

Evolution in adaptive landscapes: examples of science and technology development

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DISCUSSION PAPER



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Evolution in Adaptive Landscapes—
Examples of Science and Technology
Development

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ABSTRACT

Evolution in adaptive landscapes—examples of science and technology development

In science and technology studies it is very common to describe structure formation and structure development by using spatial representations. Maps of such knowledge landscapes allow the dynamic character of the research processes to be visualized. In this paper, we discuss how concepts, methods and mathematical models that allow the dynamics and the evolution of complex systems to be described can be applied to this area. A special approach is considered, which we call “geometrically oriented evolution theory” (G_O_E_THE). First steps towards implementing this new method in the context of the development of national science systems are discussed.

ABSTRAKT

Evolution in adaptiven Landschaften - Beispiele aus der Entwicklung von Wissenschaft und Technologie

In Wissenschafts- und Technologieuntersuchungen wird für die Beschreibung von Strukturbildungs- und Strukturveränderungsprozessen häufig auf räumlich-geografische Metapher zurückgegriffen. Mit Hilfe von veränderlichen Wissenslandschaften lässt sich die Dynamik des wissenschaftlichen Suchprozesses veranschaulichen. In der vorliegenden Arbeit, wird die Anwendung von Konzepten, Methoden und mathematische Modelle aus der Komplexitätsforschung für die Beschreibung von Suchprozessen in Wissenslandschaften diskutiert. Ausgangspunkt bilden dabei sog. geometrisch orientierte Evolutionstheorien (G_O_E_THE). Erste empirische Anwendungen im Bereich der Entwicklung nationaler Wissenschaftssysteme werden präsentiert.

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“There is a growing mountain of research. But there is increased evidence that we are being bogged down today as specialization extends”
Bush, 1945¹

1. Introduction²

The information society is confronted increasingly with problems of information retrieval and knowledge management. Because knowledge is not generated in one piece from a single source, but spawned over many, highly differentiated social layers in a fragmented way, combining knowledge resources and competence becomes a prerequisite for adequate problem solving strategies in many complex decision-making processes. Considering science and technology, we find massive accumulations of data—scientific publications, patents, and technical manuals. To visualize this information in virtual spaces and develop corresponding navigational tools has become a main part of information science. In recent decades, several mapping techniques have been developed that generate two- or three-dimensional maps of “knowledge landscapes” from such data bases. Still more recently, animated 3D presentations further suggest to us the existence of unknown knowledge landscapes waiting to be explored. The aim of this type of data visualization consists in the strategic use of information as well as in the understanding of the underlying mechanisms of knowledge production. However, large accumulations of data are often confronted with a lack of theoretical understanding of the process of knowledge production.

In this paper, a method is developed which uses concepts and models drawn from physical theories of complex systems to construct and interpret knowledge landscapes. A bridge will be built between these concepts and the analysis of empirical data in the field of science and technology. The term “landscape” functions as linking element in knowledge transfer.

¹ Bush, V. (1945), *As We May Think*. *Atlantic Monthly* (Boston, Mass.). 176 (1), pp. 101-108.

² Paper presented at the “Workshop on Scientometrics and Informetrics/Collaboration in Science”, Gesellschaft für Wissenschaftsforschung Berlin e. V., Berlin, August 16-19, 1998.

The landscape concept is one of the key concepts in the analysis of the dynamics of complex non-linear systems. The emergence of self-organized structures can be understood as the result of a search for optimal solutions to a specific problem, and the corresponding models (conceptual and mathematical) describe characteristics of search processes in unknown landscapes.

The science system, like many other complex systems in nature, faces the task of providing, in a reasonable length of time, using resources economically and efficiently, good solutions to (or resolutions of) certain problems. This common task provides us with the motivation for the present analysis. The intention is to look for possible relations between spatial knowledge representations in science and geometrically oriented models of search and evolution in complex systems.

In this paper, we first construct a bridge-head in each field (SciTech, physics). As the result of a related knowledge transfer process, a new method is applied to a particular meta-system, the system of national science systems. Using this strategy, we start with a “gallery” of maps and landscapes produced in the field of science and technology (section 2). In section 3, the idea of modeling evolution in adaptive landscapes is introduced and the explanatory potential of this concept is discussed. In section 4, this modeling framework is used as guideline to design alternative ways of collecting, presenting and interpreting empirical data; the development of research profiles of national science systems in the 90’s serves as an example. In this way, we attempt to construct the missing link between knowledge representations and modeling tools.

2. Visualization of Structure Formation in Science and Technology — Examples of Maps and Landscapes

In science and technology studies it is very common to describe structure formation and structure development by using spatial representations. If scientific progress and technological change are understood as the exploration of unknown knowledge landscapes comparable to the real exploration of an unknown, geographic territory, spaces and landscapes are used metaphorically. Examples are given in [figure 1](#).³ (All figures appear at the end of this text.)

³ Nelson, R. and S. G. Winter (1977), In Search of a Useful Theory of Innovation. *Research Policy*, 6

Knowledge or problem spaces assume more concrete form when constructed from empirical data. Scientific publications, patents or technological parameters of product models can be used to set up databases. In bibliometric studies different methods have been applied to visualize scientific development. Maps⁴ and landscapes⁵ based on co-citation clustering techniques may serve as examples (figure 2). They permit the formation of scientific fields and the movement of research areas in a problem space to be made visible. Another widespread mapping technique in bibliometrics is based on co-word analysis⁶ (figure 3).

In evaluating national science systems, the position of a country or a research unit can be visualized in spaces whose axes are related to different bibliometric indicators⁷. Figure 4 shows the position of different countries in a two-dimensional space constructed from their expected and observed citation rates. The productivity of the different countries defines a landscape over this space (figure 4).

Concerning technological development, mapping techniques are based on patent literature. For instance, by means of co-word analysis of patents, maps of inventions can be produced.⁸ Such maps show leading technological fields and the linkage between different technological areas.

(Amsterdam), pp. 36-76; Dosi, G. (1982), Technological Paradigms and Technological Trajectories. *Research Policy*, 11 (Amsterdam). pp. 147-162; Sahal, D. (1985), Foundation of Technometrics. *Technological Forecasting and Social Change*, 27 (New York), pp. 1-37; Saviotti, P. P. and J. S. Metcalfe (1984), A Theoretical Approach to the Construction of Technological Output Indicators. *Research Policy*, 13 (Amsterdam), pp. 141-151; Böhme, G., W. van den Daele and W. Krohn (1973), Die Finalisierung der Wissenschaft. *Zeitschrift für Soziologie*, 2 (2) (Stuttgart), pp. 128-144. Noyons, E. C. M. and A. F. J. Van Raan (1998), Monitoring Scientific Developments from a Dynamic Perspective. Self-Organized Structuring to Map Neural Network Research. *Journal of the American Society for Information Science* (New York). 49 (1), pp. 68-81.

⁴ Small, H. and B. C. Griffith, The Structure of Scientific Literature I: Identifying and Graphing Specialties. *Science Studies* (London). 4(1974), pp. 17-40; Small, H., Update on Science Mapping: Creating Large Document Spaces. *Scientometrics* (Oxford). 38(1997)2, pp. 275-293.

⁵ See <http://www.cs.sandia.gov/projects/VxInsight/Vxfull.html>, <http://www.sandia.gov/LabNews/LN10-11-96/land.htm>, and <http://www.sandia.gov/media/mapping.htm>.

⁶ Callon, M., J.-P. Courtial and H. Penan (1993), *La Scientometrie*. Paris: Presses Universitaires de France; Noyons, E. C. M. and A. F. J. Van Raan (1998), Advanced Mapping of Science and Technology. *Scientometrics*, 41 (1-2) (Oxford), pp. 61-67.

⁷ Braun, T. and A. Schubert (1991), The Landscape of National Performance in the Sciences, 1981-1985. *Scientometrics*, 20 (Oxford). pp. 9-17.

⁸ Van Raan, A. F. J. and R. J. W. Tijssen (1990), Numerical Methods for Information on Aspects of Science, Scientometric Analysis and Mapping. In Ch. Oppenheim, J.-M. Griffiths and Ch. L. Citroen (eds.), *Perspectives in Information Management, Vol. 2*. London: Bowker-Saur/Butterworth-Heinemann, pp. 203-228; Grupp, H. (ed.) (1992), *Dynamics of Science-Based Innovation*. Berlin: Springer.

Another way to visualize technological development is based on the concept of a characteristics space of technological output indicators proposed by Metcalfe and Saviotti.⁹ This permits products or product models to be located in a technological space according to their technical and/or service characteristics. The concept was empirically tested for aircraft development (figure 5) and for motor vehicle development.

Such maps not only mirror the state of the art in a certain area of science and technology, they also allow the dynamic character of the research processes to be visualized.¹⁰ From an evolutionary point of view, the temporal sequence of such maps and landscapes is of particular interest. We can consider the different maps shown above as the result of a process of searching and competing “populations” in different science and technology spaces. The searching populations are groups of scientists and engineers. They are represented by their “products”, i.e., scientific papers, patents, and product models. The location of these research “products” in science or technology spaces marks the areas of already explored knowledge. Further, the frequency or intensity with which certain areas are occupied can be visualized by means of a landscape over the space of knowledge characteristics.

Knowledge maps and landscapes serve different purposes. On the one hand, they help to integrate information often hidden in different information channels. This development is supported by the rapidly growing capability of graphical representations combining computerized graphical techniques and computerized handling of large databases. The purpose of such approaches is to navigate inside growing information masses, to retrieve information effectively, and use it strategically. Thus, the construction of science or knowledge landscapes over problem spaces helps recognize innovative areas with rapid growth rates, and identify paths and areas for future research investment. On the other hand, such maps can be used as an empirical or experimental base for understanding scientific and technological development mechanisms. This is where an evolutionary perspective might be helpful.

In the following, we discuss how concepts, methods and mathematical models that allow the **dynamics** and the **evolution** of complex systems to be described can be

⁹ Saviotti, P. P. and J. S. Metcalfe, A Theoretical Approach to the Construction of Technological Output Indicators. *Research Policy* (Amsterdam). 13(1984), pp. 141-151.

