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DETECTING AND VALIDATING GLOBAL TECHNOLOGY TRENDS USING QUANTITATIVE AND EXPERT-BASED FORESIGHT TECHNIQUES

BASIC RESEARCH PROGRAM
WORKING PAPERS

SERIES: SCIENCE, TECHNOLOGY AND INNOVATION

WP BRP 82/STI/2018

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DETECTING AND VALIDATING GLOBAL TECHNOLOGY TRENDS USING QUANTITATIVE AND EXPERT-BASED FORESIGHT TECHNIQUES[5]

This paper contributes to the conceptualisation and operationalisation of the “technology trend” discussion in the scope of the Technology Foresight paradigm. It proposes a consistent logical approach to analysing technology trends and increase predictive potential of futures studies. The approach integrates Big Data analysis into the Foresight studies’ toolset by means of applying text mining, namely computerised analysis of large volumes of unstructured text-based industry-relevant analytics. It comprises methodological results such as analytical decomposition of the trend concept, including trend attributes (inherent characteristics) and various trend types and empirical results of detection and classification of global technology trends in the agricultural sector. The study makes a significant contribution to the development of a conceptual apparatus for trend analysis as a sub-area of Foresight methodology. The agricultural field is used to demonstrate the application the methodology. The empirical results can be applied by federal and regional authorities responsible for promoting development of the sectors to design relevant strategies and programmes, and by companies to set their long-term marketing and investment priorities.

Keywords: technology trends, innovation, science and technology forecasting, science and technology progress, foresight, text mining, survey, bibliometrics, patent analysis

JEL: C55, O1, O3

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[5] The working paper was prepared within the framework of the Basic Research Program at the National Research University Higher School of Economics (HSE) and supported within the framework of a subsidy by the Russian Academic Excellence Project '5-100'.

Introduction

Initially, the "trend" concept was applied in mathematics to denote generalised characteristics of functions' behaviour in specific intervals (for example, Arlinghaus, 1994). Various linear, logarithmic, and exponential equations are used in mathematics to calculate trends. Subsequently this concept was borrowed, at first for use in quantitative economics techniques to describe and forecast financial and economic developments (for instance, Bianchi et al., 1999), and then in socio-economic sciences generally, in a loose sense as any pronounced tendency (Bertrand & Corty, 1962). Among other things the concept of trend was increasingly used in such senses as, e.g., dominating vector of a political discourse (among the recent examples is Habermas, 2015), or topic of public debates prevailing for a rather long time (Glynn, 2018), etc.

"Technology trends" traditionally come as concepts of *trend*, *megatrend*, and *global trend* are applied in studies as artefacts , firstly, which are considered given but not requiring any specific explanations, and secondly, as synonymous (see for example, Mudd, 2010; Khanna, 2012; Koh & Ng, 2016; Ouma, 2016). These concepts and terms aren't analysed but even the desire for this need remains unrecognised. Analytical materials users are guided by the context and general semantic logic, understand global trends as series of unidirectional incremental changes about which it is known that they either were steadily growing for a certain period of time (from a few months to many years), or there are reasons to expect them to steadily grow in future.

"Technology trend" conceptualisation in quantitative research is frequently aligned to Big-Data analysis related concepts. Numerous Big Data-related studies are also devoted to trends (understood approximately in the same sense as Foresight practitioners understand them), first of all text mining studies (to name a few: Lee, 2008; Sungchul et al., 2011; Shang et al., 2011; Kim et al., 2012; Feng- Hyunseok et al., 2013; Byunghoon et al., 2014; Janghyeok et al., 2014; Zhang et al., 2014; Chen, 2014; Wang et al., 2015). Though they usually do not include definitions of the trend concept, the context of deliberations on how trends can be detected using computerised text mining techniques occasionally allows to make important conclusions about how the authors understand the terms "trend" or "technology trend". Wang et al. (2015), speaking about the importance of identifying technology trends and the need to apply for this purpose not only statistical text processing but semantic analysis techniques, never define a technology trend – probably because this concept seems to be self-evident to them. However, the context suggests that for the authors technology trends are synonymous with, on the one hand, technology tendencies, and on the other, technological development trends. The latter are understood as the process of technological innovation. Important technology trends' properties in the authors' understanding include possibility/impossibility of their implementation, and presence/absence of actors contributing to/enabling such implementation. The phraseology employed by the authors to review literature allows to conclude that they believe in both actually emerging and potentially possible (future) trends; the latter may be theoretically predicted, which is exactly where text mining trend analysis techniques come in, and why they should be developed. Finally, the authors perceive technology trends as something actually existing and requiring identification – as opposed to an arbitrarily constructed notional category. On the whole, implicit consensus among various researchers can be detected regarding the nature of technology trends. The research community does not see trends as artificial scientific tools (like, e.g., taxons) – which cannot be said about, for example, technology classifications.

