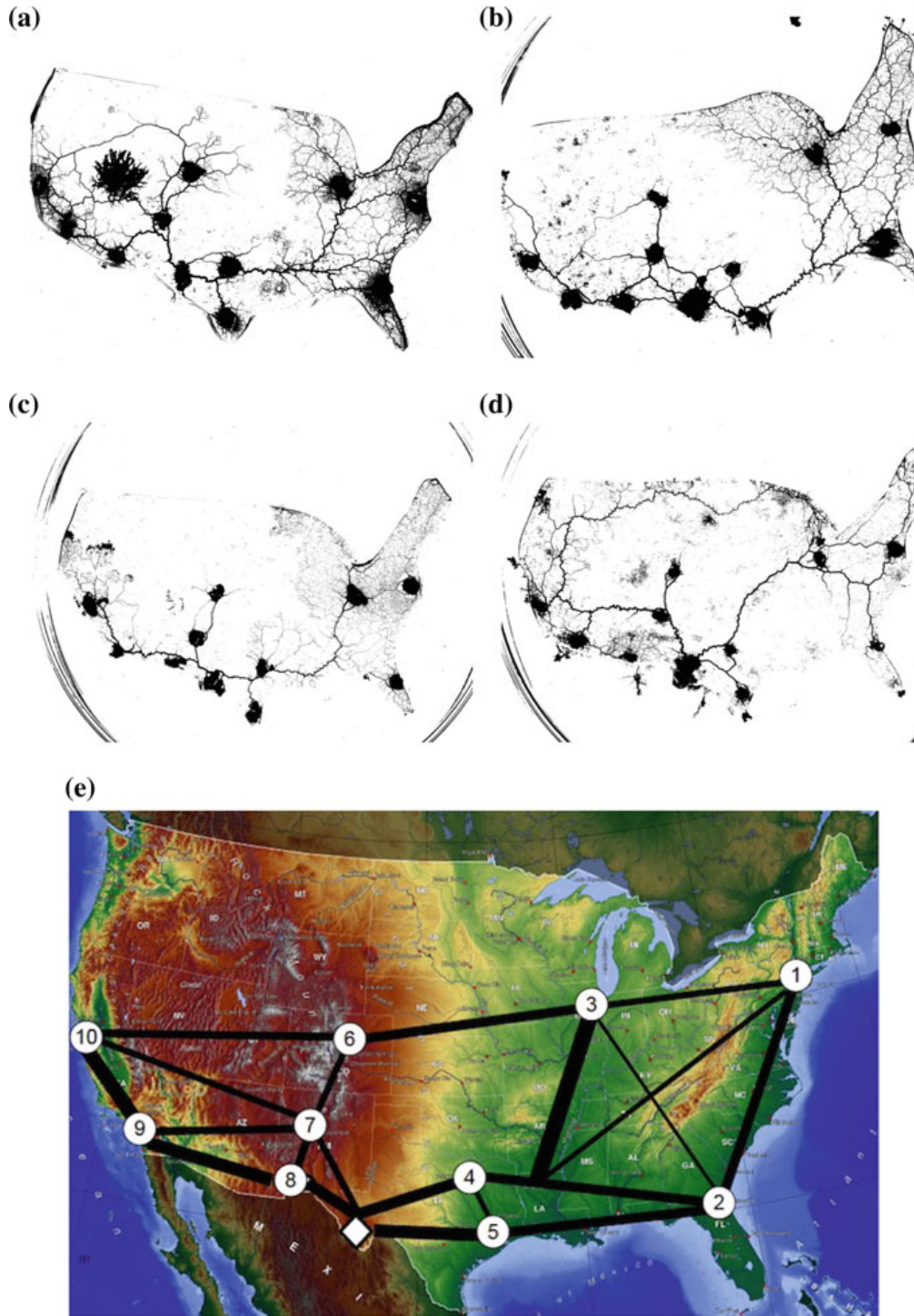
Fig. 3 a–d Snapshots of protoplasmic tubes spanning nutrients in **U**. **e** Weighted graph representing occurrences of slime mould links between areas of **U**. Thickness of an edge is proportional to a number of trials where the edge is represented by a protoplasmic tube. Site of plasmodium inoculation is shown by rhomb

bears substantial economically influence on Mexican community in USA. Migratory links between Chicago area and New York area serves social and economical needs of Mexican migrants for years; an anecdotal demonstration of the Chicago area's importance is an abundance of Spanish languages signs in transport and TV.

