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Interdisciplinarity in biotechnology, genomics and nanotechnology

Gaston Heimeriks*

Department of Innovation Studies, Copernicus Institute, Utrecht University, Heidelberglaan 2, 3584 CS Utrecht, The Netherlands
**Corresponding author. Email: GHeimeriks@gmail.com.*

In this paper we study developments in biotechnology, genomics and nanotechnology in the period 1998–2008. The fields show changing interdisciplinary characteristics in relation to distinct co-evolutionary dynamics in research, science and society. Biotechnology emerged as a discipline in publication patterns at the same time as the number of biotechnology departments increased, whereas genomics emerged as a stable discipline, while the number of genomics departments declined. Nanotechnology maintains an interdisciplinary journal citation pattern while the number of nanotechnology departments increased. In all three fields the importance of industry–university collaborations increased, albeit to different degrees. Patterns of interdisciplinarity can thus be distinguished, as different ways in which the three dynamics co-evolve. From a governance perspective, this conceptualization provides distinct rationales for policy interventions in relation to interdisciplinarity in research, science and society.

Keywords: interdisciplinarity; indicators; convergence; biotechnology; genomics; nanotechnology.

1. Introduction

The notion of interdisciplinarity has received a lot of attention from researchers and policy-makers in discussions around the changing social and intellectual organization of the sciences. Interest in these issues has made both funding agencies and scholars increasingly concerned about how to define and operationalize interdisciplinarity (Klein 2006). For example, according to the US National Science Foundation the interdisciplinary convergence of nano-scale science with modern biology and medicine is a trend that should be reflected in science policy decisions (Roco and Bainbridge 2002).

The production of knowledge is intellectually and socially organized within disciplines, and the intellectual and social order of the science system is based on and reflected in disciplinary identities (Whitley 2000). The term ‘discipline’ particularly refers to the educational context of teaching and learning a certain body of knowledge, as manifested in curricula and textbooks (Schummer 2004). Disciplines have been very dominant in the organization of the science system, in the reward system, in the career system, and in the socialization processes for new scholars, and are reflected in the institutional properties of the modern university system.

As a consequence of the importance of disciplines, both funding agencies and scholars in science studies have become increasingly concerned with how to define and identify disciplinarity and interdisciplinarity in science. As Huutoniemia et al. (2010) point out, a considerable amount of different categorizations of interdisciplinarity have appeared, focusing on varying dimensions of knowledge production (for a review of interdisciplinarity categorizations, see for example Aboelela et al. (2007)).

Of all the concepts that have appeared, the distinction between multidisciplinarity, a conglomeration of disciplinary components (Glänzel et al. 1999); transdisciplinarity, an application-oriented type of heterogeneous knowledge production (Gibbons et al. 1994); and interdisciplinarity, a more synthetic attempt at mutual interaction (Tomov and Mutafov 1996), have been the most influential. While interdisciplinarity has this specific meaning, it also remains the generic concept and includes all activities which combine, synthesize, integrate or transcend parts of two or more disciplines (Miller 1982; Huutoniemia et al. 2010).

Indicators of interdisciplinarity are generally defined in contrast to what is seen as normal—that is disciplinary—knowledge and the prevailing classification of research in disciplines, sub-disciplines and research fields is often taken for granted (Van den Besselaar and Heimeriks 2001). Consequently, indicators for interdisciplinary research are generally based on co-occurrences of what can be considered discipline-specific items, such as: keywords, classification headings, author's affiliations, or citations. The literature reveals that the co-occurrences of discipline-specific items on different levels of analysis reveal the strength of the relationship or the exchange between the corresponding disciplines (Schummer 2004).

However, the nature of disciplinary identities and the mechanisms through which various forms of interdisciplinarity emerge remains a topic of discussion. Klein (1996) argues that the term 'interdisciplinary' has conflicting meanings. She views the solitary term as no longer adequate to describe the underlying phenomena.

Numerous existing studies have focused on interdisciplinarity (Meyer and Persson 1998; Glänzel et al. 1999; Schummer 2004; Leydesdorff and Rafols 2011). However, these studies have several shortcomings. First, as Heimeriks and Leydesdorff (2012) point out, most strategies to understand knowledge dynamics have mainly focused on a single evolutionary context. The research dynamics of knowledge production (the context of discovery) was first addressed in laboratory studies (Latour 1987). Kuhn (1970) focused on paradigm-led developments in science (the context of justification), and in recent years attention has shifted to the 'context of application', that is, the growing importance of the socio-economic environments of knowledge production (Nowotny et al. 2001).

Second, researchers and policy-makers often have problems treating dynamic situations, and interdisciplinarity is certainly a dynamic phenomenon. Most measures of interdisciplinarity provide a static representation of the social and intellectual organization of the sciences, without taking into account the dynamics and their interactions on different levels of analysis (Heimeriks and Leydesdorff 2012).

The aim of this paper is to fulfill the need for a robust and nuanced approach that is grounded in a deeper knowledge of interdisciplinarity. We argue that disciplinarity has to be understood more holistically, as a combination of dynamics. As Wagner et al. (2011) point out, interdisciplinary research involves both social and cognitive phenomena, and both these phenomena should be reflected in any measure or assessment of interdisciplinarity. Furthermore, interdisciplinarity emerges within the dynamics of a larger knowledge system, which includes external, societal drivers (Wagner et al. 2011).

We propose a conceptualization of different forms of interdisciplinarity that allows for empirical operationalization by introducing different dynamics in knowledge production. It is important to consider knowledge production, not as something static, but rather as a process of continuous transformation. Therefore, it is important to assess the determinants that affect the production, diffusion and commercialization of knowledge. The mechanisms associated with the production of new knowledge have the potential to be different from the production of past knowledge (Leisyte and Horta 2011). In this paper, we refer to these three developments as: research, science and society (Rip 1990; Latour 1998).

This conceptualization allows us to elaborate the changes taking place in the sciences with respect to disciplinary identity formation and to discuss how different modes of interdisciplinary knowledge production are emerging (Heimeriks and Leydesdorff 2012). Each of the three contexts can be considered an analytically distinct evolutionary environment with distinct drivers of change. Consequently, it has often been argued that it is important to take into account all three contexts of research, science and society involved in knowledge production because the observed knowledge dynamics result from a co-evolutionary development among these analytically distinct processes (Rip 1990; Heimeriks and Vasileiadou 2008; Heimeriks and Leydesdorff 2012).

Our conceptualization and empirical examples show that interdisciplinarity refers to activities in research (collaboration between researchers with different skills from different departments), to the position in a body of literature in science (publication patterns), and the type and intensity of societal interactions (user interaction and non-academic collaborators).

For example, a field may be characterized by a strong and stable disciplinary identity in terms of publication patterns, while a diverging variety of skills and tools is used in research practices. The developments of the three analytically distinct dynamics are not a priori coordinated and may thus develop in some dimensions and at some places more than at others (Heimeriks and Leydesdorff 2012). Knowledge production remains in transition because the different dynamics generate feedback that continuously provides change to one another (Leydesdorff 2010). Furthermore, new dynamics are continuously introduced by developments in information and communication technologies (ICT) (Heimeriks and Vasileiadou 2008). The three dynamics are substantially very different and patterns of interdisciplinarity can be distinguished as different ways in which the three dynamics co-evolve (Heimeriks and Leydesdorff 2012).

The implication for research policy is that generic measures can sometimes be helpful but there is a clear need for measures targeting field-specific knowledge dynamics. Successful measures involve not only the different dynamics, but also the interactions between local research practices, emergent scientific landscapes, and the field's relationship to its societal context.

As cases for our empirical operationalization of interdisciplinarity we chose biotechnology, genomics and nanotechnology. These fields are characterized by rapid growth, divergent dynamics, and new complementarities creating the need for wide-ranging cross-disciplinary competences (Heimeriks and Leydesdorff 2012; Bonaccorsi 2008). Moreover, the fields have been extensively studied as relevant examples of interdisciplinary dynamics (Meyer and Persson 1998; Rafols and Meyer 2007).