Other studies devoted to quantitative trend detection techniques include approaches to the application of simple algorithms for calculating text statistics (Byunghoon et al., 2014); more complex algorithms allowing to identify semantic structures and conduct network analysis (Lee, 2008; Sungchul et al., 2011; Janghyeok et al., 2014); complex analytical approaches combining bibliometric and patent analysis, on the one hand, and computerised text mining, on the other (Feng-Shang et al., 2011); application of the so-called patent maps and patent networks (Hyunseok et al., 2013; Zhang et al., 2014); building multiple modular trend detection and analysis systems (Kim et al., 2012); and systems integrating semantic text analysis with statistical data obtained from various sources (Chen, 2014).

Obviously, further development of conceptual and terminological apparatus for trend analysis purposes was not the main objective of the abovementioned Big Data-related studies. They were primarily aimed at discovering efficient techniques, i.e. ones which would allow to save experts' time, and reduce relevant qualification requirements, to identify facts representing various analytical categories such as trends, technologies, important research areas, etc.

Technology trends detection and validation techniques are sufficiently well covered in relevant literature (Mühlroth & Grottke, 2018; Ena et al., 2016; Dotsika & Watkins, 2017; Ondrus et al., 2015; Afanasyev et al., 2014). Authors usually agree to divide techniques into expert-based and quantitative ones (Popper, 2008).

Various techniques, beginning with aggregation of expert opinions, and numerous indicators, qualitative and quantitative ones, can be applied to detect and validate trends. Sources of data for these indicators comprise a wide range of resources such as collections (volumes) of texts for text mining, including texts from social networks, web pages, news agencies, etc.; statistical data sources; bibliometric (general ones such as, e.g., Web of Science or Scopus, and specialised such as Medline, etc.) and patent databases (such as United States Patent and Trademark Office (USPTO), European Patent Office (EPO), Japan Patent Office (JPO), etc.), etc. Examples of indirect technology trend indicators include data about public support provided in specific subject areas (Pardo & Calvo, 2002; Meckin & Balmer, 2017); amounts and areas of investments by private and public companies, including venture capital investments (Dranev & Chulok, 2015; Kaminski et al., 2016); emergence of new market players (Segers, 2015); extended geography of research and development (Keeble & Wilkinson, 2017); emergence of new professions (Marty, 2014; Mezzana, 2018); new R&D infrastructures (Hayter & Link, 2015), etc. Other sources of data for technology development monitoring include: news media (Daim et al., 2006); business information resources (such as, e.g. LexisNexis database) (Porter & Cunningham, 2005); reports of venture funds, startup companies, etc. (Cozzens et al., 2010); conference proceedings (Porter & Cunningham, 2005), etc.

A tool for measuring technology readiness level (TRL) can be applied to identify technology trends' development stages, with certain modifications (EC, 2014). Originally it was developed by the NASA and adapted by the US military to coordinate and manage innovative high-technology projects (see for example, Fast-Berglunda et al., 2014; Straub, 2015). However, if project management covers all aspects down to individual technological processes, analysing country-specific and especially global technology trends implies certain generalisation, implicit and fuzzy classification of thousands of technological processes into such groups as “technological solution”, “technology”, “group of technologies”, etc. Therefore in the course of technology trend analysis the TRL scale should be used carefully, and probably in the framework of expert-based techniques. A possible approach would be to ask experts to assess the technology readiness level of, primarily and most likely, technological solutions which constitute a specific trend.

Main data processing techniques for validating (as well as monitoring) global technology trends are bibliometric and patent analysis (Popper, 2008); in numerous studies they are used in combination with such supplementary methods as network analysis, clustering, trend analysis, etc. (to name a few: Dotsika & Watkins, 2017; Sungchul et al., 2011). Specific range and variety of relevant techniques depend on the type of technology trends researchers are trying to identify, and various other factors.