¹⁰ See, e.g., Saviotti, P. P. (1985), An Approach to the Measurement of Technology Based on the Hedonic Price Method and Related Methods. *Technological Forecasting and Social Change*, 27 (New York). pp. 309-334.

applied to the field of science and technology development. A special approach is considered, which we call “geometrically oriented evolution theory” (G_O_E_THE). First steps towards implementing this new method in the context of science and technology development are discussed.¹¹

3. Space and Landscapes in the Description of Complex Non-Linear Systems

In the mathematical description of the dynamics of complex non-linear systems¹², spatial representation of, for example, the state space or the space of control parameters plays a central role in visualizing divergent temporal system behavior. In the state space the state of a system, expressed by certain values of the state variables at a certain time, is represented by a point. Temporal changes in the state of the system result in a movement of the location of this point in the state space, and the sequence of these locations defines the trajectory. Concerning the long-term behavior of the system, different types of stationary states, i.e., attractors like fixed points and limit cycles or chaos can be distinguished. Correspondingly, trajectories have different shapes. If the inner composition of the system (types and strength of interactions) or its embeddedness in the environment changes, a stabilization or de-stabilization of stationary points can be observed. Possible paths or trajectories in the evolution of a system will then also change. Sometimes, such changes can be visualized as bifurcation diagrams in the space of control parameters.

In physics, the dynamics is often governed by extremum principles. Famous examples are the maximization of entropy in isolated thermodynamic systems or the minimization of energy in mechanical and quantum mechanical systems. The dynamics of the system can then be described by potential functions, the geometry or shape of these functions determining the behavior of trajectories and the location of attractors. So-called gradient systems, described by catastrophe theory, are a well-known example.¹³ In this case, the stationary points correspond to the minima of a potential

¹¹ See also: Scharnhorst, A. (1998), Citations—Networks, Science Landscapes and Evolutionary Strategies. *Scientometrics*, 43 (1) (Oxford), pp. 95-106.

¹² Cf. Ebeling, W. and R. Feistel (1994), *Chaos und Kosmos*. Heidelberg: Spektrum. For the mathematical techniques cf. Nicolis, G. (1995), *Introduction to Nonlinear Science*. Cambridge: Cambridge University Press.

¹³ Thom, R. (1975), *Structural Stability and Morphogenesis*. Reading, PA: Benjamin; Poston, T. and I. Stewart (1978), *Catastrophe Theory and Its Applications*. London: Pitman; Arnold, V. I. (1984), *Catastrophe Theory*. Berlin/Heidelberg: Springer.

function. Further, the temporal development of state variables follows the gradients of this potential function. In general, such functions can be visualized as a landscape over the state space and the current state of the system as a ball moving along the valleys of this landscape. Then, the system dynamics can be interpreted as an optimization process. As has been discussed elsewhere¹⁴, for many complex systems, i.e., for systems in which self-organization and evolution occur, it is not possible to determine a (globally valid) criterion governing the evolution of the system. This means that the target function for the optimization process or the governing function for the system dynamics is not known and can not be written down in an analytical way. Nevertheless, the concept of a special function or functional that governs system dynamics remains useful. In particular, for systems in which competition and selection occur, a comparison of different states according to a hypothetical valuation function, even if only locally, is necessary. In recent decades, links between complex (potential) landscapes in disordered materials, fitness landscapes of biological macromolecules, and target functions for complex optimization problems have successfully been established and discussed to determine certain characteristics of such landscapes and the system dynamics involved. Multimodality, chaotic shape, stochasticity, but also the existence of correlations of the fitness or value function seem to be common characteristics of different complex systems. Therefore, transferring problem solving techniques between dynamical descriptions in physics, biology and cybernetics is useful.

It also seems possible to establish a link with learning processes in social systems. The different empirically constructed knowledge landscapes described above can be seen as a mirror of the state of a social system in the process of knowledge production. As in other complex systems, the searching and learning process in a society faces the task of providing good solutions for (or resolutions of) problems, within a reasonable period, and making economic and efficient use of resources. In the following we consider how the observable dynamics in a landscape picture of knowledge production can be interpreted and analyzed within an evolutionary framework.

¹⁴ Ebeling, W., A. Engel and R. Feistel (1990), *Physik der Evolutionsprozesse*. Berlin: Akademie-Verlag.

3.1. *Evolution in an Adaptive Landscape or Geometrically Oriented Evolution Theory (G_O_E_THE)*

The method referred to in the present paper was mainly developed in physics.¹⁵ The approach uses the analogy between certain evolutionary models (Fisher-Eigen type or Lotka-Volterra type) and problems in quantum mechanics. Only the key elements of this modeling framework are presented here (figure 6).

We start with a system whose elements are identified by a number of characteristics, similar to phenotypic characteristics in biological evolution. These characteristics can be expressed in terms of quantitative variables q_i which change continuously. Then, the set of variables $\{q_1, q_2, \dots, q_i, \dots\}$ defines a *characteristics space* Q . In general, this will be a high-dimensional space. Each element of the system has a certain location in this space at a certain point in time t . If elements change their characteristics, the individual points change their location. All points together represent the state of the system at the time t .

Now, we introduce an occupation function over this space $x(\vec{q}, t)$. Defined as a density function, $x(\vec{q}, t)d\vec{q}$ gives the number of elements with characteristics in a certain range. This seems to be reasonable if the system consists of many elements and some combinations of characteristics are more frequent than others (clustering). Then, the *occupation function* (or population density function) forms a *first landscape* in the characteristics space. Hills in this landscape that are relatively isolated from each other stand for groups of elements with similar characteristics. The shape of a hill expresses the inner-group variance of characteristics. The height of a hill stands for the frequency or strength at which a certain type of characteristics appears. The existence of different hills *at the same time* corresponds to a coexistence of different groups. If the system evolves, the shape of the landscape $x(\vec{q}, t)$ will change. Other places become occupied, the variance inside groups can change and the locations of the centers of the groups will move. Finally, a competition between groups can lead to the decrease and extinction of certain hills and to the growth of hills at other places.

¹⁵ Feistel, R. and W. Ebeling (1982), Models of Darwin Processes and Evolution Principles. *BioSystems*, 15 (Amsterdam), p. 291; Ebeling, W., A. Engel, B. Esser and R. Feistel (1984), Diffusion and Reaction in Random Media and Models of Evolution Processes. *Journal of Statistical Physics*, 37 (New York), pp. 369; Feistel, R. and W. Ebeling, Evolution of Complex Systems. Dordrecht: Kluwer 1989.

Evolution is described by a process of competition between groups or populations. Two main processes are present: *mutation* and *selection*. In the widest sense, the appearance of elements with changed characteristics is understood as mutation. These can be characteristics not yet represented in the system. In this case, occupation extends to regions in the characteristics space that have so far been empty. In the other case, the characteristics are already present in the system, then simply the occupation at the point under consideration will increase. The mutation process can be thought of visually as a kind of diffusion process spreading the occupation landscape over the space.

The selection process implies a comparison between different locations in the characteristics space according to certain criteria. Growth or decline of the occupation at different locations will depend on this comparison. Such a *valuation* can theoretically be visualized as a *second landscape* over the state space. Mathematically, it is described by a function or a functional $w(\vec{q}; \{x(\vec{q}, t)\})$. For most complex systems this valuation or fitness landscape will have a rich structure, for instance, exhibiting multimodality and a chaotic shape. In general, the valuation function will be unknown, or known only in a local region around the searching individuals and groups. One approach to model the uncertainty about this landscape consists in employing a stochastic function with certain statistical properties. For instance, the existence of correlations of this stochastic function is necessary to ensure that the evolution can proceed. This indicates a certain smoothness in the geometry of the valuation function.¹⁶

From the elementary processes of selection and mutation an evolutionary process can be constructed. It describes the change in the occupation landscape as the result of an interplay between the two landscapes (the occupation landscape and the valuation landscape). We call this approach *geometrically oriented evolution theory (or G_O_E_THE)*.¹⁷

In a first step, the valuation landscape can be assumed to be stationary in time. Then, the system dynamics generates a search process of elements and/or groups of elements in this valuation landscape. Relatively simple evolutionary models (like the

¹⁶ Conrad, M., W. Ebeling and M.V. Volkenstein (1992), Evolutionary Thinking and the Structure of Fitness Landscapes *BioSystems*, 27 (Amsterdam), pp. 125-128.

¹⁷ Ebeling, W., A. Scharnhorst, M.A. Jiménez-Montaño and Karmeshu (1999), Evolutions- und Innovationsdynamik als Suchprozeß in komplexen adaptiven Landschaften. In K. Mainzer (ed.), *Komplexe Systeme und Nichtlineare Dynamik in Natur und Gesellschaft*. Berlin: Springer 1999.

Fisher-Eigen approach) lead to a hill-climbing process of the occupation in the valuation landscape. In this case, the valuation landscape is given by the difference of a local valuation and an ensemble average:

$$w(\vec{q}) = E(\vec{q}) - \langle E \rangle,$$

$$\langle E \rangle(t) = \frac{\int E(\vec{q})x(\vec{q}, t)d\vec{q}}{\int x(\vec{q}, t)d\vec{q}}$$

The local valuation $E(\vec{q})$ remains unchanged in time but the ensemble or social average of local valuations $\langle E \rangle$ changes with the changing occupation. The landscape $w(\vec{q})$ is merely shifted, not changing its shape in time. According to the above formula occupation will increase at places where the local valuation exceeds the social average and decrease at others (see also figure 6). At the same time, the concentration process of the population at higher valued locations leads to an increase in the social average. Due to the resulting hill-climbing process, occupation is more or less concentrated in the long run around the maxima of the valuation landscape, and to a certain extent the first landscape mirrors the second. The paths of this hill-climbing process are the trajectories of the system dynamics.

More interesting, in particular for social science applications, is the case when the valuation landscape changes endogenously in time. This can be modeled, for instance, within a Lotka-Volterra approach. Then, the valuation landscape can be described in the following way:

$$w(\vec{q}) = a(\vec{q}) + \int b(\vec{q}, \vec{q}')x(\vec{q}', t)d\vec{q}' .$$

In this case, valuation directly depends on the occupation itself. Then, the shape of the landscape, i.e., the location of maxima or the number of maxima can change. This approach seems to be useful for describing the often mentioned co-evolution between the selection process of competing groups and the change in the selection criterion itself during this process. In this case, valuation is to a certain extent “created” by the elements of the system themselves.

The framework sketched above has certain advantages over other model approaches that start with a typological description of populations. The formation of populations can be described as an endogenous process and the change of variety in the course of this process can be discussed. Further, by implementing different types of feedback

between the occupation landscape and the valuation landscape the co-evolution of these two landscapes can be analyzed. The role of different time scales of changes can also be discussed. Thus, it seems to be reasonable to assume that the valuation landscape changes more slowly than the occupation landscape moving within it. Then, occupation will first be concentrated around the hills of the fitness landscape. Further, we can ask how in the course of evolution a reached optimal state can be left for a “better” one? What kind of dynamics (or coupling between first and second landscapes) leads to which kind of transitional behavior? What structure of the valuation landscape allows what kind of occupational dynamics or what kind of occupational dynamics mirrors what kind of valuation landscape? Can optimal paths for the search be defined?