Being placed on a 3D terrain with a source of nutrients slime mould would propagate towards the source of nutrients and navigate around elevations due to positive geotropism and relatively lower humidity of the elevations (Fig. 4). The slime mould
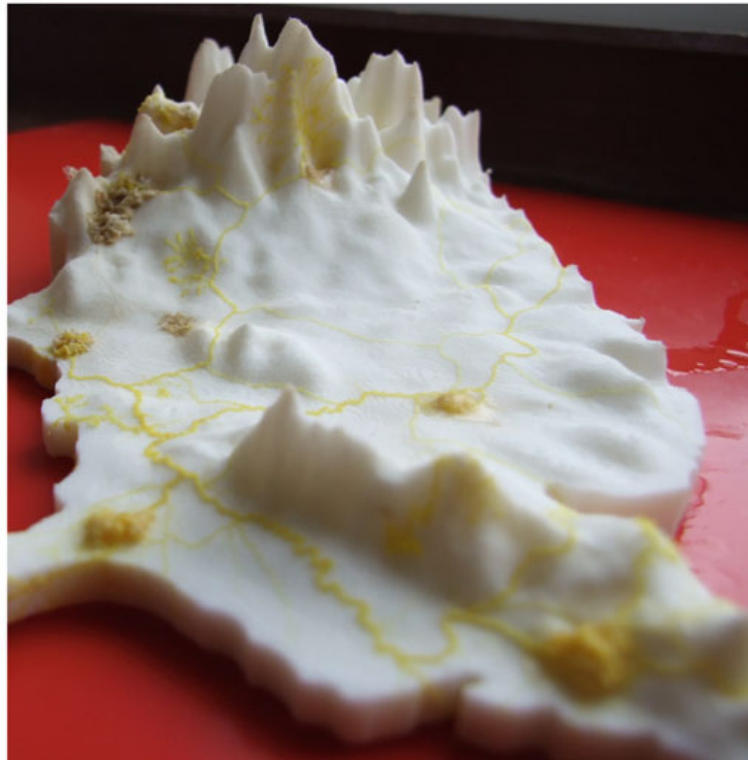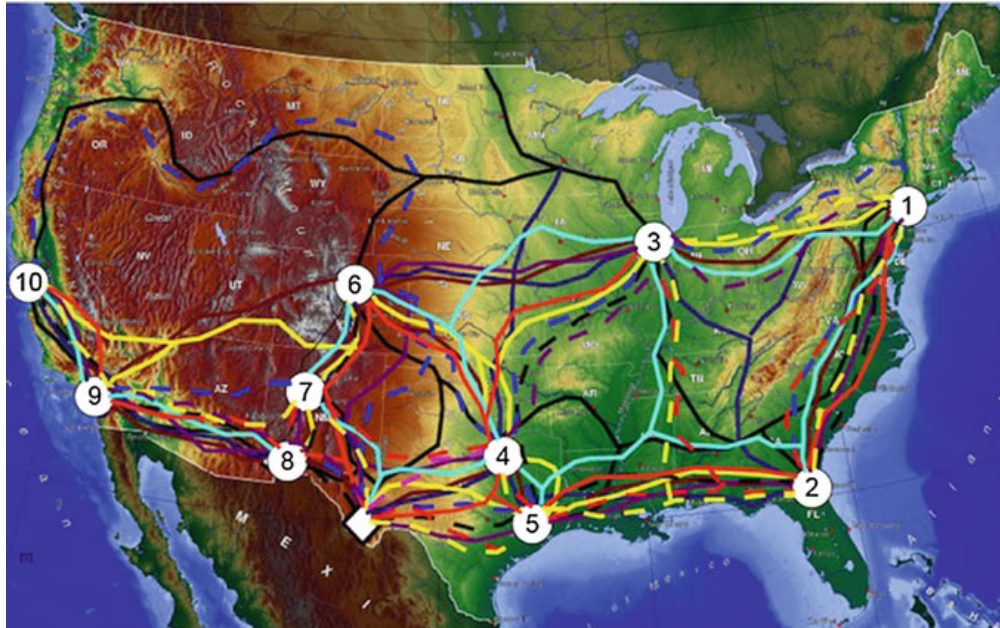