Citation analysis as a bibliometric technique is commonly applied to process structured data. The level of documents’ (publications, patents, etc.) citation may indicate emergence of new research areas (fronts) reflecting promising technology development areas (Igami & Saka, 2007; Kim et al., 2008; Morris et al., 2002; Upham & Small, 2010; Chen, 2016; Shibata et al., 2008; Kajikawa et al., 2008; Noma, 1984). Apart from citation, other technology trends monitoring techniques may include analysis of structured data provided in documents’ bibliometric characteristics, such as keywords (Kim et al., 2008; Cobo et al., 2011; Guo et al., 2011); organisation names; authors; titles; abstracts (Morris et al., 2002); classification groups (Spasser, 1997), etc.

Monitoring patent activity allows to determine the current stage of technologies’ life cycle, and assess the level of competition (or partnership) between companies operating in relevant industries. Patent analysis is oriented towards practical forecasting, and typically serves as a basis for decision-making in the public and private sectors (Amy & Charles, 2008). It can help to assess the status of the technology under consideration – emergence, maturing, or decline. The growth rate of the number of patents related to a specific technology typically tends to match the relevant trend, along an S-like curve. At early technology development stages the number of patents is small; then comes a period of rapid growth when both the number of patents and the range of their application areas rapidly increase until the development potential is exhausted (Amy & Charles, 2008). Data on the number of patent applications, grants, and withdrawn, cancelled, or expired patents can provide a more thorough understanding of technologies’ development stages.

In most cases the authors kept aggregating expert evaluations – which is clearly demonstrated by, e.g., Newman et al. (2014). Therefore, it should be concluded that computerised text mining techniques are still not sufficiently developed, and only allow to perform semi-automatic procedures which require significant expert input (which was unequivocally stated by the authors of the abovementioned study). Accordingly, it would be premature to talk about a revolution in validation – i.e. moving on from expert evaluation of computerised analytics to verifying experts’ qualifications and opinions on the basis of computerised analysis results.

On the whole, our literature review indicates that more precise definitions of concepts and terminology applied for trend analysis purposes in futures studies, including the “technology trend” concept in Foresight studies, and a more thorough substantiation of tools researchers use to detect such trends and validate the results, would not only contribute to further development of futures studies’ methodology but also help adopt a common language for use in industry-specific studies of history, current state, and future prospects of relevant industries.

Operationalisation of the “technology trend” concept defines a trend as a directed systemic change of quantitative and qualitative parameters of an external to the humankind environment, or of the anthroposphere. A classification of trends based on the STEEPV(LD)+ system is reasonably sufficient for futures studies purposes, i.e. dividing trends into social (including demographic), technology (science and technology), economic, environmental, political (including normative and legal), and value (i.e. cultural and mental) ones, with a possibility to add other groups as the need arises (e.g. genetic or phenotypic trends in living nature, etc.). By “technology trends” directed systemic changes in the science and technology sphere which lead to emergence of new, or modifications of existing technologies, or (in environments with predominantly adverse socio-economic changes) result in loss of technologies is understood. “Ttechnologies” are sets of codified knowledge about ways to manipulate matter, energy, and information to accomplish specific practical objectives. It should be noted that in the general case, research trends may differ from science and technology (or, synonymously, technology) ones, because whole areas of science exist where a significant proportion of research is not directed at developing technologies (e.g. historical and cultural studies). However, in the Technology Foresight domain which includes only technology-related research fields there is no need to distinguish between research and technology trends.

In the authors’ opinion, a major inherent characteristic of trends, including technology ones, is their development stage (anticipated, emerging, mature, declining, and past trends; more stages can be suggested depending on specific objectives of the study). Another attribute of trends is their intensity (concentration in time). At the one end of the scale there are slow, practically invisible evolutionary processes (e.g. gradual increase of the average growth rate of the human population), at the other – catastrophic sequences of events occurring in a few months’, or even weeks’ or days’ time (e.g. a stock exchange crash, or a major pandemic). Of course the question about the scope of a trend remains open, i.e. when events should be considered as isolated (“black swans”, wild cards, etc.) and when the trend is so slow it must be considered as a permanent external condition, a practically constant characteristic of the external environment (e.g. the slow proliferation of HIV/AIDS, the very gradual rise of the sea level, or finally, the extremely slow, only perceptible on the millions of years scale increase of the Sun’s brightness). A quite wide range of interpretations can be suggested here, again depending on the objectives and scope of specific studies.