Nanotechnology and life sciences such as biotechnology and genomics have been identified by many as key future technology areas, with economic growth potential (OECD 2009). Governments and companies have invested substantial financial resources to further R&D and to translate research results into commercial applications. Government programmes in nanotechnology, biotechnology and genomics are often associated with the idea of broadly converging technologies and 'interdisciplinary' research. The effort surrounding nano–bio–information–cognitive technologies in the USA can be seen as an example of this type of interdisciplinary convergence activity (Roco and Bainbridge 2002). In Europe, increasing attention has also been given to the 'importance of interdisciplinary approaches' in nanotechnology and lifesciences (Malsch 1997). As such, these fields are expected to provide good examples of various forms of disciplinary developments.

Elsewhere, we have shown that biotechnology, genomics, and nanotechnology can all be characterized by rapid growth and divergent interdisciplinary developments, but that the dynamics in research, science and society are very different (Heimeriks and Leydesdorff 2012). In this paper we study the co-evolutionary dynamics of interdisciplinary knowledge production.

The paper is structured as follows: Section 2 discusses interdisciplinarity in terms of the different dynamics of knowledge production. Building on insights from this literature, Section 3 specifies the co-evolutionary dynamics of interdisciplinary knowledge production. Section 4 describes the methodologies underlying our analyses. Section 5 provides some empirical operationalizations of interdisciplinarity in the light of our conceptualization. Section 6 discusses the results and Section 7 concludes the paper.

2. Interdisciplinarity in knowledge production

We propose a conceptualization of different forms of interdisciplinarity that allows for empirical operationalization by introducing different dynamics in knowledge production to assess the determinants of change in research activities, science dynamics and societal interactions. 'Research' relates to localized research processes and practices, 'science' refers to codification and communication in scientific journals. 'Society' is about interactions with non-academic institutions.

2.1 Research

Research relates to the everyday activities of researchers in their local context of work: gathering data, using equipment and infrastructures, data analysis, and writing up results. Research activities take place in specific institutional contexts (e.g. a faculty or a university department) which in turn influence the type of research activities. At the same time, these research activities involve different collaboration patterns, as well as the distinct reputational strategies that researchers pursue (Whitley 2000).

With the growing specialization in science and progressive professionalization (Cronin et al. 1998), it is becoming increasingly difficult for a researcher to possess the necessary skills and technologies to solve problems singlehandedly (David 1994). Consequently, in research practices interdisciplinarity relates to the variety of skills and infrastructures that are required for formulating research designs, applying methodologies, using tools and data gathering in knowledge production. On this level of analysis, disciplinary identity is reproduced through local research traditions and the institutional organization of teaching and research. For example, Schummer (2004) notes that a co-author analysis can cover different aspects of interdisciplinarity than other methods, especially related to the institutional context of research practices through co-occurrences of disciplinary affiliations of co-authors.

The use of ICT has provided increasing variation in researching practices by enabling additional models, maps and tools to be generated: simulated experimentation *in silico*, algorithms for pattern identification in biomedicine, visualization tools, modeling and simulations have allowed not only new methods of analysis, but also new types of output to be generated (Heimeriks and Vasileiadou 2008). For example, the availability of digital databases and data mining technologies have pushed research practices in the life sciences in new directions, sometimes giving rise to new fields altogether (Lenoir 1999).

Additionally, ICT influence the institutional organization of research, by facilitating collaboration between researchers thus resulting in increasing numbers of authors per publication, increased numbers of publications with international co-authors, and the allocation of research money for ever larger groups of researchers in new institutional settings (Heimeriks and Vasileiadou 2008). On the other hand, general purpose technologies (GPT) have a significant impact on research activity through radical technological change and wide technological diffusion. ICT, biotechnology and nanotechnology are viewed as existing or potential GPT that bring together previously separate fields of knowledge production (Helpman 1998).

2.2 Science

The dissemination of results through scientific journals translates the 'research output' into an emergent 'body of knowledge' where claims are utilized (accepted, criticized, rejected) by other scientists. This dynamic of science relates to the collective and distributed activity where disciplinarity translates into the position of a publication in this changing landscape of distributed scientific contributions. Here, disciplinarity is reproduced through journals and their citation patterns. For example, Porter and Rafols (2009) insist that this collective and distributed dimension of science is the most appropriate level of analysis to study interdisciplinarity (e.g. through citations and references).

The disciplinary patterns emerging from distributed journal publications are visible in fields as clusters of related publications. The sequence of knowledge claims constitutes the research front of a field, and brings the field further by emphasizing the differences with previous claims (Fujigaki 1998). At the same time, it can lead to a relatively stable definition of the field: in as far as the knowledge claims remain referring to a common literature, which constitutes the intellectual foundation of the field. When a field is stabilized in this way, the process of circular causality may lead to further stabilization and even globalization: the new researchers are inclined to position themselves in terms of both the intellectual base, and the research front, and therefore a constant referring to the evolving literature base takes place. This can reinforce the stability and global generalization of the field. For example, several new indicators for interdisciplinarity have been developed recently using these mechanism of journal citations (Leydesdorff and Rafols 2011).

Because of the availability of digital resources, scientists increasingly look beyond the borders of their own field. Recent research shows that one-third of the researchers using electronic journals claim that new types of research are introduced to their own research agenda thus giving rise to increased interdisciplinarity (Roosendaal et al. 2010).

In science, convergence may occur by the emergence of stable patterns of related knowledge claims in publications. It has been argued that new developments in science first manifest as specific journals focusing on the issues under study (Leydesdorff and Cozzens 1993). The new journal(s) attract the attention of scholars in neighboring disciplines. This interdisciplinary convergence among disciplinary structures can be stabilized over time. For example, previous research has shown that information science and artificial intelligence developed into stable communication structures among journals that are reproduced over time. These fields are only ‘interdisciplinary’ from the perspective of the traditional disciplines, but have a similar communication network as disciplines (Van den Besselaar and Heimeriks 2001). However, this is not always the case. Cognitive science failed to stabilize as an independent field between computer science, artificial intelligence, brain research and cognitive psychology (Van den Besselaar and Heimeriks 2001).

2.3 Society

The societal dynamics refer to the ways in which knowledge production provides resources to social and economic developments and the extent to which societal dynamics contribute to the social and intellectual organization of knowledge production. Science is an open system that is coupled to other parts of society. Its development is caused by a complex interplay of internal and external factors, with an internal axis of intellectual organization (Leydesdorff 2010). This latter codification makes the system relatively autonomous. However, in recent years increasing interaction with socio-economic developments in society has been emphasized. Fields of knowledge production constantly capture societal phenomena for particular purposes through non-academic collaborators and user–producer interactions (Lundvall 1988). As such, socio-economic developments provide an increasingly important influence on the coordination and organization of knowledge production.

Efforts to understand the emerging knowledge economy have paid particular attention to the shifting boundary between academic and commercial research, especially in the life sciences. Empirical studies suggest that interaction between university and commercial science has increased, blurring the boundary between them and generating a new knowledge regime (Van Rijnsoever and Hessels 2011; Heimeriks et al. 2008). Consequently, at this level, interdisciplinarity relates to the intensity of knowledge use in society and the importance and variety of non-academic collaborators.

For example, the triple helix model implies that the knowledge system has recently gained a degree of freedom under the pressure of socio-economic developments reinforced by globalization and the new communication technologies. The perspective of knowledge production, consequently, is changed to transdisciplinary as based on an external societal perspectives (Etzkowitz and Leydesdorff 2000; Heimeriks et al. 2008). The main institutions in knowledge production have been defined as university, industry and government (Etzkowitz and Leydesdorff 2000). These institutions correspond to three sub-dynamics of: wealth generation in the economy, novelty generation by organized science, and the governance of the interactions among these two sub-dynamics by policy-making in the public sphere and management in the private sphere (Leydesdorff 2010).