The model approach presented so far seems to offer an interesting framework for heuristic explanations of observable changes in landscapes characterizing complex systems. In the following, starting points for applying this methodology to the problem of knowledge landscapes are discussed.

4. G_O_E_THE as a Framework for Learning Processes in Science and Technology—Constructing the Missing Link for National Science Systems

4.1. The Characteristics Space

To illustrate the aim of the framework presented above, we consider the development of national science systems in terms of bibliometric indicators. Braun and Schubert had already proposed constructing three-dimensional landscapes of bibliometric indicators.¹⁸ For instance, they visualized the position of a country in a two-dimensional space of *mean expected* and *mean observed citation rates*, and used publication output as the third dimension (see figure 4).

In accordance with our own previous studies¹⁹, we relate other bibliometric indicators to the axes of the characteristics space. The publication output of each country is distributed over different scientific fields. At the macro-level and for the natural sciences it is common to consider differentiation into five main fields or disciplines *Life Sciences, Physics, Chemistry, Engineering, Mathematics*. At a certain point in time each

¹⁸ See note 6 (above) and Braun, T. and A. Schubert (1971), Dimensions of Scientometric Indicator Datafiles: World Science in 1990-1994. *Scientometrics*, 38 (1) (Oxford), pp. 175-204.

¹⁹ Bonitz, M., E. Bruckner and A. Scharnhorst (1993), The Science Strategy Index. *Scientometrics*, 26 (1) (Oxford) pp. 37-50.

country has a special pattern or distribution of its publications over these fields. The shares of a country's publications in the main fields are arranged into a vector $\{q_1, q_2, q_3, q_4, q_5\}$, whereby

$$q_i = \frac{\text{number of publications of a certain country in the field } i \text{ in the period of time } t}{\text{number of all publications of this country in the period of time } t},$$

$$0 \leq q_i \leq 1,$$

$$\sum_i q_i = 1.$$

In the following, we consider only the first two elements of this vector, the share in *Life Sciences* (L) and in *Physics* (P) ($q_1 = \text{L}[\%]$, $q_2 = \text{P}[\%]$), which are the main components and which, as we will see, are to a certain extent complementary. Then, the **characteristics space (space of publication structure)** is set up by the two variables q_1 and q_2 which can change continuously in the interval $[0,1]$. At a certain point in time t each country is characterized by certain values of q_1 and q_2 .

We use data drawn from the *Science Citation Index*[®] (*SCI*), the bibliometric indicators (publication per field and country) being constructed by the *ISSRU* group and *RASCI e. V.* The following comments are included for readers not familiar with this database.²⁰ The *Science Citation Index*[®] produced by the *Institute of Scientific Information* in Philadelphia covers yearly about 3500 journals (and some monographic series titles) across all fields. Articles, notes, letters, editorials, reviews etc. are the source items taken from these journals. Each record includes the authors names, their addresses, the title, the journal name (volume, number, pages), the abstract and the full bibliographic list of references of the document. To construct the country-specific bibliometric indicators from this material one has to classify the documents with respect to the countries of origin (here according to the first author) and by fields (via the affiliation of journals by fields). Of course, the selection of journals covered by the database determines the meaning of publication and citation indicators on a national level. For the *SCI*, the resulting publication profile does not directly represent the output or performance of a certain country. Rather, it reflects how the performance of a certain national science system is perceived by the international scientific community.

Considering the period 1980-1994, we look at what changes can be made visible by means of the proposed framework. During this period, the importance of biologically

²⁰ Garfield, E. (1977-1993), *Essays of an Information Scientist, Vols. 1-15*, Philadelphia: ISI Press.

oriented research obviously increased. The question is to what extent these changes can be made visible and how different countries adapt to these changes.

Countries are the elements in our model. Each country is characterized by certain values of the characteristics and is accordingly located at a certain point in the space of the publication structure. In previous studies we compared the publication profiles of different countries by similar distance measures without visualizing this characteristics space. We found several clusters (or groups of countries) with a similar structure. Some of the linkages found seem to reflect mutual national influences in the history of the construction of the science system (e.g., we may refer to the similarities between some South American and European countries). Further, publication profiles do not change rapidly and dramatically. The shares of the main disciplines seem to reflect basic characteristics of the composition of a national science system, which change only in the long run. In this paper we focus on the temporal fluctuations that are nevertheless observable in the national publication profiles. We ask whether countries change their structure in a coherent way or if changes are more like random fluctuations.

4.2. *The Occupation Landscape*

According to the framework introduced above, we next define an occupation or population density function over the characteristics space. Here, the problem is that we have only a small number of elements (countries): in total we consider 44 countries²¹. Then, each country can be represented by a δ -function. To visualize the landscape, we approximate the different δ -functions by Gaussian curves:

$$x^i(q_1, q_2) = C \exp\left[-a\left((q_1 - \tilde{q}_1^i)^2 + (q_2 - \tilde{q}_2^i)^2\right)\right], \quad C = \frac{a}{\pi}, \quad i: \text{country index}, i = 1, \dots, 44 .$$

²¹ Abbreviations used: ARG—Argentina; AUS—Australia; AUT—Austria; BEL—Belgium; BGR—Bulgaria; BRA—Brazil; CAN—Canada; CHE—Switzerland; CSK—Czechoslovakia; DEU—Germany; FR; DNK—Denmark; EGY—Egypt; ESP—Spain; FIN—Finland; FRA—France; GRC—Greece; HKG—Hong Kong; HUN—Hungary; IND—India; IRL—Ireland; ISR—Israel; ITA—Italy; JPN—Japan; KOR—South Korea; MEX—Mexico; NGA—Nigeria; NLD—Netherlands; NOR—Norway; NZL—New Zealand; POL—Poland; PRC—PR China; PRT—Portugal; ROM—Romania; SAU—Saudi Arabia; SGP—Singapore; SUN—USSR; SWE—Sweden; TUR—Turkey; TWN—Taiwan; UKD—UK; USA—USA; VEN—Venezuela; YUG—Yugoslavia; ZAF—Republic of South Africa. *Nota bene*: Because the starting point for our studies is 1980, some national states that emerged subsequently in Eastern Europe in the wake of the transformation process are still considered as part of the countries they belonged to formerly.

The center of a certain Gaussian curve is located at the point $\{\tilde{q}_1^i, \tilde{q}_2^i\}$, whose coordinates are given by the shares of the *Life Sciences* and *Physics*. We choose, by experience, the spread of these curves in such a way that occupied points located in a neighborhood overlap and that points far from each other still remain visible as single points ($a=2500$). Further, to a certain extent, the width of these curves can be considered as an expression of error in measurement. All curves have the same height. The shaping of an *occupation landscape* results from the overlapping process of all these curves:

$$x(\bar{q}, t) = \sum_{i=1}^{44} x^i(q_1, q_2) \quad \text{occupation landscape}$$

Figures 7, 8 and 9 show the occupation landscape for the three periods: 1980-1984, 1985-1989, 1990-1994 in a three-dimensional representation. The countries are not homogeneously distributed over the space. We clearly see groups of countries and isolated countries. Further, the shape of the occupation function changes remarkably in time. The corresponding contour maps visualize these changes (figures 7, 8, 9). In the first period 1980-1984, we observe one main group located in the region $\{0.34 < L[\%] < 0.74, 0.08 < P[\%] < 0.28\}$ surrounded by a periphery in the region $\{0.18 < L[\%] < 0.34, 0.2 < P[\%] < 0.4\}$ (north-west). The main group is also structured in itself. The main peak (P1) is located around $\{0.6, 0.18\}$, a second peak (P2) in a south-easterly direction and broader extended foothills exist to the north-west. In the second period 1985-1989, the main group spreads out, becoming less compact and extends both in a north-westerly and in a south-easterly direction. The periphery also spreads out and more isolated peaks appear. In the last period from 1990-1994, a re-concentration process for the main group seems to be visible. The main peak P1 and the second peak P2 seem to merge. The foothills are more extended towards the north-west and seem to lose contact with the main part, also the periphery is moving away.

In terms of our approach one could speak of two different phases: a spread and exploration phase from the first to the second period, and a re-concentration phase from the second to the third period. But, this remains a hypothesis as long as we have not yet checked whether the picture is stable against different choices of periods (e.g., 1 year or 3 year periods) for the data aggregation.

If we look to individual countries, we find certain regularities (figures 10, 11). Most of the OECD countries are grouped together, independent of size in terms of absolute

publication numbers or geographical location. Inside the main group, the main peak P1 is located around the U.S.A., whereby P2 is formed by a “Scandinavian group” and some African/Pacific countries. Most of West European countries are located in the foothills of this group, and most of the former socialist countries appear in the periphery as more or less isolated points.

To interpret the observable changes in a more serious way, one has to relate them to case studies about fundamental research changes in single countries or regions. As the aim of this paper is to introduce the reader to some methodological approaches we will stop the discussion at this point. Summarizing, one can say that the life sciences experience an increase in occupation and dominance within different national science systems, and that for certain parts of our ensemble the publication structures seem to approach each other.

Another way to visualize the changes relies on the construction of a “vector field”. For this purpose, the locations in two subsequent periods are linked by arrows (figures 12, 13). Obviously, some coherent movements can be observed. The arrows mostly follow a diagonal south-east/north-west line. Comparing the second with the first period (figure 12), most movements to the right of a hypothetical point at $\{0.55,0.15\}$ increase the share in life sciences, most movements to the left of this particular point seem to drift in the opposite direction. Comparing the third period with the second (figure 13), opposite flows occur. Points in the right lower corner move upwards in the direction of this hypothetical point, and a movement from the left towards this point can also be recognized. At the periphery, more fluctuations can be observed.

4.3. The Valuation Landscape

In physics or mathematics, conclusions can (under certain assumptions) be drawn about the shape of the underlying potential function from a vector field. This leads us to discussion of the second, **valuation landscape**. Following this line, one might say, that in figure 12 this hypothetical potential function could have a hill at the point $\{0.55,0.15\}$, so that the moving elements are repelled from this point in all directions. Accordingly, for the valuation function one would expect a valley at this point. Comparing figure 12 and figure 13, not the location but the character of this hypothetical potential seems to change. Now the points are moving towards this point,

as if there were a valley (or, in the inverse formulation in terms of a fitness function, a hill). At the periphery, the potential function would probably be flat (metastability), so that fluctuations occur more easily.