This study is devoted not only to improving the conceptual apparatus applied for trend analysis in Foresight studies to reach a certain (definitely not the ultimate) level, but also to practical testing of the global technology trend concept as a specific analytical tool, using the agricultural sector (AS) as an example.

The study's originality and scientific value primarily amount to operationalisation of the "trend" and "technology trend" concepts for application in Foresight studies; a more precise definition of the scope for trend analysis as a Foresight category; and a suggested system of substantiated formal requirements to describing technology trends. These results not only contribute to further development of the emerging Russian Technology Foresight school (Sokolov & Chulok, 2016; Gokhberg & Sokolov, 2017), but have a significant scope for practical application in the National Technology Foresight System which is currently being established in the Russian Federation (by the decree of the President of the Russian Federation N596 "On the long-term national economic policy", May 12, 2012). They enrich methodology for conducting national-level and industry-specific S&T Foresight studies, and adjusting their results. The conceptual results of the study may also be of interest to Foresight practitioners (and more broadly, futures scientists) on the international level. At the same time the empirical results will be interesting to decision-makers in the agricultural sector, both in the public and corporate domains.

The paper is structured as follows: the Methodology section includes a conceptual and terminological analysis, presents a decomposition of the trend concept, and a justification of formal requirements to describing trends and a number of practical testing techniques and the sequence they should be applied in to test the proposed conceptual scheme. The Results section describes the key empirical results of the study, including a list of global technology trends and the results of their bibliometric and expert-based validation. The Conclusions gives a brief summary of the main results of the study, estimates practical applicability and limitations of the proposed methodology, and outlines possible areas for further research.

Methodology

In this study we concentrate on global technology trends, i.e. major, primarily future-oriented trends present in many countries. The "future-oriented" property means we are mostly interested in trends which will make the biggest impact on the future shape of the economic sector under consideration, in this case agriculture (i.e. relevant structures, functional interconnections of various subsystems, and the latter's roles in larger systems). Accordingly, specific trends have or have not been included in the quite short final list (the first few dozens of identified trends) on the basis of their growth potential in the foreseeable future, or their ability to engender new important trends, or promote growth of emerging trends (formal requirements see in subsection 1 below).

Detecting these trends in the first place, and *selecting relevant keywords* for quantitative analytical methods was possible on the basis of an expert review of analytical literature on the agricultural sector (AS) and 22 in-depth expert interviews (8 interviews with representatives of the Ministry of Agriculture of the Russian Federation – directors and deputy directors of the Departments; 6 with directors, rectors and vice-rectors of agricultural scientific centres and leading researchers; 8 with industrial managers and business associations representatives). The sample of experts was formed with the so-called "snowball" method when respondents recommend other participants for interviews. These steps were combined with computerised processing of large volumes of unstructured or minimally structured textual data, around one hundred of thousands of full-size analytical documents both in English (primarily) and in Russian (details see in subsection 2).

Developed analytical apparatus was tested on materials of more than 200 questionnaires filled in by the surveyed experts, with both open and closed questions about global technology trends in the AS (details see in subsection 3) during the Science and Technology Foresight Study of the Russian Agricultural Sector (Gokhberg & Kuzminov, 2017; Gokhberg et al., 2017).

After that innovative Big Data-based approach developed by the authors (Bakhtin et al., 2017; Kuzminov et al., 2018) included a dynamic comparative analysis of international patents and academic publications using sets of keywords representing the identified technology trends. The whole study algorithm is described in subsection 4 below.

1. Formal requirements to naming and describing global technology trends

Apart from actually identifying technology trends, it is important to present them in a format that would allow avoiding misinterpretation or double meaning. Also, describing technology trends in line with established formal requirements (based on the operationalised trend concept) would serve as an additional validation tool. E.g. an initial trend list may include descriptions which could only represent technologies or technology groups, but not trends. In that case the wording should be changed after answering several specific questions such as, e.g., is there any evidence that the technology in question is developing, or its application area is extending, or its sales are growing? Or maybe all such aspects remain constant and in reality there is no movement, change, or transformation – which are inherent attributes of a trend?