Similarly, the ‘Mode-2’ thesis of the new production of scientific knowledge (Gibbons et al. 1994) argues that in the past interdisciplinary research was considered relatively marginal within the science system. Gibbons et al. (1994) argued that this has changed radically in the knowledge society where increasingly two different ‘modes’ of knowledge co-exist. Mode 1 knowledge production is the production of traditional ‘disciplinary science’, in which the academic interest in ‘pure’ knowledge prevails. The locus of Mode 1 is the university organized along disciplinary lines in faculties and departments. Consequently it is homogeneous in terms of organizational structures and practitioners; it is hierarchical, and relatively stable. In contrast, Mode 2 is application-oriented and transdisciplinary knowledge production. According to Gibbons et al. (1994), transdisciplinarity goes one step further in integration than interdisciplinarity, as the former is based upon a common theoretical understanding, and a mutual interpenetration of disciplinary epistemologies. In addition, Mode 2 is heterogeneous, as a wider set of organizations and types of researchers are involved, operating in specific contexts on specific application-oriented problems. Various different organizational forms co-exist within Mode 2, and research is not exclusively based in universities.

3. Co-evolving modes of interdisciplinarity

Section 2 not only highlighted the different dynamics of knowledge production that are relevant for mapping interdisciplinarity, but it also identified several mechanisms through which disciplinary changes may occur. Consequently, and contrary to most classification systems of scholarly work, bodies of knowledge are not organized as stable structures, but are dynamic and characterized by overlaps, links, and fractal distinctions (Abbott 2001). What is currently thought of as a highly interdisciplinary field is a point-in-time perception of how far apart the present constituent categories were at an earlier time, suggesting that a measure of the distance between two topics or between fields of science should be based on the analysis of large amounts of data over time (Wagner et al. 2011). Contrasting disciplinary and interdisciplinary research in terms of homogeneity versus heterogeneity, and stability versus flux, is not always convincing (Van den Besselaar and Heimeriks 2001).

Elsewhere (Van den Besselaar and Heimeriks 2001) we showed that the characteristics of the publication landscape in interdisciplinary fields can be studied and mapped in the same way as we study and map disciplinary fields. We noted limitations in the use of existing categories for measuring interdisciplinarity because of the dependence upon a pre-defined taxonomy or category structure. Studies using pre-defined categories are often viewed as biased due to a lack of consensus around the accuracy of any particular journal category system (Wagner et al. 2011). Some ‘interdisciplinary’ fields turned out to exhibit a strong disciplinary identity as reflected in the publication patterns (Van den Besselaar and Heimeriks 2001).

Interactions between the local research practices, scientific fields and society are multidirectional and involve positive and negative feedback loops. In other words, research, science and society interact and shape each other in a process of co-evolution (Whitley 2000; Rip 2002).

New institutional research settings emerge in response to developments in research practices (new technologies, infrastructures, collaborations etc.). Furthermore, a scientific field (‘the codified body of knowledge’) constrains the set of trajectories that a researcher may explore, as well as the range of available strategies, competencies and forms of organization (Whitley 2000). At the research level, the final outcome of research efforts has to be contextualized, written and edited. In these local actions, researchers respond to the emergent science level in an anticipatory mode in which the existing claims in the body of knowledge are partially deconstructed and reconstructed, but also accepted to a large extent (Fujigaki 1998). The new contributions in turn, change the science landscape to which researchers and organizations respond.

Similarly, in a knowledge-based society, most societal problems and innovation challenges require new knowledge developments, and these developments influence the direction of scientific research (e.g. through corporate funding, university–industry collaborations or governmental research programmes). These socio-economic developments give rise to the emergence of new fields and departments (e.g. science and innovation studies, environmental sciences etc.). Socio-economic innovative advances increase the general level of scientific opportunity and scientific and technological advances originating outside academia, represent an important source of knowledge for the researchers’ innovative processes (Breschi et al. 2000). As such, the transdisciplinary developments outside academia are an increasingly important driver of change in the coordination and organization of knowledge production.

In summary, we argue that interdisciplinarity is best conceptualized and measured by an interaction among interdisciplinary dynamics in relation to activities in research (collaboration between researchers with different skills and resources from different institutional settings), to the position in a body of literature in science (publication patterns), and collaboration with non-academic stakeholders in order to answer practical questions or to solve societal problems (user interaction and non-academic collaborators). While existing studies to understand interdisciplinarity often focused on only a single evolutionary context (Heimeriks and Leydesdorff 2012), these different dynamics are subject to change and can be expected to interact and shape each other in a process of co-evolution.

4. Data and methodology

In this empirical section we operationalize the dynamic developments of knowledge production in biotechnology, genomics and nanotechnology. Our delineation is based on the distributed scientific publication patterns in these areas in terms of the fields emerging in the journal landscape. As such, a field can be operationalized as an evolving set of related documents (Lucio-Arias and Leydesdorff 2009).

The fields are delineated using aggregated journal–journal citation patterns (Cozzens and Leydesdorff 1993) for the period 1998–2008 (described below).

Many other delineations are possible and inevitably, these different methodologies will highlight different developments (Huang et al. 2011). However, methods of using keywords to identify key cognitive developments in science are problematic (Van den Besselaar and Heimeriks 2006). It is difficult to distinguish empirically how much of the observable variation in words over time is dependent on change in terms of the changing positions of individual words against a more stable background vocabulary, or on change in the vocabulary itself. The journal delineation method used in this study provides a relatively unambiguous representation of the fields (Cozzens and Leydesdorff 1993; Van den Besselaar and Heimeriks 2001).

Scientific communications are extremely well archived, and therefore, we have a wealth of data at our disposal. After obtaining these sets of journals, all publications for the period 1998–2008 were downloaded from the Web of Science. The data thus obtained provides us with the information to study the dynamics of knowledge production in research, science and society. Each publication in our dataset contains one or more institutional addresses that enable us to specify the type of organization and the university departments that the authors are affiliated to. Furthermore, the data allows us to specify the companies and public research organizations that are involved in knowledge production.

We begin our examination by studying collaboration and the extent to which institutional resources are combined in research. Following Schummer (2004), research can be considered interdisciplinary if researchers from different disciplines, according to their departmental affiliation, are involved. We can further assume that in general, the affiliation of the authors corresponds to their disciplinary knowledge contribution. Thus, co-author analysis measures interdisciplinarity in terms of successful research interaction between disciplines. Because of the very large number of publications involved, for practical reasons we used all publications with at least one Dutch address to map the departmental affiliations. According to the UNESCO Science Report 2010, the Dutch science system is similar to many other developed countries and very international in its orientation (UNESCO 2010). As such, the set of publications from The Netherlands provides what we assume to be an indicative sample to map the disciplinary affiliation of authors. The smallest organizational unit mentioned in the author address is used to classify the affiliations. For the purpose of this study, we can interpret the names of the departments as belonging to a limited set of disciplines. For example, an address in one of the biotechnology publications containing ‘Dept Biochem’ will be labeled with a biochemistry affiliation. Less frequent and multidisciplinary affiliations were coded as ‘other’.

Each publication can be expected to contribute to the further development of the field at the research front. Thus, the dynamics of the emergent science system can be made visible by mapping the stability of the field through time in terms of the citational environment (Van den Besselaar and Heimeriks 2006). In a number of studies, it has been shown that journal–journal citations can be used as an operational indicator for the disciplinary organization of the sciences at the science level (Leydesdorff and Rafols 2011). Following these studies, we use the method for delineating specialties as described by Cozzens and Leydesdorff (1993). This method is based on a factor analysis of the journal–journal citations matrix of the core journal of a specialty, the ‘central tendency journal’. For every year, we determine the relational citation environment of that journal, using a threshold of 1% in the citing dimension. For the resulting set of journals we can make the journal–journal citation matrix, with the citing behavior as the variables. One can expect strong citation relations within and between journals belonging to a discipline, and (much) weaker relations with other journals.