What the character of this potential or valuation function could be remains hidden. It seems to be very difficult to formulate an objective evaluation of a certain publication profile. But, within the framework used we can discuss variants. The search for a criterion is determined by the level of selection and competition to which we are referring. One possible approach might be to consider competition between countries in the economic sphere, selection being influenced by the national innovation system and, finally, also by research strategies and the corresponding change in the publication structure. One would then search for indicators of economic growth and wealth as an expression of a selective valuation landscape over the bibliometric space of publication structures. But the influence of research strategies on economic performance is mediated through different levels, and while the economic wealth of nations will determine research conditions, it is unlikely to determine publication output in different fields directly. An alternative approach consists in describing changes in national publication profiles as the outcome of a selection process within the world scientific system. Countries compete for excellent scientists, for research results and, in bibliometric terms, for visibility in international journals. Visibility measured by citations could then serve as selection criterion.²² According to such an approach, countries would compete for citations on the basis of (possibly implicit) national research strategies. In a forthcoming paper we will investigate in more detail what kind of citation indicator might serve as an expression of a valuation landscape.

5. Summary

Virtually constructed science or knowledge landscapes make hidden or distributed information visible. They can facilitate orientation and navigation in existent knowledge landscapes and the comparison of different institutional structures. Links to the theories of evolutionary search in complex adaptive landscapes and to evolutionary strategies can provide some insight into the mechanisms for the formation and re-shaping of such

²² Leydesdorff, L. and P. Wouters (1999), Between Texts and Contexts: Advances in Theories of Citation? *Scientometrics*, 44 (2) (Oxford). pp. 169-182.

landscapes. They can probably help to better understand the conditions for successful and effective searches for innovations and supporting institutional frameworks.

In this paper, a special framework of continuous evolutionary models (geometrically oriented evolution theory—G_O_E_THE) is presented. In the case of the development of national science structures, the approach is used as a framework to establish questions, from a novel perspective, for empirical research. In particular, the focus is on dynamical changes and their possible interpretations. In this paper, the case of national science systems serves as an illustration for different graphical representations of data inside the model framework. Examples are the construction of an occupation landscape in a knowledge space or the use of vector field approximations for temporal changes.

To a certain extent, the conclusions remain preliminary and, in part, hypothetical. They have to be tested for their significance and complemented by other qualitative and quantitative studies of national science systems. Nevertheless, it could be shown that the approach proposed generates a set of interesting research questions. A further step in using the explanatory power of the model framework is to construct a model process of competition between research institutions and national science systems. Such a model process should then produce results similar to the empirically observable changes.

Acknowledgement

I would like to thank Manfred Bonitz, Werner Meske and Werner Ebeling for a critical reading of the text and valuable comments.

Figures

Scientific and technological development as search in a knowledge landscape

technology studies

- natural trajectories of technological change
Nelson, Winter, 1977, 'In search of a useful theory of innovation'
- technological trajectories
Dosi, 1982, 'Technological paradigms'
- topography of technological evolution
Sahal, 1985, 'Foundation of technometrics...'
- characteristics space of technologies
Metcalf, Saviotti, 1984

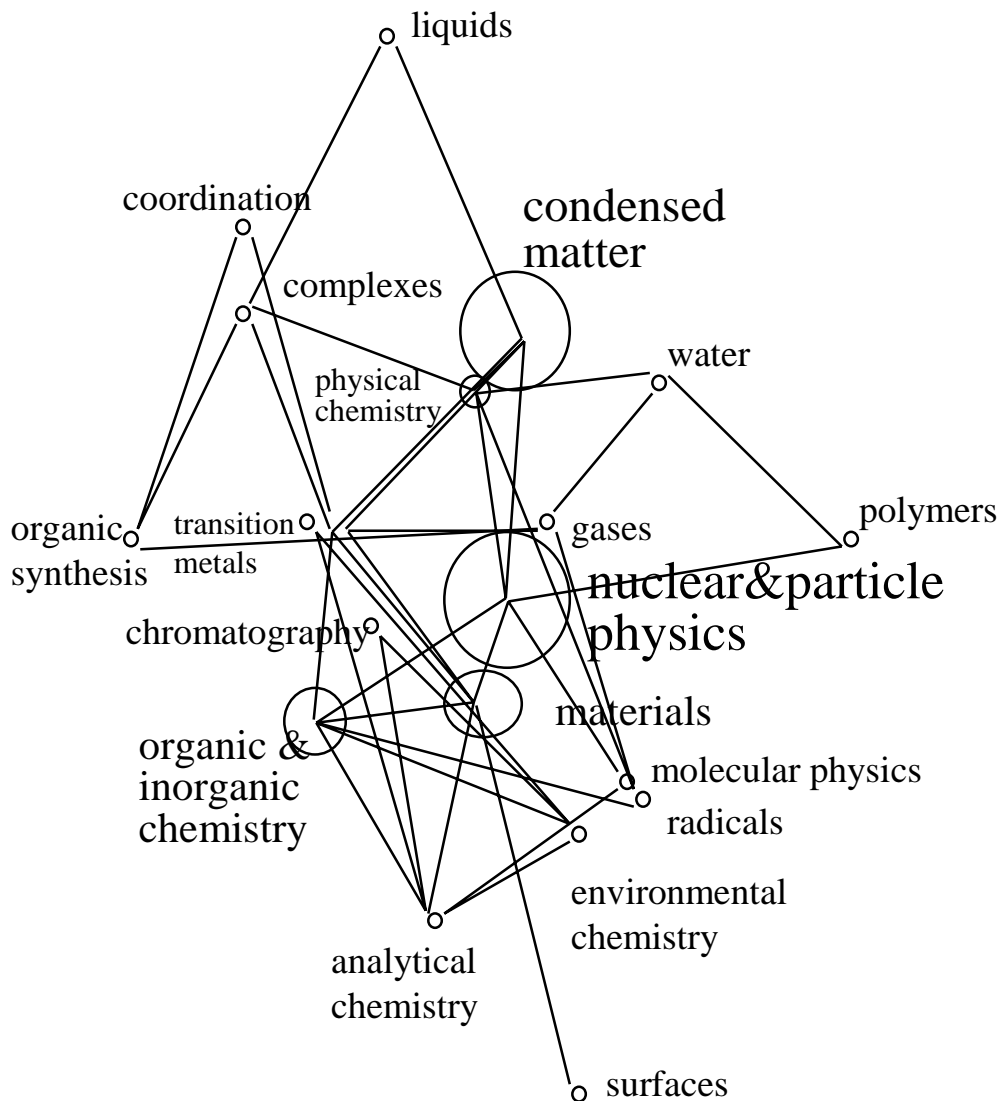
science studies

- “Normal science is then no longer forced to exhaust the given field of recognition for every possible scientific viewpoint; rather, with aid of scientific-theoretical cartography (mapping), it can hasten directly to politically determined points.”
Böhme, van den Daele, Krohn, 1973
- “... our approach opens up new avenues for analyzing specific successful trajectories of scientific or technological progress”
Noyons, van Raan, 1998, 'Monitoring scientific developments...'

Figure 1

*Examples of mapping science and technology:
I. Co-citation analysis of scientific articles*

Structure of physical science, 1990-1994

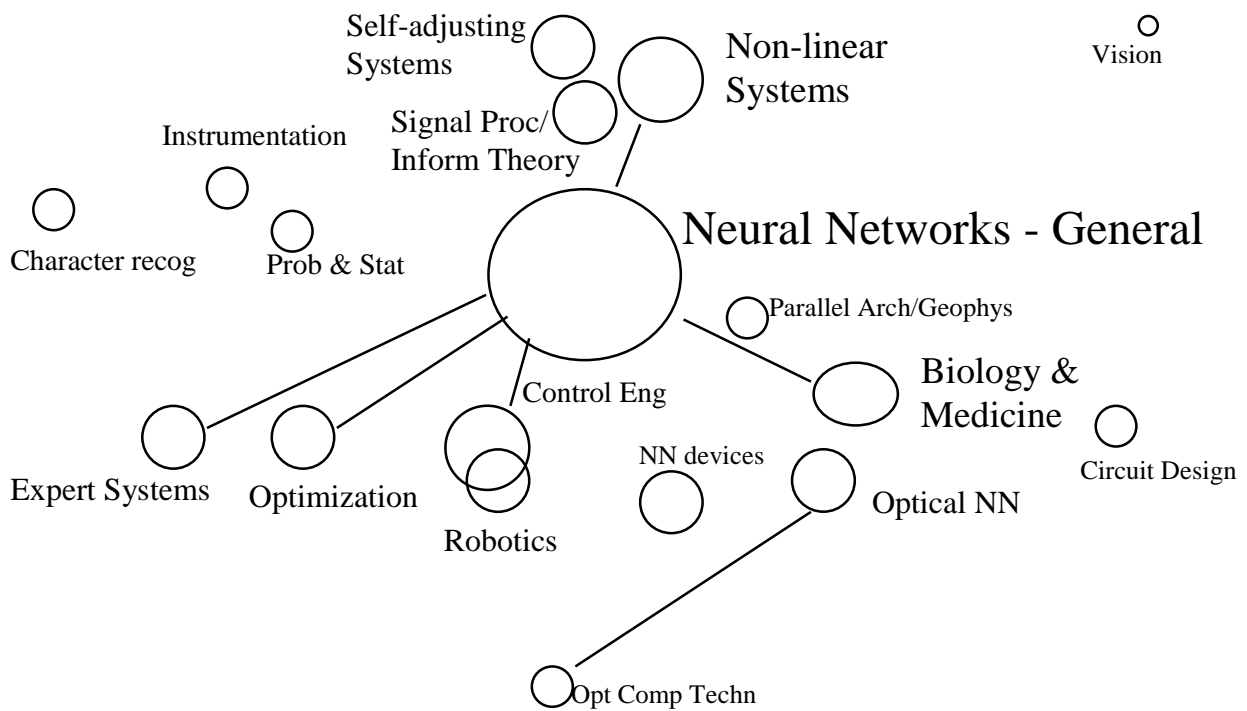


Produced with the SCIVIZ System (ISI Philadelphia), the map shows 21 cluster (points) which represent different subfields in physics and their links.
Graphical representation after *H. Small, Scientometrics 41(1998)125.*

Figure 2

*Examples of mapping science and technology:
II. Co-Word analysis of scientific articles*