The following set of formal requirements to describing global technology trends is suggested:

1. Trend description by the specialist must include a reference to some kind of dynamics reflecting new elements, while also mentioning already known ones. For example:
   - changes in the level of the technology's coordination (automated process, semi-automated process, non-automated process);
   - changes in the technology's components (poly-, mono-);
   - further sophistication/improvement of the technology, or, on the contrary, simplification of technological processes it comprises;
   - changes of relevant running costs (increase or decrease);
   - substitution/replacement of one technology by another.

2. Trend description must match certain syntactic and semantic criteria (see them in the next subsection).

2. Quantitative analytical methods applied

Syntactic-semantic analysis is an area of in-depth textual analysis aimed at identifying semantic meaning of the text. Syntactic-semantic analysis implies syntactic analysis of word links; analysis of properties and functions of words in the sentence; retrieval of triplet subject-action-object linkages, etc. At the core of this text processing stage lies syntactic analysis of linkages between words in the sentence. Word dependency chains are identified for all words in the sentence on the basis of linguistic rules, common heuristics, and machine learning models (see for example, our previous works: Bakhtin et al., 2017; Kuzminov et al., 2018). Analysis of properties and functions of words in the sentence (property-function analysis) amounts to identifying such linkages for every significant noun in the sentence, which determine their properties and functions. Such linkages are believed to be the basis of meaningful terms (i.e. words and phrases each of which are individually important for understanding the meaning of the text and meeting relevant needs of experts (such as detecting current trends, emerging technologies, prospective markets, etc.).

Retrieval of triplet subject-action-object linkages (subject-action-object analysis, SAO) is the process of retrieving basic meaning of sentences describing certain objects' manipulations with other objects. By "subjects" and "objects" are meant the terms identified at the properties analysis stage, while "actions" mean functions which describe interaction between the terms (e.g. *"information system includes analytical module"*).

The above algorithms allow to sufficiently accurately and precisely identify meaningful terms in any textual data sample; create ontologies of S&T and economic topics; collect and aggregate primary data for practically any kind of highly specialised targeted industry-specific analysis.

In this way, in terms of helping experts to learn and more quickly digest meaningful information, automated data retrieval and text mining techniques are becoming extremely important tools. In order to speed up and deepen experts' immersion in the subject field in the course of this study experts were given the following analytical samples: ranked n-gram lists; extracted quantitative forecasted estimates; extracted first mentions of new technological or organisational solutions; clustered technology-oriented concepts. An example of the latter is given in Attachment A.

3. Expert polling description

At the same time the authors of this study hold an opinion that given the current development level of information technologies (which is clearly insufficient for full-fledged semantic analysis of texts and computerised synthesis of meanings), text mining or other Big Data analytical tools cannot yet fully replace experts when it comes to studying existing trends or creating visions of future socio-economic systems (or their specific components). Therefore, expert polling validated the results of the text-mining methods.

The survey designed to identify relevant technology trends was conducted between 1–7 December, 2015. . The form of the questionnaire with explanations was sent by e-mail to the administration of 54 Russian agricultural universities with a cover letter signed by the Deputy Minister of Agriculture of the Russian Federation with a request to organize the participation of leading researchers in the survey. It is important to note that the sample was formed spontaneously: at the first stage, the management of the institution decided to involve its employees in the survey (we received questionnaires back only from 30 universities), then the administration of higher educational institutions decided which of the employees to send the questionnaire to be filled in. 213 completed questionnaires were received and processed. The respondents included 87 PhDs and 126 Doctors of Science (6 of them members of the Russian Academy of Sciences). The average work experience of the experts surveyed in the field of the agrarian industry was 27 years (the maximum work experience was 55 years), a quarter of respondents had 15 years of work experience and less, more than 30% of respondents had at least 35 years of experience in the agricultural sector

The key results of the survey, and their quantitative validation are presented in Attachments B and C. These include the experts' estimates of specific time horizons when the trends' effects were expected to fully emerge (trend implementation), the trends' importance to Russia, and the nature of this importance (for each trend included in the questionnaire, see table B.1). In addition to 31 trends suggested by the authors and included in the questionnaire, the experts proposed 32 other trends (see table B.2) many of which did not match the formalised technology trend definition and trend description requirements suggested by the authors of this study (see above). It should be noted that these requirements were not made available to the surveyed experts. The fact that the experts frequently named various static states, or problems which they believed had to be dealt with, as trends (together with steps the authorities should take, technologies, socio-political institutions or concepts, etc.) indicates that the concept of trend remains very much ambiguous not only in the mass consciousness, but also among members of the scientific community who are not engaged in futures studies. It is yet another evidence of this study's practical value, in terms of making a contribution to developing the conceptual and terminological apparatus for trend analysis for futures studies purposes. Table C.1 consists of a comparative brief description of trends development stage based on bibliometric and patent analysis conducted as well as on expert polling.