Matrices formed from these journal–journal citation data can be analysed in terms of their structural dimensions using factor analysis. This enables analysis at the journal level by placing journals into disciplinary categories and then viewing the extent to which they have relationships with journals outside of that disciplinary category. In other words, a factor analysis of this matrix results in factors consisting of journals that entertain similar citation patterns. The factor on which the seed journal has it highest loading represents the field under study. The other factors can be considered as a set of research fields that are related to the field under study. The lower the number of journals and factors, the more selective the communication network is, and the more codified the communication. The rank of the factor that represents the field under study indicates the dominance of the field within its own communication network (Van den Besselaar and Heimeriks 2001). If this rank is low, the journal has often relative high loadings on other factors, implying that the entrance journal ‘belongs’ to different fields. This can be considered an indicator for interdisciplinarity on the science level. In this study, all factor analyses are performed using SPSS principal component analysis (varimax rotation with Kaiser normalization).

The third dynamic under study in this paper is provided by the societal environment in which the science system evolves. In this study, we focus on the so-called triple helix interactions: the participation of universities, companies and governments in knowledge production as an indicator for knowledge use in society and non-academic research involvement. The triple helix model assumes the traditional forms of institutional differentiation among universities, industries and government as its starting point. The model thus takes account of the expanding role of knowledge in relation to the political and economic infrastructure of the larger society (Etzkowitz and Leydesdorff 2000). Table 1 summarizes the discussion of indicators for dynamics in research, science and society.

5. Results

The seed journals *Biotechnology and Bioengineering*, *Nanotechnology* and *Genomics* were used to delineate the fields. These journals not only have the highest impact factors of the set, they also have the highest factor loadings on the factor indicating the respective fields for most of the years. They can therefore, be considered as a 'central tendency journals' as defined by Cozzens and Leydesdorff (1993). With hindsight, this legitimates our initial selections as the starting point for the analyses.

In nanotechnology, the journals *Advanced Materials*, *Nanotechnology*, *Applied Physics Letters*, *Journal of Applied Physics* and *Nano Letters* are used for our analyses. The field of genomics is composed of the journals *Genomics*, *Genomics Research*, *Nucleic Acid Research*, *BMC Genomics*, *Bioinformatics* and *Genome Biology*. In biotechnology there is a narrow definition of the field consisting of only the three journals: *Biotechnology Progress*, *Biotechnology Bioengineering*, and *Journal of Biotechnology*, and a broader definition interwoven with applications of microbiology. We used the narrow set of journals for further analyses.

After obtaining the set of journals, all the publications for the period 1998–2008 were downloaded from the Web of Science. The total number of articles were 8,617 (biotechnology) 21,833 (genomics) and 84,044 (nanotechnology). In this period, nanotechnology showed the largest increase in the number of publications, from 4,696 in 1998 to 10,823 in 2008.

5.1 Research dynamics

The first set of analyses focused on geographically localized research practices. In all three fields, the average number of authors per paper showed a steady increase in the period under study. In genomics, the numbers increased from 4.69 to 6.03 authors per article on average, while in biotechnology this number increased from 3.60 to 4.61. Nanotechnology showed a relatively modest increase from 4.38 to 5.13.

All three fields are characterized by increasingly pronounced patterns of international collaboration as indicated by the number of articles with authors from more than one country (see Fig. 1). Genomics not only showed the highest proportion of internationally co-authored papers, but it also showed a high increase in collaborations in the period under study: from 60.78% of the publications in 1998 to 74.15% in 2008. Our analyses of the Dutch publications (discussed below) show that in later years more than 90% of the co-authored publications in all fields result from collaborations between different departments.

The departments contributing to the publications provide an indication of the institutional context of research in the fields. We can assume that in general, the disciplinary affiliation of co-authors corresponds to their disciplinary knowledge contribution. Fig. 2 shows the affiliations of the authors of all publications with at least one Dutch address.

Fig. 2 shows that the relative contribution of physics departments to nanotechnology declined slightly in the period of study, while there is an increase in departments of nanotechnology. The relative contributions of material sciences, chemistry and engineering remained fairly constant in the period 1998–2008. The rise of departments of biotechnology that contribute to nanotechnology is interesting, indicating a process of convergence between nano-scale science and the life sciences.

As mentioned, scientific research can be considered interdisciplinary if researchers from at least two different disciplines, according to their departmental affiliation, are involved. Within the field of nanotechnology, almost all papers in the dataset are co-authored by researchers from different types of departments. Furthermore, the variety of departments that substantially contribute to research in nanotechnology is increasing. Looking at the institutional affiliation alone, this indicates an increase in interdisciplinarity.

A different development is visible in biotechnology (see Fig. 2a). In this field the number of collaborators per paper increased in the period under study with almost all papers

Table 1. Overview of levels of analysis and associated indicators

Level of analysis	Relevant concepts	Indicator
Research	Variety of skills and research technologies, institutional settings	Number of contributors, number of departments, types of departments
Science	Journal communication network	Stability and 'informational' closeness of a field
Society	Knowledge use in society, audience plurality and diversity, non-academic collaborators	Out of academia (co-) authors, collaborations between different types of organizations