Structure of neural network research, 1992/1993

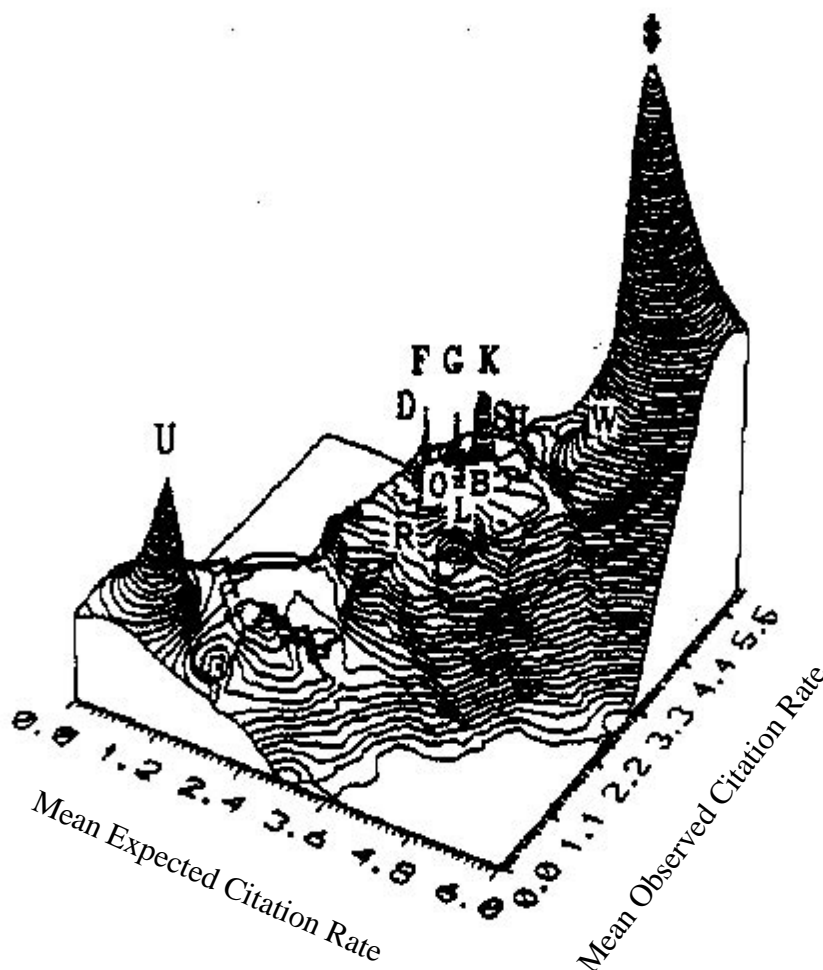


The surface of the circle of a subdomain represents the number of publications in this area. Graphical representation after *Noyons, van Raan, Scientometrics 41(1998)61*.

Figure 3

*Examples of mapping science and technology:
III Landscapes of scientometric output indicators*

Landscape of observed vs. expected citation rates, 1990-1994



Data source are the bibliometric datafiles based on the Science Citation Index. The third dimension is given by the cubic root of the total number of publications in all fields combined.

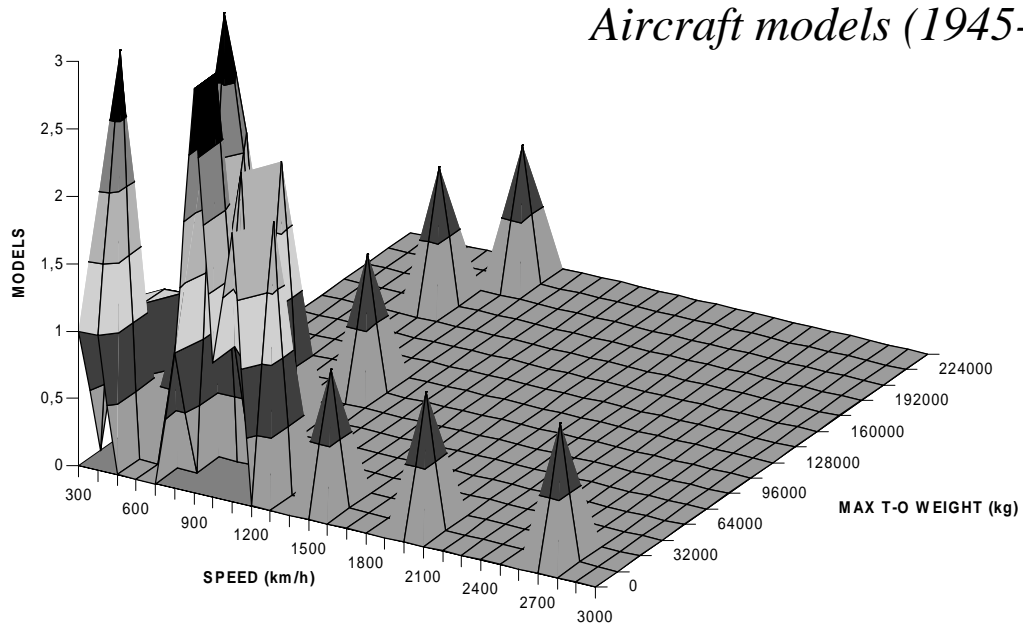
\$. USA, B: BEL, C: CAN, D: DNK, F: FRA, G: DEU, H: NDL, K: UKD, L: ISR, O: FIN, R: IRL, S: SWE, U: SUN, W: CHE

Graphical representation after *Braun, Schubert, Scientometrics 38(1998)175*

Figure 4

*Examples of mapping science and technology:
IV Mapping technological change in a characteristics
space of technological output indicators*

Aircraft models (1945-1960)



Source: Saviotti, P. P. / Bowman A., Indicators of Output of Technology. In: Science and Technology Policy in the 1980s and beyond. Ed. by M. Gibbons / P. Gummert / B. Udgaonkar. London, New York: Longman 1984.

Figure 5

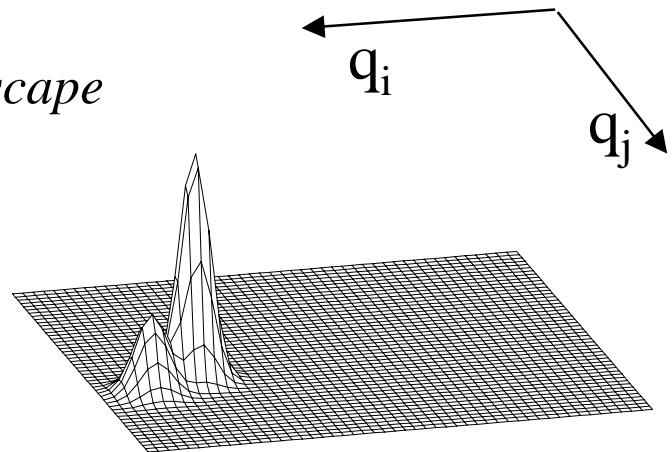
Elements of a geometrically oriented evolution theory

CHARACTERISTICS SPACE

OCCUPATION = 1. *Landscape*

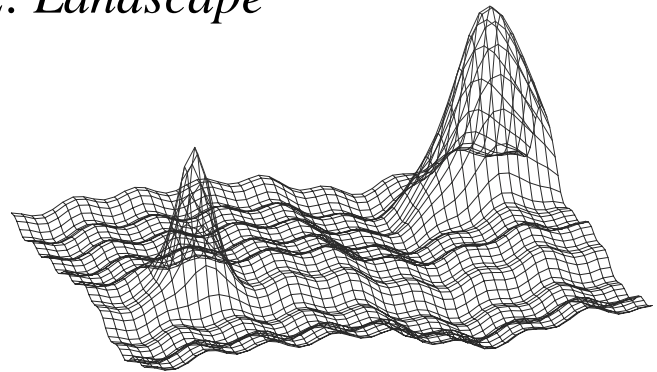
$$x(\vec{q}, t)$$

*population density
function*



VALUATION/FITNESS = 2. *Landscape*

$$w(\vec{q}, t)$$



$$\partial_t x(\vec{q}, t) = \boxed{x(\vec{q}, t)w(\vec{q}; \{x\})} + \boxed{Mx(\vec{q}, t)}$$