**Fig. 4** Photographs of 3D terrain of USA colonised by slime mould

Fig. 5 Protoplasmic links developed in experiments with 3D terrain of USA. Links developed in each experiment are shown by a unique combination of colour and type of *line*. Site of plasmodium inoculation is shown by rhomb

usually grows around mountains or cross mountains in the site of lowest elevation. Trajectories of protoplasmic tubes recorded in laboratory experiments are shown in Fig. 5. We can select three main stages of USA colonisation recorded in experiments with 3D terrain. Each stage takes 1–3 days of plasmodium growth. At the first stage, plasmodium develops protoplasmic links from inoculation site to Dallas area, Houston area, Albuquerque area, and Phoenix area. At the second stage, slime mould propagates from Dallas area to Houston area, or sometimes from Houston area to Dallas area; from Houston area to Jacksonville area and Chicago area; from Dallas area to Chicago area and Denver area; from Albuquerque area to Denver area; and, from Phoenix area to Los Angeles area. At the third stage, the plasmodium grows from Jacksonville area to New York area; from Chicago area to Denver area and New York area; from Denver area to Los Angeles area; and, from Los Angeles area to San Jose area. When all source of nutrients colonised the plasmodium may also develop a long-distant link between Chicago area and San Jose area (Fig. 5).

Strong components, observed in over 40 % of laboratory experiments with flat agar and 3D terrain are shown in Fig. 6a, b. In experiments with flat agar there are strong pathways from the entry point (inoculation site) to Phoenix area, Houston area and Dallas area (Fig. 6a). From Phoenix area the migratory route develops to Los Angeles area and then further north to San Jose area. Migration from Dallas area and Houston area proceed to Jacksonville area, and from Jacksonville area to New York area. Also, there are well-established migratory pathways from Dallas area to
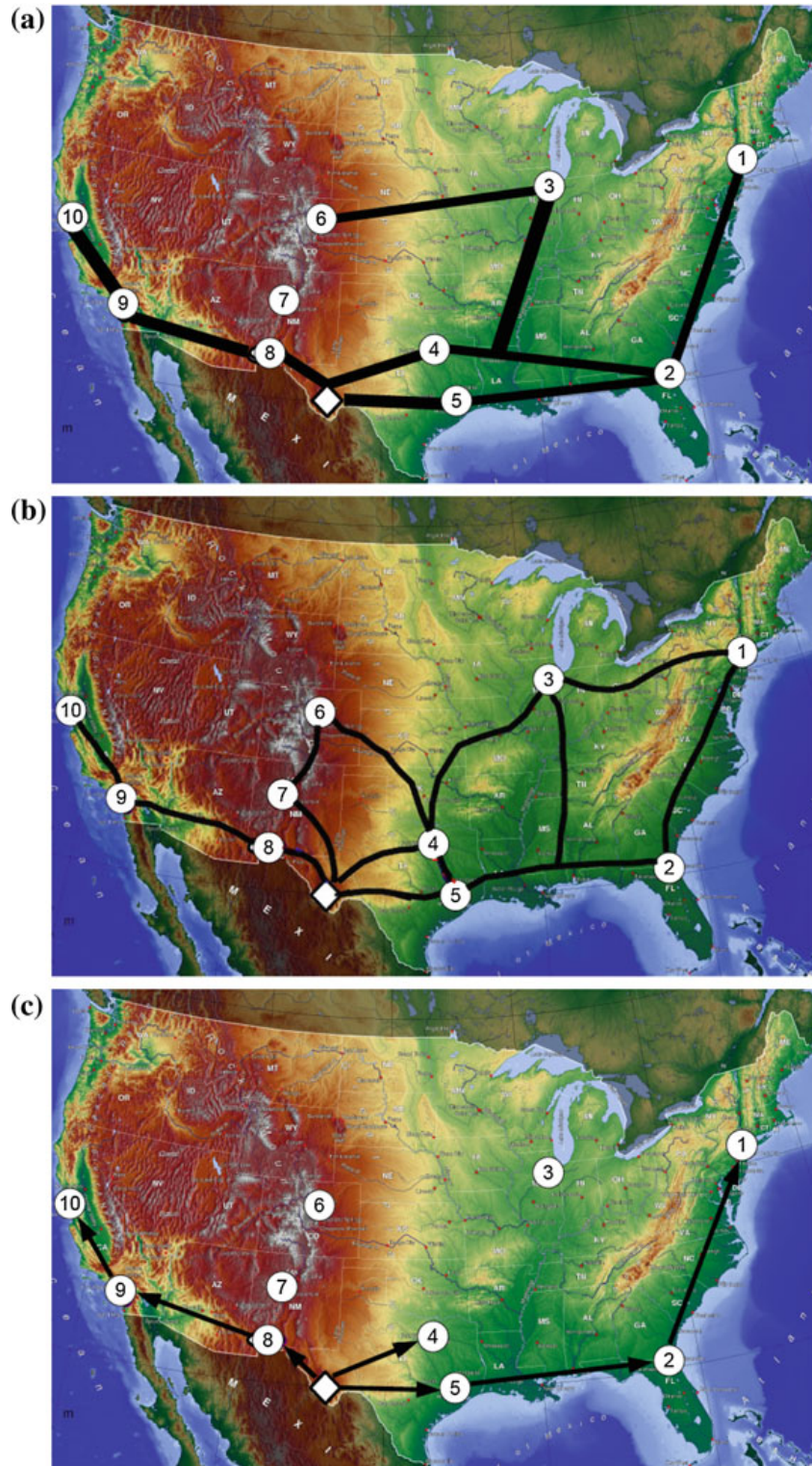
Fig. 6 Strong components of migration graphs. **a** at least in 6 out of 14 experiments (43 %) on flat agar. **b** 5 out of 12 experiments (42 %) on 3D terrain. **c** a skeleton of migration: intersection of graphs (**a**) and (**b**), i.e. only edges represented in over 40 % of experiments on flat agar and 3D terrain are shown