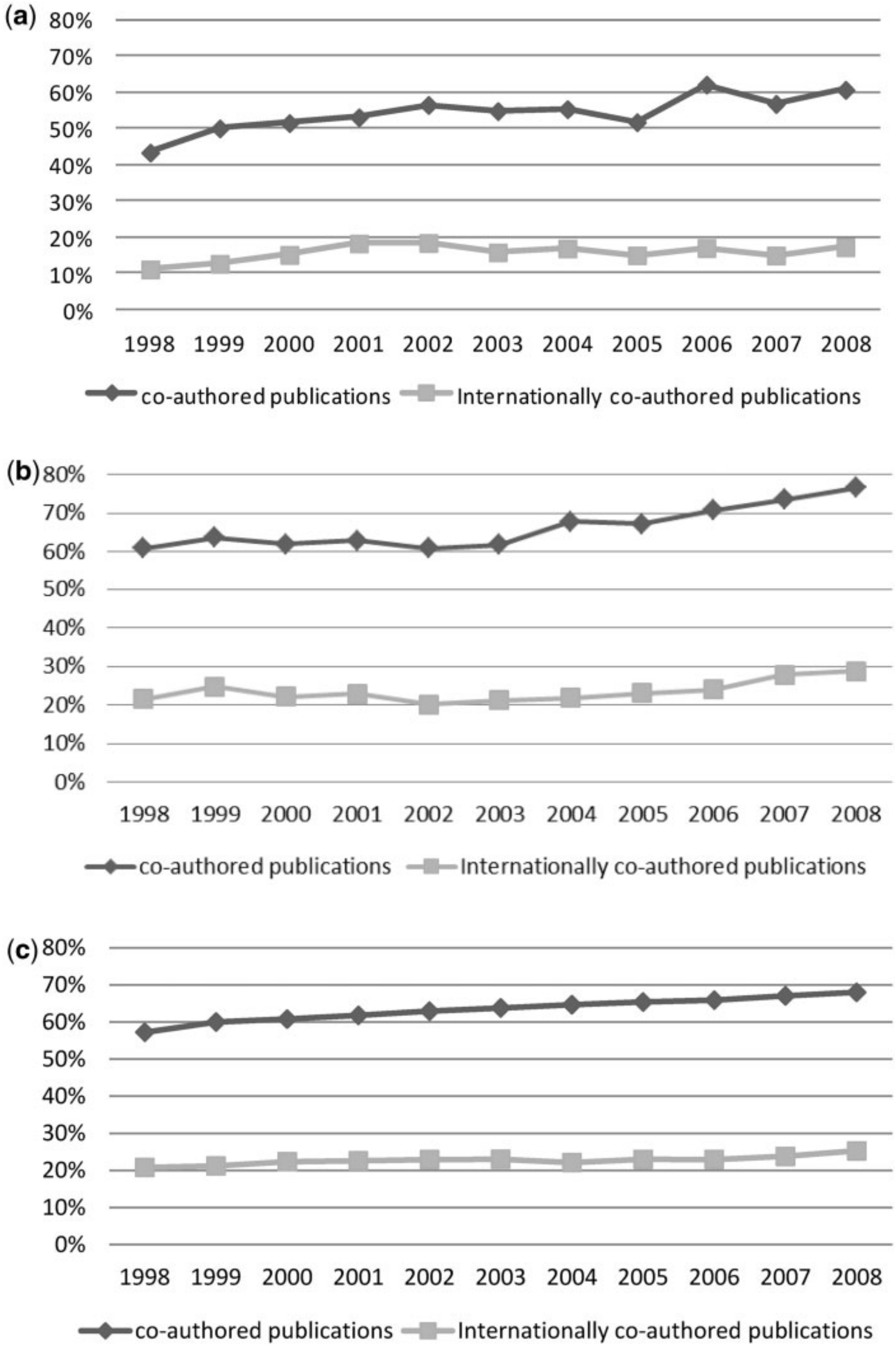

Figure 1. Share of co-authored publications and internationally co-authored publications in period 1998–2008 in: (a) biotechnology; (b) genomics; (c) nanotechnology.

having authors from various academic backgrounds. As in nanotechnology, the number of departments with the name of the field showed a steady increase. However, in the field of biotechnology the institutional variety seemed to decrease, with biotechnology departments becoming dominant in later years. In 2007 and 2008 more than half of the authors' affiliations indicated biotechnology departments.

Genomics (see Fig. 2b) shows a slightly different pattern. Initially, the field was dominated by genome research departments. In later years, the relative importance of departments in biochemistry, medical sciences and especially information science increased. Furthermore, physics departments increased their contributions to genomics research.

5.2 Science dynamics

Section 5.1 discussed interdisciplinarity in terms of the local research dynamics in the fields under study. Having taken these developments into account, a further question deals with the developments at the level of the emergent scientific landscapes. At the science level the fields show very distinct patterns of development as indicated by the journal–journal citation patterns.

Biotechnology is surprisingly stable in terms of its journal structure. In the entire period, among the journals that together define the field of biotechnology, *Biotechnology and Bioengineering* not only has the highest impact factor of the set, it also has the highest

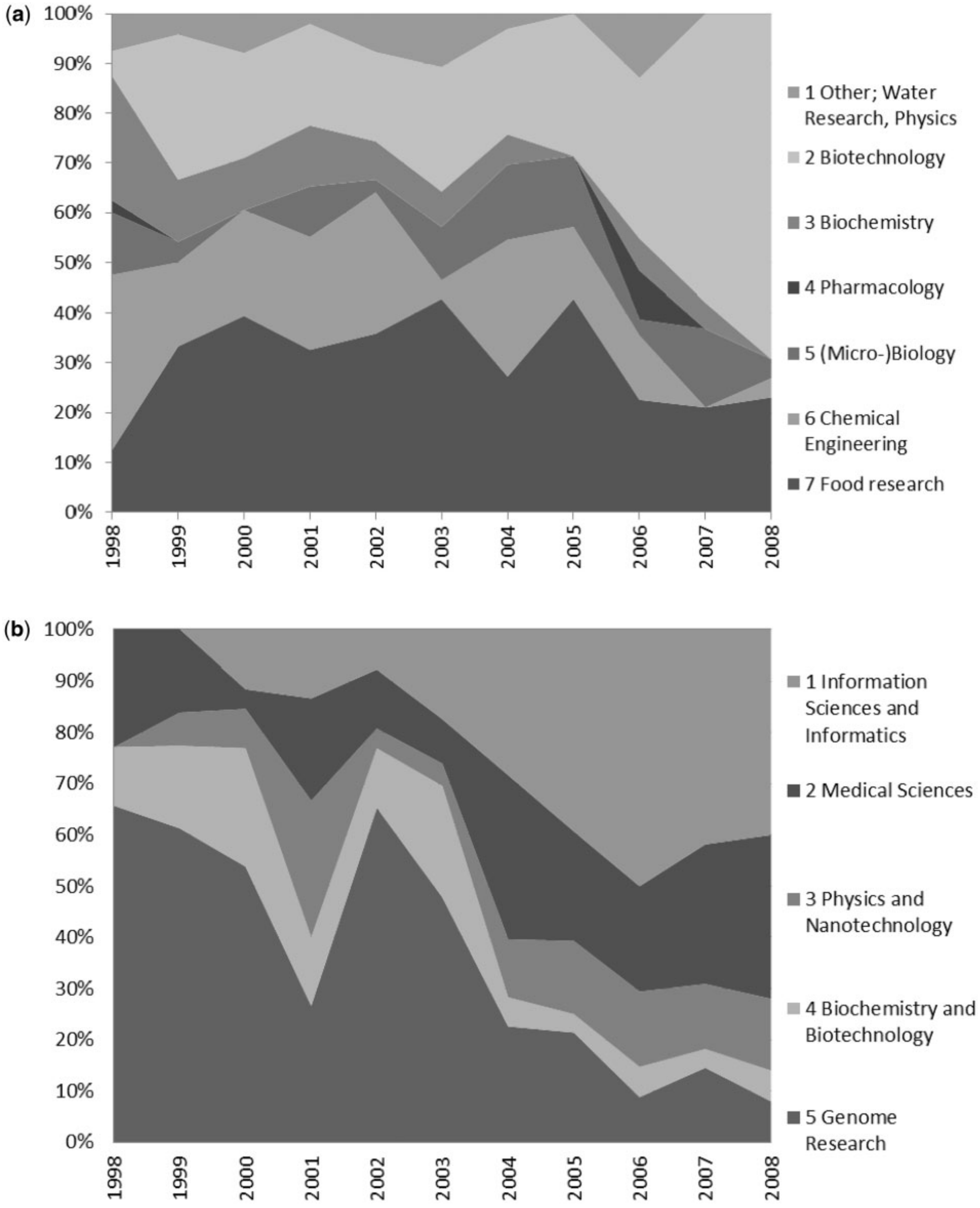

Figure 2. Contributing departments in the Netherlands in the period 1998–2008 in fields of: (a) biotechnology; (b) genomics; (c) nanotechnology.

(continued)