4. The study algorithm

1. In the course of this study experts responsible for drafting keyword lists were provided with ranked lists of n-grams (uni-, bi-, tri-, and quadrigrams, separately) generated by processing around one hundred of thousands of agriculture-related analytical documents, including FAO, OECD, USDA, Springer Books, MarketLine and other publications covering a period of more than ten years, using proprietary HSE ISSEK's text-mining algorithms.

Since ultimate data sources for bibliometric/patent analysis comprised databases of academic papers' and patents' metadata, they were not used during computerised generation of keyword lists to avoid the hard-to-predict, at the current stage, positive feedback effects, or "vocabulary resonance". As to resulting n-grams, technically they should be called skip-grams since they were generated after clearing the texts from auxiliary words (prepositions, conjunctions, articles, interjections) using standard, readily available algorithms. However, the skip-gramming was limited because, e.g., we did not remove verbs from the texts, so the n-grams did not include only noun phrases. Stemming was applied to generate lists of n-grams (using standard tools), with subsequent dynamic lemmatisation using HSE ISSEK's proprietary algorithms. Dynamic lemmatisation implies restoring lemmas to the form most commonly encountered in a specific array of texts. With no significant limitations on computational power, we have used whole text arrays available in the databases as learning samples for dynamic lemmatisation. The simplest example of dynamic lemmatisation is restoring the lemma technolog* to "technology" or "technologies", depending on which of these words is encountered in the text array more frequently. The applied algorithm was more complex than may seem from the above example. E.g. to decide on restoring the said lemma to the adjective "technological" or the noun "technology(ies)", a sufficiently sophisticated syntactic analysis logic was applied. N-grams were created within sentences. This means that all texts were preliminary tokenised into sentences using proprietary algorithms (due to the slow speed of the open-access ones), and pairs "last word of previous sentence" – "first word of next sentence" were not considered as n-grams in calculating their frequency of occurrence.

2. Three indicators measuring n-gram usage patterns were calculated; two of them were very simple: *absolute number of occurrences* (how often the n-gram was encountered in the array), and *relative frequency of occurrences* (the share of words present in all n-gram occurrences in the total number of words in the text array). We also calculated n-gram *specificity* indicator, using an original formula (Bakhtin et al., 2017; Kuzminov et al., 2018). 32 thematic text arrays were used to measure specificity (which included, along with agriculture-related texts, other topics such as medicine, energy, transport, etc.). The specificity indicator is supposed to show how the relative frequency of the n-gram occurrence in the text array is related to the relative frequency of its occurrence in other arrays. In a way the specificity indicator can be seen as an approximation of the tf/idf measure (Bakhtin et al., 2017; Kuzminov et al., 2018), but with a number of specific features, distinct strengths and weaknesses.

3. The experts responsible for drafting lists of keywords representing various global technology trends had an opportunity to interpret the data in the generated n-grams. Typically, the experts had access to several tens of thousands n-grams. They were provided with an interface for sorting n-grams by various fields or their combinations; filter n-grams by various conditions, including length (measured in words or characters), presence or absence of specific character sets in n-grams, and on the basis of complex criteria. A typical number of resulting keywords for trend analysis purposes was tens and low hundreds (i.e. several keywords per each technology trend).

4. The resulting keywords were additionally checked by applying frequency analysis to an array of agriculture-related texts, among other things to identify potential cases of inadequate translation from Russian into English, less-than-obvious grammatical mistakes, etc.

5. It should be noted that future trend analysis should be supplemented, among other things, with text mining tools for validating experts' competency, and for their categorisation. E.g. comparing a list of most frequently used and at the same time highly subject area-specific n-grams with a list of keywords suggested by the expert (e.g. using rank correlation) told us how relevant the expert's knowledge is to the thematic structure of the subject area in question, and how biased is the sample generated using this set of knowledge compared with the entire assembly. This technique could help identify generalists and narrow specialists in particular fields, and weed out incompetents pretending to be experts. Successful application of this method requires access to a quite wide collection of relevant analytical materials.