SELECTION MUTATION

Figure 6

Publication Profiles 1980 - 1984

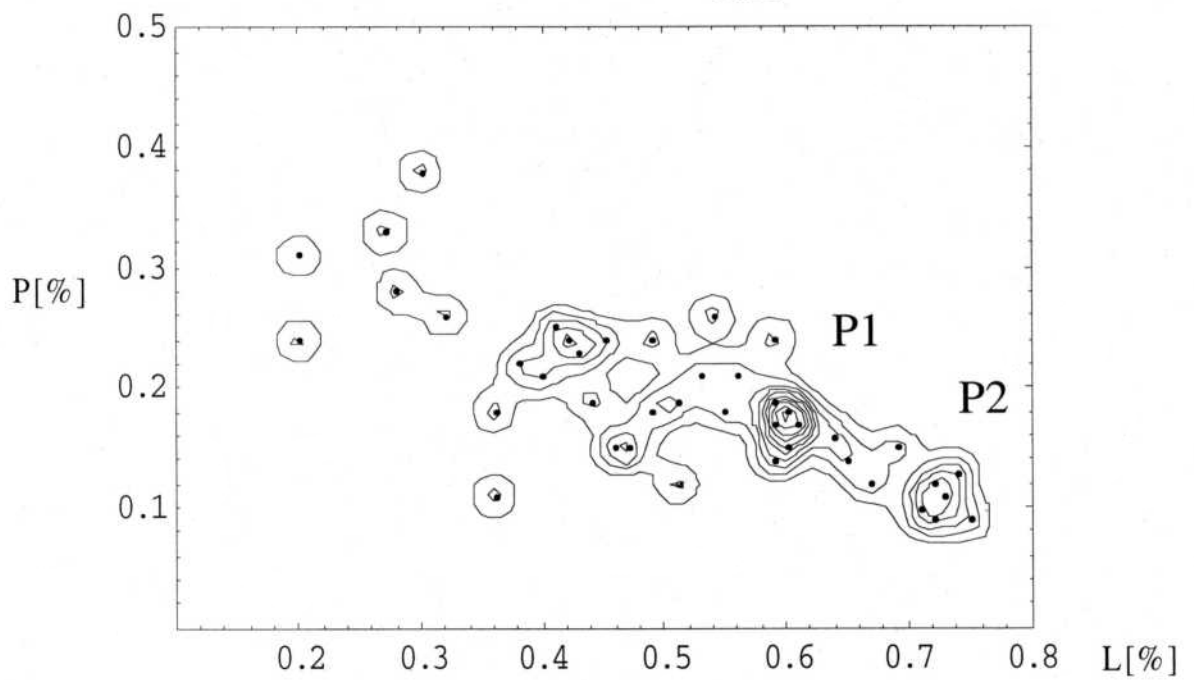
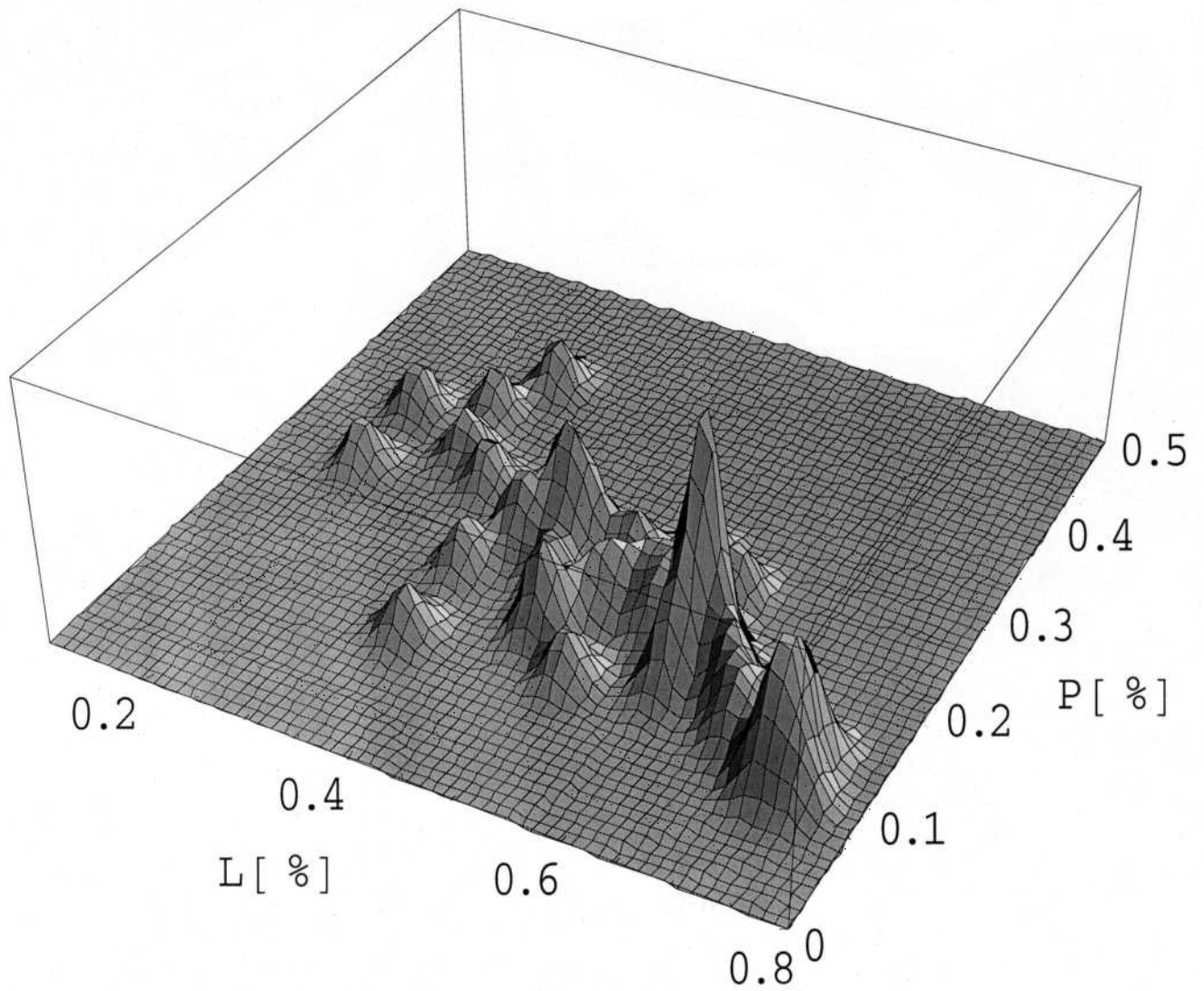


Figure 7

Publication Profiles 1985 - 1989

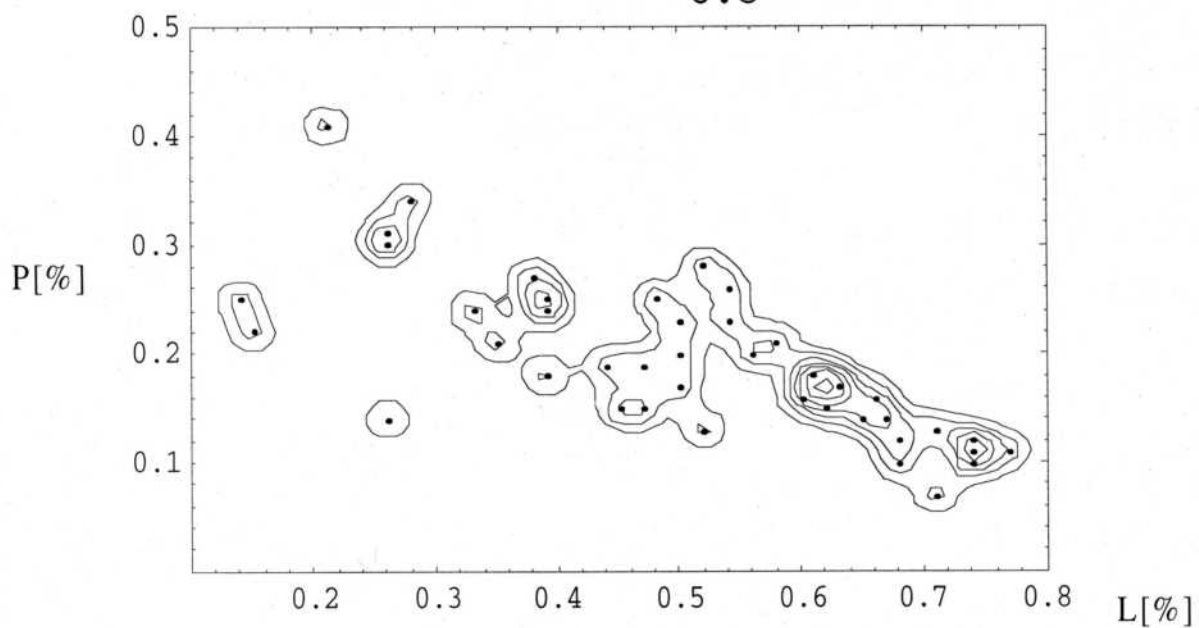
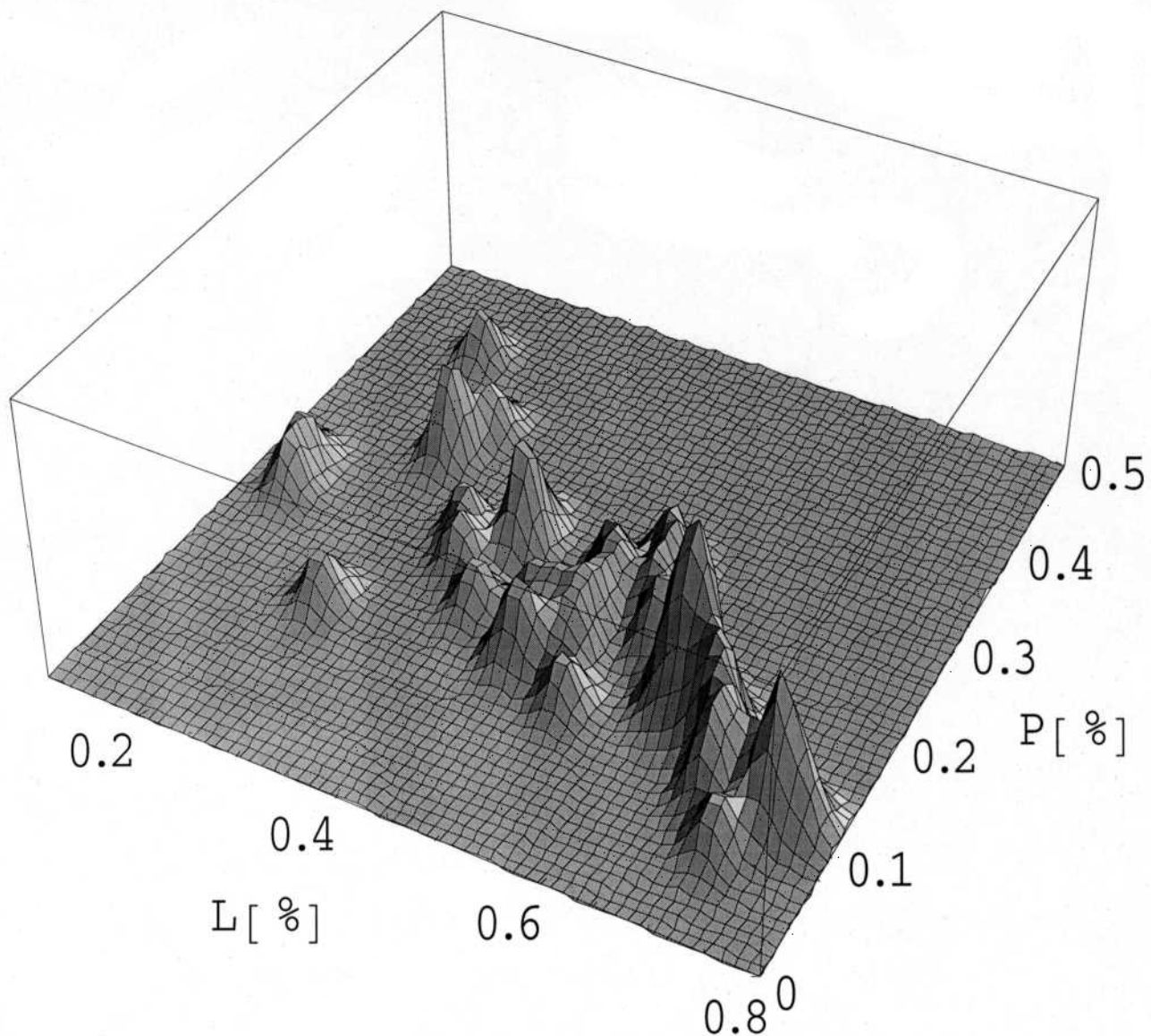