Chicago area (via branching point in south Louisiana), and from Chicago area to Denver area (Fig. 6a).

Migratory routes developed by *P. polycephalum* on a 3D terrain include most of the strong routes observed in experiments with flat substrate. Topology of protoplasmic routes reflect configurations of elevations in the routes' vicinity (Fig. 6b). Thus we witness remarkable avoidance of the Appalachian Mountains; Sierra Nevada, Cascade Range, Rocky Mountains and Ozark Plateau (Figs. 5 and 6b). Also, additional strong pathways observed in experiments with 3D terrain include links connecting New York area and Chicago area, Dallas area and Denver area, Denver area and Albuquerque area.

A skeleton of migration links, with proposed directions of inward migration, is shown in Fig. 6c. The skeleton includes only edges observed in strong components of migratory graphs observed in both flat agar and 3D terrains experiments. The skeleton of migration consists of three components: links connecting the entry site to Dallas area, Houston area and Phoenix area; west coast migration from Phoenix area to Los Angeles area to San Jose area; east cost migration from Houston area to Jacksonville area and further to New York area (Fig. 6c).

4 Discussions

Slime mould *P. polycephalum* is now well recognised living computing device which performs remarkably well in experimental laboratory conditions. We presented an experimental laboratory prototype for analog modelling of human migration at a large scale. The prototype developed is a bionic devices, consisting of a living slime and a 3D plastic model of the USA. Experiments detailed in the paper can be classified as bio-computing, future and emergent computing paradigms, bionics and analog computing and modelling. A protoplasmic network of slime mould Physarum transport nutrients and metabolites. The network plays a role of a primitive distributed sensorial and nervous system, responsible for a choice of appropriate habitat and avoidance of harsh environmental conditions. Contents of the protoplasmic network is always in the flux. We speculate that the protoplasmic network is a good biological model of a migration network emerged in a transnational communities of people living between Mexico and USA [20].

In laboratory experiment with the slime mould we imitated Mexican migration on a flat agar and 3D Nylon terrain. Migratory links developed on a flat substrate may represent air transportation while routes on 3D terrain signify ground transportation. We found that the plasmodium imitates human movements amongst elevations because *P. polycephalum* is gravisensitive and positively geotropic [15, 16] and geopolar [17].

The experimental setup adopted well represents principle mechanics of migration [5]:

- To imitate a social capital formation we place oat flakes in areas with high population of Mexican migrants.
- Human capital formation is imitated by *P. polycephalum* via self-reinforcing of protoplasmic tubes: ticker tubes become thicker and thinner become weaker.
- Market consolidation trends are 'hard-wired' in the slime mould behaviour via its foraging activity.

Strong component of migration routes extracted from laboratory experiments, represent all types of migration [21]:

- 'internal' migration to North Mexican ex-territories (routes Phoenix area to Los Angeles area and San Jose area);
- diaspora migrations, e.g. links between Denver area and Albuquerque area, New York area and Chicago area, Dallas area and Houston area, New York area and Jacksonville area, Chicago area and Dallas area, Jacksonville area and Houston area;
- returned migration, e.g. links connecting the migrants' entry point to Phoenix area, Albuquerque area, Dallas area and Houston area.

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