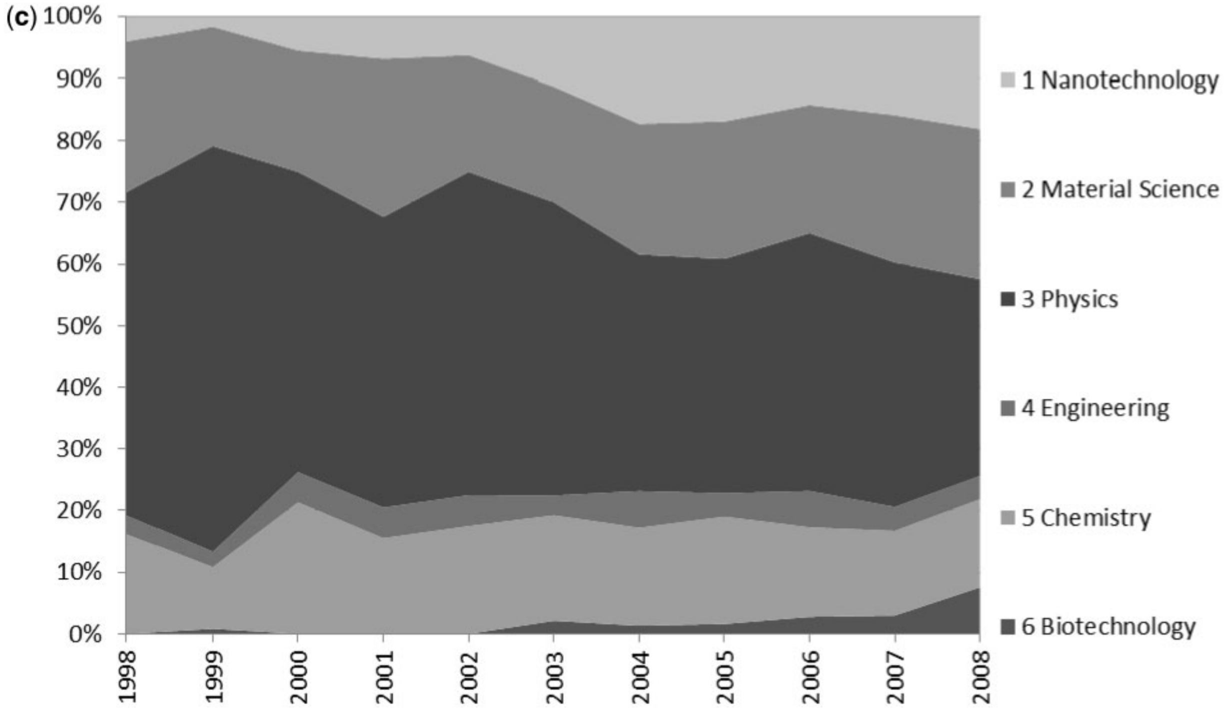

Figure 2. Continued.

factor loading on the factor indicating biotechnology (see Table 2).

Around the field of biotechnology, the neighboring fields of microbiology, water research (including environmental sciences in later years), biochemistry and chemical engineering are to be found in all years. However, the cluster of biotechnology journals grew smaller in the period under study. In the late 1990s, the cluster contained 12 journals, in 2008 that number had shrunk to five.

The journal *Genomics* was launched in September 1987. For a long time, *Genomics* did not represent a field within the journal landscape. In 1998, *Genomics* shows the lowest loading factor in its own factor and at the lowest factor number. This low rank, combined with relative high loadings on other factors, implies that the journal contributes to different fields (see Fig. 3). The rotated component matrix (see Table 3) informs us that SPSS has extracted three independent dimensions from this data.

In 2004, *Genomics* becomes the most important citing journal in its field for the first time. The emergence of bioinformatics facilitated the development of a cluster of journals with *Genomics* as the most important one. The linkages with other disciplines remain stable, although the central position of the field is less prominent since genetics also has ties with the broad group of journals. In the period 2004–7 *Genomics* climbed from the second factor to the first factor, always maintaining a leading position in its own factor. In this period, the field of genomics has developed into a relevant and dominant communication system through the years in the citing dimension. The number of disciplines involved also grew through the years, providing a further indication of a growing and stabilizing field. However, the bioinformatics journals increased in importance and in 2008 the journal *Bioinformatics* took over the highest ranking position within the genomics cluster.

In 2008 the field of genomics evolved from only being dominant in its own field into being dominant in other fields. Together with bioinformatics, the field it plays an important role in the citing pattern of other disciplines (see Table 4).

The results suggest that the relevance of genomics increased through the years, as indicated by the dependency of other fields on the genomics knowledge base through increased citations. The citing pattern of genomics has an interdisciplinary character. Through the period 1998–2008 it became increasingly integrated into its own field.

Nanotechnology does not exhibit disciplinary characteristics in terms of its journal environment in the period under study. The journal *Nanotechnology* was included in the Science Citation Index in 1996. The journal was initially part of the field of ‘applied physics’ journals, but developed increasingly into a central focus of attention within the field of nanotechnology towards the end of the millennium. In the period 2000–3, nanotechnology became a priority funding area in most advanced nations (Leydesdorff and Schank 2008). At the level of aggregated journal–journal citations, this revolution led to a reorganization of the interface between applied physics and physical chemistry, with the *Nanotechnology* journal occupying a position between the two fields.

Table 2. Rotated component matrix of factor analysis of journal–journal citations (2008) in biotechnology

		1	2	3	4	5	6	7
Biotechnology	*Biotechnol. Bioeng.*	**0.94**						
	Biotechnol. Prog.	**0.93**						
	Bioproc. Biosyst. Eng.	**0.90**	0.27			−0.21		
	Biotechnol. Adv.	**0.71**	0.24		0.54	0.24		0.21
	J. Biotechnol.	**0.59**		−0.21	0.41		0.55	
Biochemistry	*Appl. Biochem. Biotechnol.*	0.24	**0.78**	−0.20	0.27			
	Bioresource Technol.		**0.75**	0.34				
	Process Biochem.	0.25	**0.75**		0.31			
	Biochem. Eng. J.	0.53	**0.69**			−0.24		
	J. Chem. Technol. Biotech.	0.24	**0.67**	0.37		−0.20	−0.20	0.22
Water research	*Water Res.*		0.28	**0.94**				
	Water Sci. Technol.		0.23	**0.90**				
	Environ. Sci. Technol.		−0.26	**0.66**				
	Appl. Environ. Microbiol.				**0.94**			
	Appl. Microbiol. Biotechnol.	0.24	0.22		**0.90**			
	Nature					**0.94**		
	Science					**0.92**		
	J. Bacteriol.				0.37		**0.79**	
	J. Biochem.					0.39	**0.76**	
	Proc. Natl Acad. Sci. USA					0.54	**0.70**	
	Biomaterials		−0.35					**0.79**
	Int. J. Hydrogen Energy		−0.30					**−0.66**

Factor analyses reveal that in the entire period under study, the entrance journal *Nanotechnology* shows high interfactor complexity, loading in several factors (most prominently applied physics and physical chemistry, as shown in Table 5). The results shown here are in agreement with the results of Leydesdorff and Schank (2008) who showed that the journal *Nanotechnology* played an important role in the reorganization of interdisciplinary development at the field level. First, the attention of citing journals in the field of applied physics was focused on this journal. Thereafter, chemistry journals began to pay increasingly attention to this field. In 2001 *Nanotechnology*, as a specialist journal, took the interdisciplinary role at this interface over from *Science* which had made this connection in 2000.

In the years after 2000, the *Journal of Nanoscience and Nanotechnology* formed a factor together with *Nanotechnology*, still displaying interfactor behavior. New journals emerged in the years thereafter, among them *Nano Letters*, published since 2001 by the influential American Chemical Society. At the same time, the multidisciplinary journal *Science* began to participate in the fine-grained citation environment of these fields, and the journal *Nanotechnology* lost its catalyzing function at the interface (Leydesdorff and Schank 2008).

5.3 Societal dynamics

In a knowledge-based society, most societal problems require new knowledge developments (Webster 2006), and thus ‘problem-based’ R&D will become increasingly important and encompassing. The perspective of knowledge production is increasingly transdisciplinary—that is, based on external societal perspectives (Etzkowitz and Leydesdorff 2000; Heimeriks et al. 2008). An important indication of the societal context in which the fields develop is provided by the so-called triple helix interactions: the participation of universities, companies and governments in knowledge production. Fig. 3a shows the percentage of publications in biotechnology resulting from collaborations between industry, public research organizations and universities.

Fig. 3a shows that biotechnology is characterized by an increase in triple helix collaborations in knowledge production. In particular, the collaborations between universities and public research organizations represent a growing part of knowledge production in biotechnology. To a lesser extent, university–industry collaborations are of increasing significance, representing 15% of the publications in 2008. Genomics shows a slightly different pattern of triple helix collaborations. University–public research collaborations are overwhelmingly important in genomics research (see Fig. 3b). A small increase is visible in industry–university collaborations in genomics research.