Figure 8

Publication Profiles 1990 - 1994

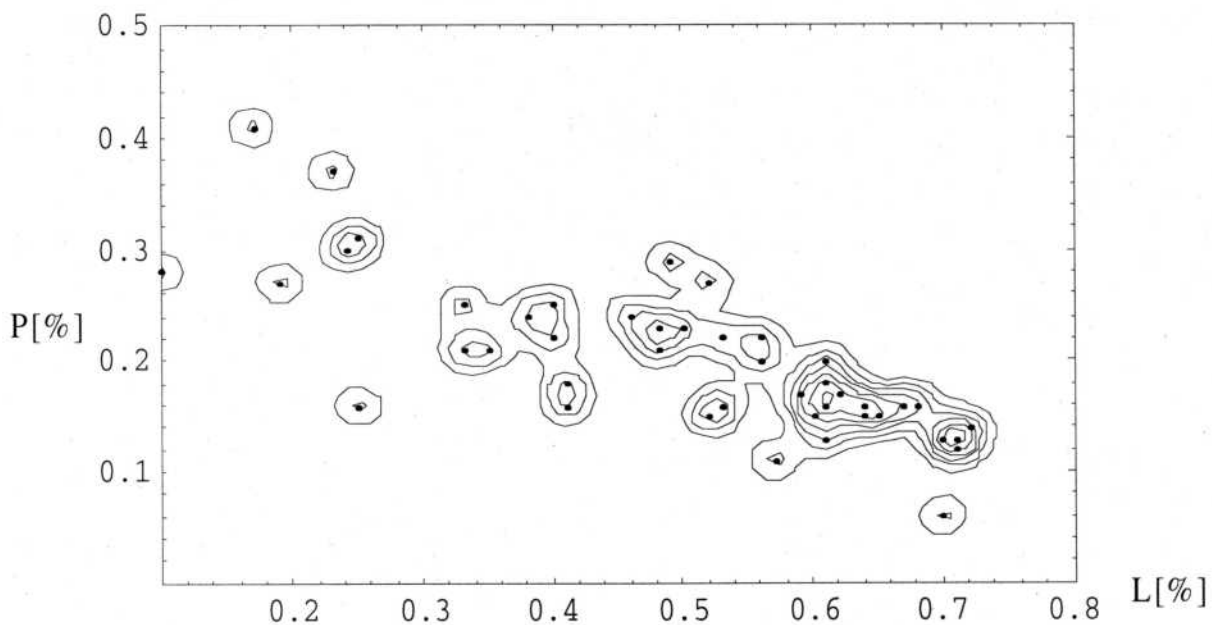
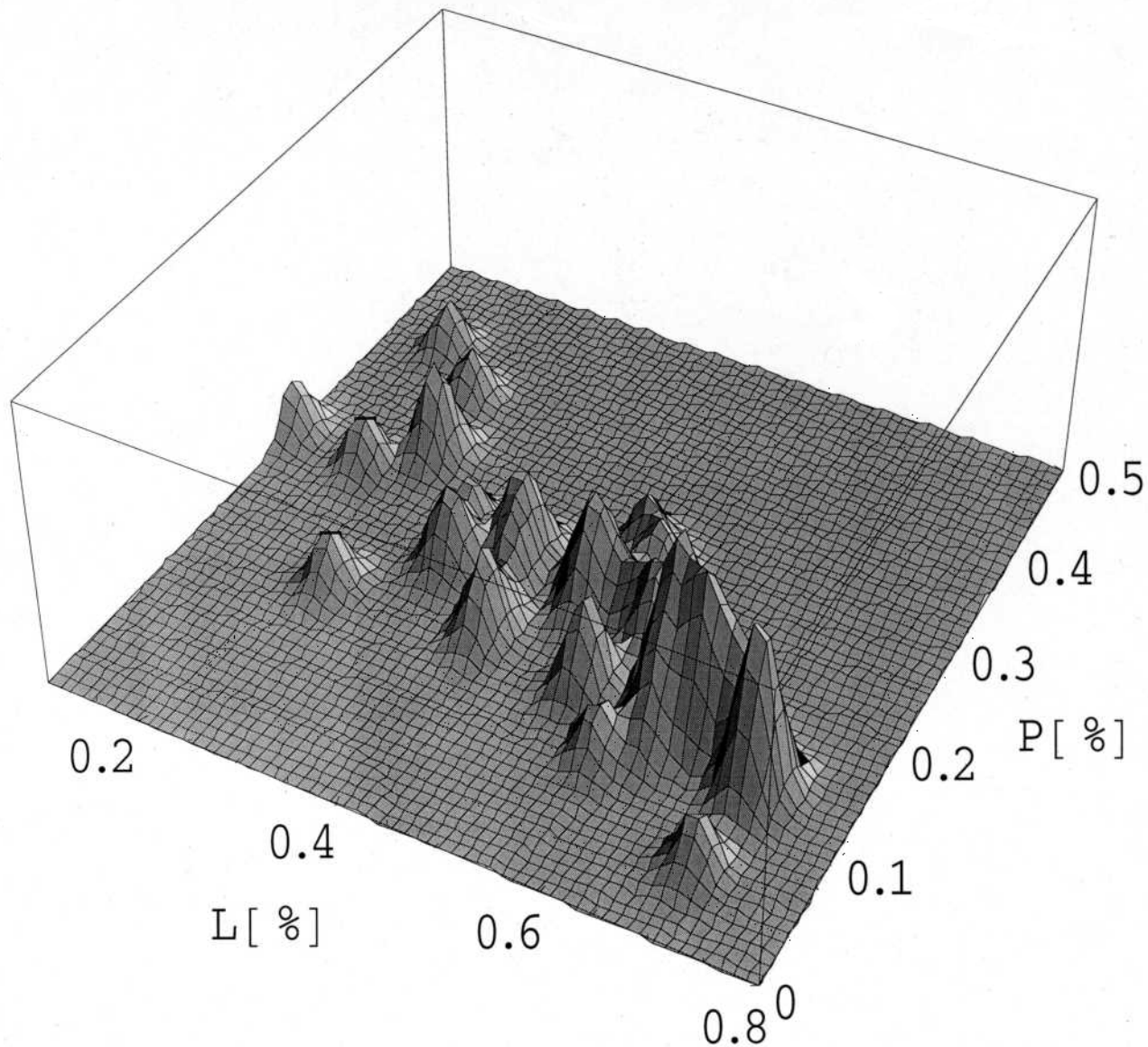


Figure 9

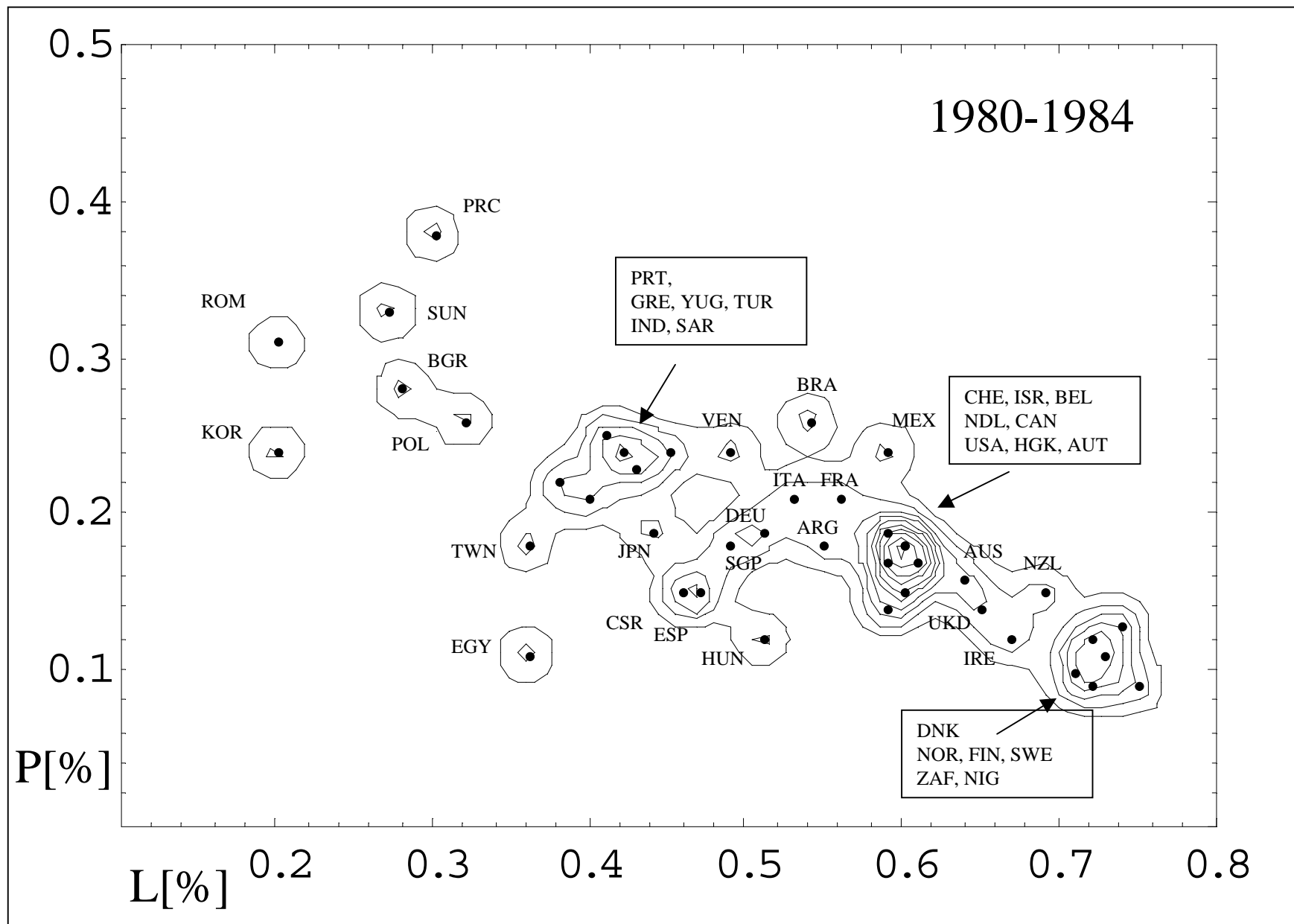


Figure 10

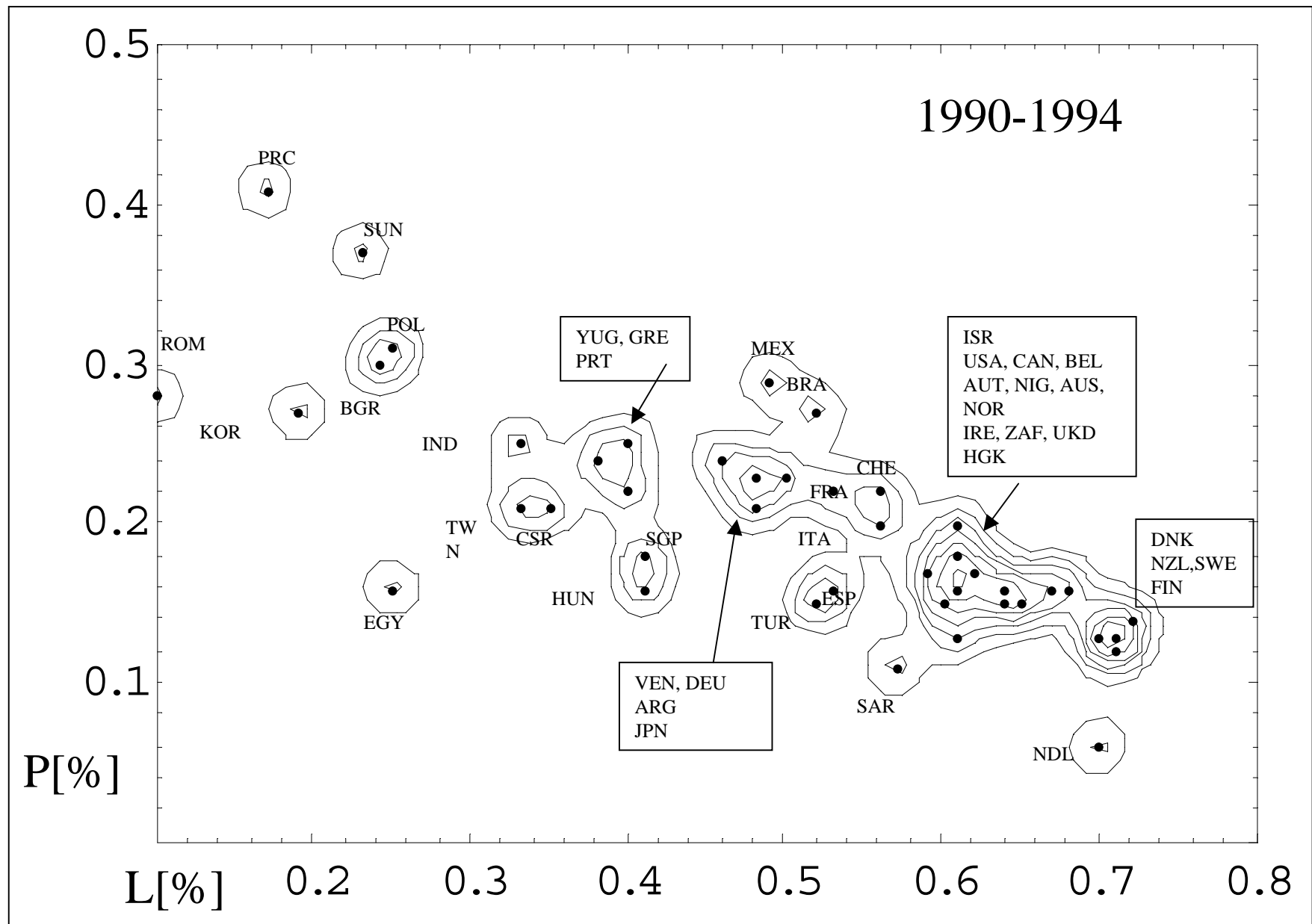


Figure 11

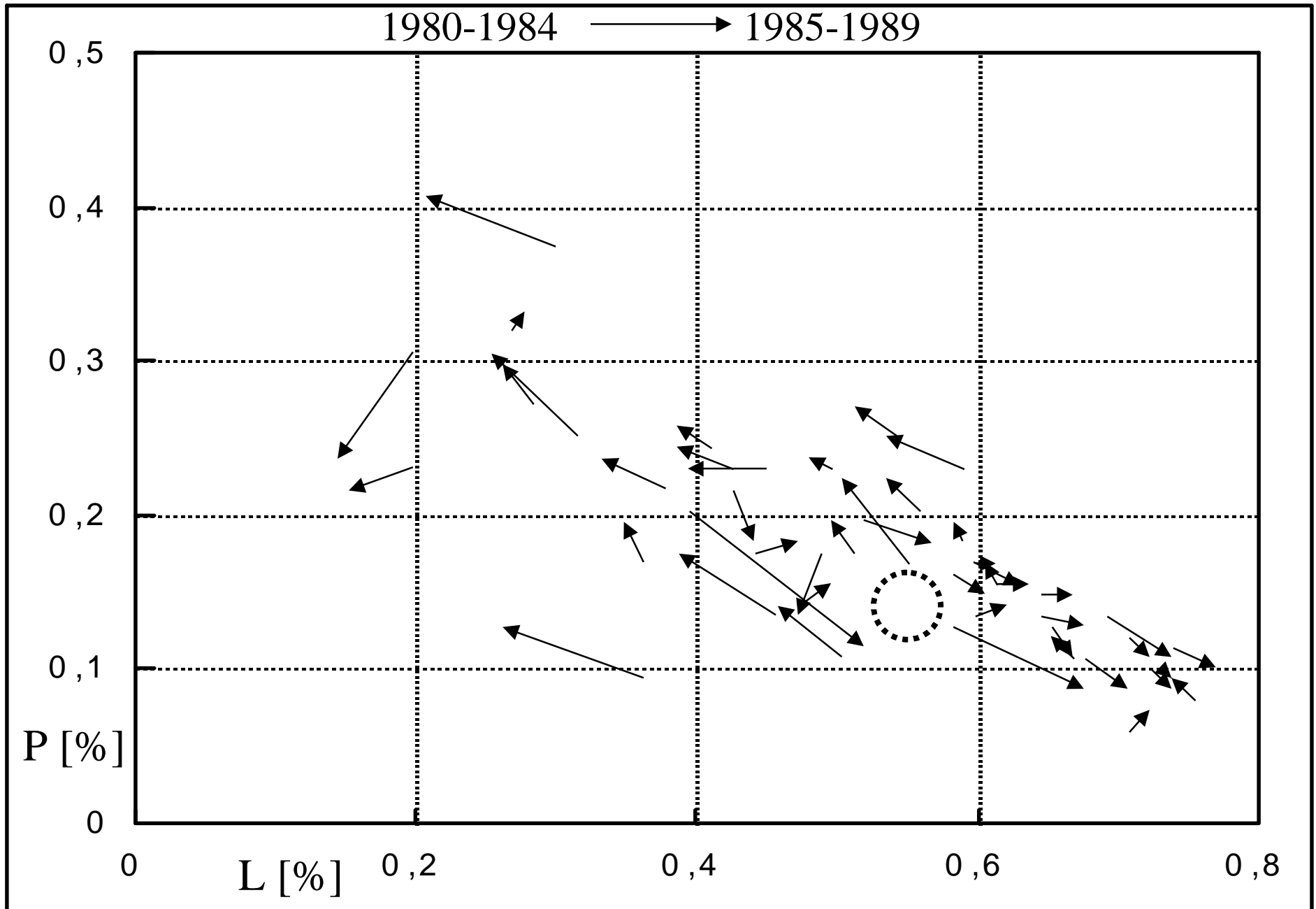


Figure 12

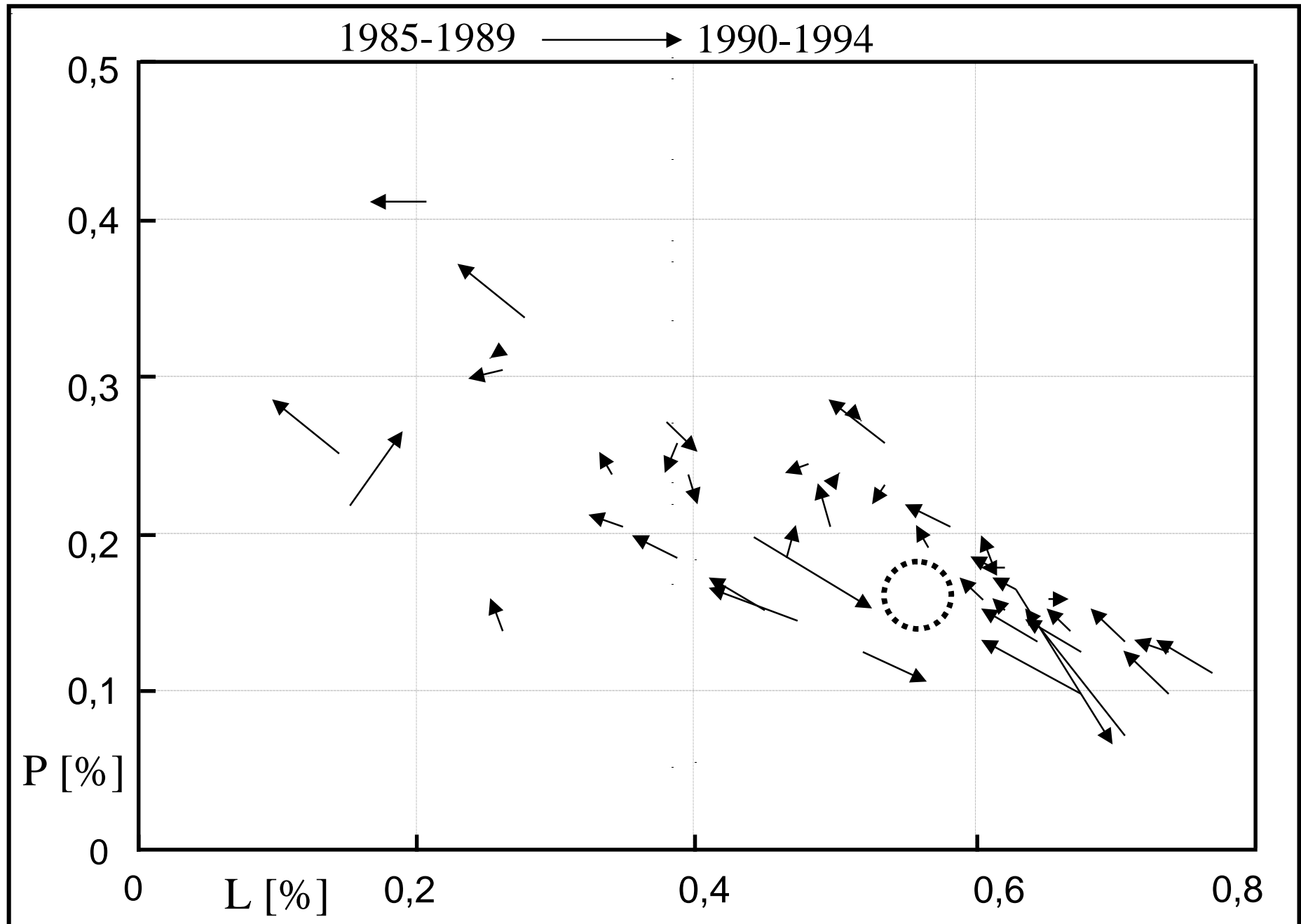


Figure 13