Nanotechnology—the science of the very small—is also likely to have a major economic and social impact in the years ahead. It may help further miniaturize information technology devices, resolve fundamental questions related to the immune system, accelerate advances in genomics, and contribute to the generation of renewable energy. Inventive activities in nanotechnology have risen substantially since the end of the 1990s although the share of

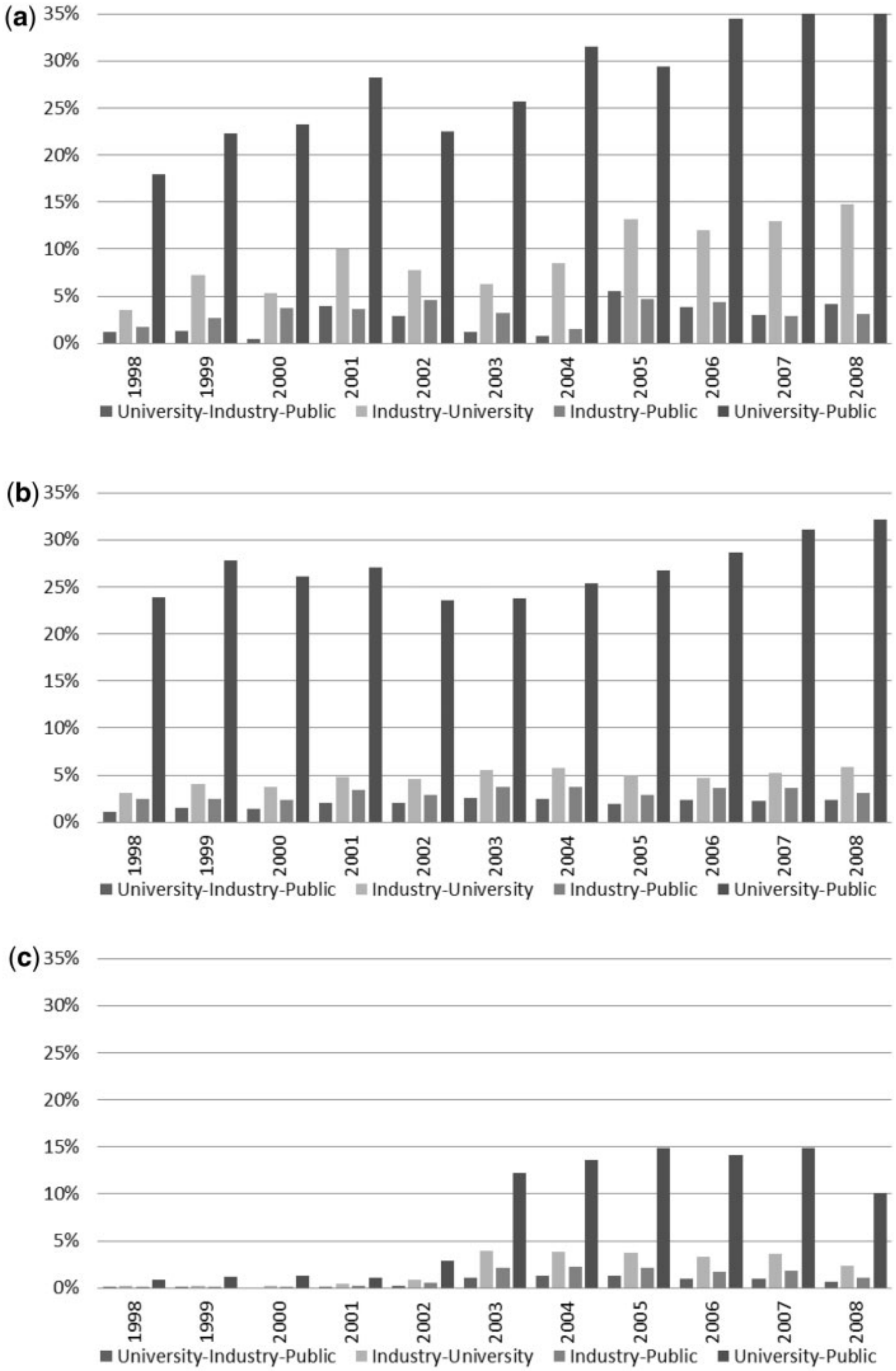

Figure 3. Relative contributions (share of publications) of collaborations among universities, companies (industry) and public research institutes in period 1998–2008 in: (a) biotechnology; (b), genomics; (c) nanotechnology.

nanotechnology in total patenting remains relatively limited (OECD 2009). Coinciding with the transition observed on the science level, in the period 2000–3, when nanotechnology became a priority funding area in most advanced nations, a radical change is visible in the transdisciplinary collaboration pattern (see Fig. 3c).

Prior to 2003, collaborations between different types of organization represented only a very small part of the publications in nanotechnology. However, from 2002 onwards, all triple helix collaborations increase dramatically, especially the university–public research organization collaborations.

6. Discussion

Knowledge is increasingly recognized as a driver of productivity and economic growth, as well as a vital resource in addressing societal challenges (OECD 1996). The

Table 3. Rotated component matrix of factor analysis of journal–journal citations (1998) in genomics

		1	2	3
Molecular biology	*Mol. Cell Biol.*	**0.99**		
	EMB. J.	**0.99**		
	Cell	**0.98**		
	Gene Dev.	**0.98**		
	Nature	**0.98**		
	J. Mol. Biol.	**0.98**		
	Proc. Natl. Acad. Sci. USA	**0.98**		
	Science	**0.96**		
	Cancer Res.	**0.95**		
	J. Cell Biol.	**0.94**		
	Gene	**0.90**		
	J. Biol. Chem.	**0.86**		
	Nucleic Acids Res.	**0.80**		
Human genetics	*Am. J. Hum. Genet.*		**0.94**	
	Hum. Genet.		**0.86**	0.24
	Hum. Mol. Genet.		**0.86**	0.34
	Nat. Genet.		**0.74**	0.47
Genome research	*Mamm. Genome*			**0.93**
	Genome Res.		0.31	**0.85**
	Cytogenet. Cell Genet.	−0.24	0.22	**0.71**
	Genomics	0.64	0.32	**0.65**

Table 4. Rotated component matrix of the factor analysis of journal–journal citations (2008) in genomics

		1	2	3	4	5
Genomics	*Bioinformatics*	**0.97**				
	Genomics	**0.90**				
	BMC Bioinformatics	**0.89**	0.39			
	Gene	**0.87**			−0.20	
	Genome Res.	**0.83**		−0.16	0.30	0.29
	Nucleic Acids Res.	**0.78**	0.25	0.51		
	BMC Genomics	**0.77**	0.47	0.41		
	Genome Biol.	**0.69**	0.66			
General	*Science*		**0.95**	0.27		
	Nature		**0.93**	0.31		
	Mol. Biol. Evol.	0.41	**0.69**			0.55
Molecular biology	*J. Biol. Chem.*			**0.97**		
	Cell		0.50	**0.85**		
	Gene Dev.		0.46	**0.81**		
	Hum. Mol. Genet.		0.27	**0.76**	0.46	
	Proc. Natl Acad. Sci. USA		0.70	**0.70**		
	Nat. Genet.				**0.99**	
	Am. J. Hum. Genet.				**0.92**	
	Genetics		0.35			**0.88**
	Nat. Rev. Genet.				0.52	**0.79**

interdisciplinarity of new developments in science is thus increasingly relevant for science and innovation policy. For example, nanotechnology research is believed to be converging and connecting different areas of science and technology (Roco 2005, 2008; Porter and Youtie 2009). As Porter and Youtie (2009) state, this convergence trend has important policy implications for nano-scale science in particular and emerging techno-sciences in general. Existing disciplinary structures do not sufficiently reflect the potential benefits of intellectual synergy in interdisciplinary projects. Widening interest in these issues has made both funding agencies and scholars increasingly concerned with how to conceptualize and measure interdisciplinarity.

This concern is particularly relevant for emerging fields like nanotechnology and life sciences with a strong context of application. Life sciences and nanotechnology have been presented in the policy discourse as intrinsically interdisciplinary, requiring collaborations among researchers with different backgrounds, and specific funding schemes supporting knowledge-integration activities (Rafols and Meyer 2007). Early bibliometric studies supported this interdisciplinary vision (Meyer and Persson 1998), but recent results suggest that nanotechnology is a loose collaboration between various mono-disciplinary sub-fields (Schummer 2004). The analyses presented here are in line with the claims of Rafols and Meyer (2007) in their study on bio-nanotechnology, that different patterns of interdisciplinarity can be found in journal publication patterns compared to the institutional dimensions (affiliation and collaborations).

However, most existing conceptualizations of interdisciplinarity insufficiently address the different dynamics in knowledge production. We argue that, in addition to horizontal disaggregation (the differences between fields and their interactions), we need to take the vertical disaggregation of knowledge dynamics (mechanism of change in different dynamics) into account in order to understand interdisciplinarity. This dynamic aspect is important because the fields are characterized by distinct co-evolutionary processes over time in research, science and society which are not necessarily occurring simultaneously. We expect that older, more established fields will be characterized by more stable patterns over time, in which research activities, publication patterns and socio-economic dynamics are more aligned. However, further research remains necessary on this issue.

From a policy perspective, this conceptualization provides different rationales for interventions related to the dynamics identified at the three levels of analysis. The analysis presented here suggests that these (combinations of) interventions are likely to have different effects in different fields. Research policy needs to address not only different dynamics, but also the interactions between local research practices, the scientific landscapes, and the field's relationship to its societal context.

Policy interventions in research practices can stimulate interdisciplinarity through localized collaboration patterns, human resource developments and GPT in order to strengthen local research capabilities. On the science level, thematic programs can introduce new dynamics in

Table 5. Rotated component matrix of factor analysis of journal–journal citations (2008) in nanotechnology

		1	2	3	4	5	6	7
Chemistry	*Chem. Mater.*	**0.92**						
	Adv. Mater.	**0.90**				0.23		
	J. Mater. Chem.	**0.89**						
	J. Phys. Chem. C.	**0.63**			0.63	0.23		
	Langmuir	**0.53**			0.25			−0.37
Physics	*Phys. Rev. Lett.*		**0.93**					
	Phys. Rev. B		**0.90**					
	Nature		**0.87**				−0.32	
	Science		**0.77**				−0.47	
Applied physics	*J. Appl. Phys.*		0.22	**0.93**				
	Proc. Soc. Photo-Opt. Instrum. Eng.			**0.93**				
	Appl. Phys. Lett.		0.24	**0.90**				
	J. Phys. D Appl. Phys.	−0.21		**0.65**				
	Chem. Phys. Lett.				**0.91**			
	J. Phys. Chem. B	0.48			**0.80**			
	J. Am. Chem. Soc.	0.35			**0.54**		−0.39	
Nano technology	*Nanotechnology*	0.24		0.26		**0.75**		
	J. Nanosci. Nanotechnol.					**0.74**		
	Nano Lett.	0.53	0.22		0.27	**0.55**		
	Mater. Lett.						**0.73**	
	Appl. Surf. Sci.			0.32			**0.70**	−0.19
	Cryst. Growth Des.							**0.90**

the scientific publication landscape and governments can influence the direction of scientific developments by articulating specific knowledge goals, for example addressing grand societal challenges. Furthermore, policies regarding non-academic collaborators can contribute to knowledge-based economic and social development.

Our analysis shows that changing research practices can provide a driving force for changing disciplinary publication patterns as was indicated by increased collaborations and possibly globalizing (general purpose) technologies and tools. According to Shinn (2005), the innovative feats of GPT derive from their capacity to reconcile differentiation and integration, while simultaneously promoting interaction between heterogeneous environments and linked to diverse interests. Research technologies breed a new constellation of intellectual and institutional transverse dynamics which selectively accommodate both stability and change. In this respect, the rise of biotechnology departments that contribute to nanotechnology is interesting, indicating an interdisciplinary process of convergence between nanoscience and the life sciences facilitated by GPT.

Furthermore, the results indicate interdisciplinary convergence in the context of application. In our knowledge-based economies, socio-economic developments are directly based on the production, distribution and use of knowledge. This development is indicated by the rising number of non-academic contributions that provide an important source of knowledge for researchers' innovative processes. A growing number of public research organizations and companies (most notably Hitachi and BASF) are involved in all three fields. The intensity of knowledge use in society and the importance and variety of non-academic collaborators further contributes to the development of disciplinary identities. The role of governmental and commercial organizations, for example, played an important role in the reorganization of the field of nanotechnology.

7. Conclusions

In this paper we proposed a conceptualization of different forms of interdisciplinarity by introducing different dynamics of knowledge production in research, science and society. The approach is useful, although additional analysis regarding its robustness remain necessary. Empirical examples in genomics, nanotechnology and biotechnology show that interdisciplinarity relates to distinct dynamic developments that interact and shape each other in a process of co-evolution, giving rise to different patterns of interdisciplinarity in each field.

Biotechnology is characterized by research collaborators among various academic backgrounds. However, the institutional variety in research seems to decrease as biotechnology departments become increasingly dominant. At the same time, biotechnology is surprisingly stable in terms of its journal environment. Around the field of biotechnology, the neighboring fields of microbiology, water research, biochemistry and chemical engineering are to be found in all years. However, the number of biotechnology journals has grown smaller in the period under study, revealing stronger disciplinary characteristics in its journal citation patterns. Furthermore, biotechnology is characterized by increasing transdisciplinarity as indicated by the triple helix collaborations in knowledge production. In particular, the collaborations between universities and public research organizations represent a growing part of knowledge production in biotechnology.

Genomics was initially dominated by genome research departments. In later years, the relative importance of departments in biochemistry, medical sciences, physics and especially information science increased, while genomics departments become relatively marginal in number of author affiliations. On the journal level however, genomics emerged as disciplinary set of journals around 2004, facilitated by the rise of bioinformatics. University–public research collaborations are an important mechanism for introducing societal drivers in genomics research.

Within the field of nanotechnology, the number of nanotechnology departments increased. However, almost all papers in the dataset are co-authored by researchers from different types of departments. Nanotechnology did not exhibit disciplinary characteristics in terms of its journal environment in the period under study. In the period 2000–3, nanotechnology became a priority funding area in most advanced nations. At the level of aggregated journal–journal citations, this led to a reorganization of the interface between applied physics and physical chemistry, with the *Nanotechnology* journal occupying a position between the two fields. Coinciding with the transition observed on the science level, a radical change is visible in the collaboration pattern, especially with respect to university–public research organization collaborations.

Genomics, nanotechnology and biotechnology all show changing interdisciplinary characteristics in relation to distinct co-evolutionary processes in research, science and society which are not necessarily occurring simultaneously. The analyses show how new institutional research settings emerge in response to developments in research practices, the science landscape and external, societal drivers. The number of departments carrying the names biotechnology and nanotechnology is increasing, while the number of genomics departments is decreasing. The research contributions originating from these departments, in turn, change the science landscape to which researchers and organizations respond in different ways within the different fields.

The emergence of stable publication patterns in biotechnology was reproduced through local research traditions and the institutional organization of teaching and research as indicated by departmental affiliation. At the same time, genomics emerged as a stable discipline in journal citation patterns while the number of genomics departments declined. Nanotechnology maintained an interdisciplinary journal citation pattern while the number of nanotechnology departments increased and the collaborations with industry and public research organizations intensified.

We showed that interdisciplinarity has to be studied more broadly than in most existing studies, as a combination of dynamics that co-evolve. Interdisciplinary knowledge dynamics involve both dynamics in local research practices and cognitive developments in publication patterns, and both these phenomena should be reflected in any measure or assessment of interdisciplinarity. Furthermore, as Wagner et al. (2011) argue, interdisciplinarity emerges within the dynamics of a larger knowledge system, which increasingly includes external, societal drivers. Patterns of interdisciplinarity can thus be distinguished, as different ways in which the three dynamics co-evolve.

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