A list comprising more than 30 AS-related trends was prepared for frequency analysis. Each trend was described using keywords and expressions (between 2 and 9 per trend), e.g.:

- Substituting conventional varieties of major crops with genetically modified ones, more resistant to pests, diseases, droughts, herbicides: new crop varieties, gm crops, genetically modified crops, genetically modified organisms, agricultural biotechnology, high-yielding varietal technology, transgenic crops hybrid maize technology; soybean varieties technologies, yield-increasing cost-reducing technologies

- Development and testing of technologies for creating industrial plantations of genetically modified trees: gm trees, genetically modified trees, gm tree plantations, genetically modified crops, genetically modified organisms, genetic improvement, genetic engineering

6. Each keyword or phrase were checked against the WIPO (World Intellectual Property Organisation) Patentscope database[6], to analyse patent activity for the selected trends (examples are provided in figures 1 and 2 below). The database contains 47,736,068 records from 40 national patent offices. The patent search was conducted in the A01 (B-P) category which relates to the Agriculture[7] section.

Search query example: **soil AND salinity AND control DP:[01.01.1990 TO 01.01.2015] A01**

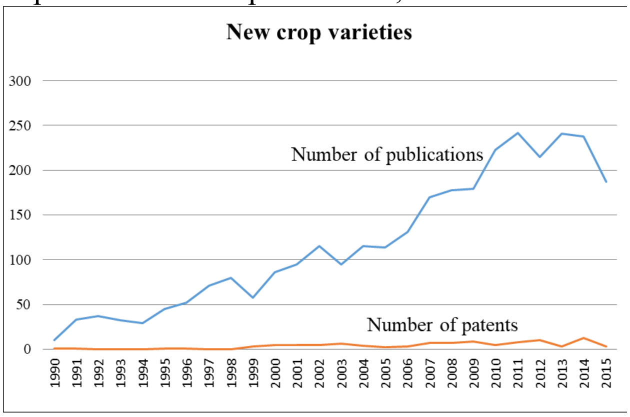
7. To analyse publication activity for the selected trends, the keywords and phrases were checked against the Web of Science (Core Collection) database.

Search query example[8]: **TS=(soil AND salinity AND control)**

The total number of patent and publication records processed was 1,937,075.

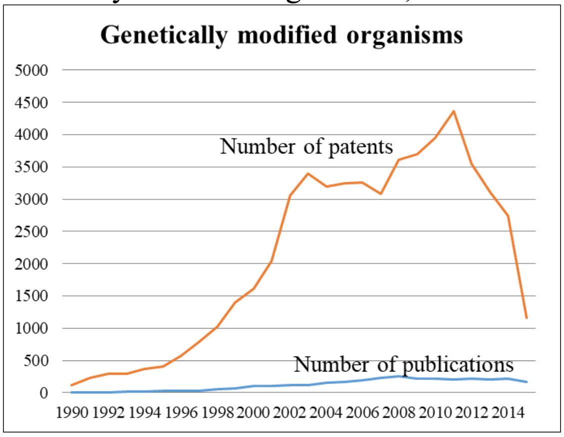
[6] URL: https://patentscope.wipo.int, last accessed on 05.07.2018.
[7] International Patent Classification (IPC). URL: http://www.wipo.int/classifications/ipc/en/, last accessed on 14.01.2018
[8] Subject areas were selected manually after the output list was generated (those unrelated to the AS were excluded)

Figure 1. Growth of the number of publications and patents containing the key phrase “New crop varieties”, 1990-2014



Source: WIPO and Web of Science

Figure 2. Growth of the number of publications and patents containing the key phrase “Genetically modified organisms”, 1990-2014



Source: WIPO and Web of Science

8. Data generated by processing the WIPO and Web of Science databases was grouped the following way: patent and publication activities in 1990 – 2014 were overlaid on the same graph to visualise each keyword or phrase describing the trend. The balance of patent and publication activities indicates the trend type. The following trend types were identified:

- Emerging
- Steadily growing
- Mature
- Past maturity

This classification was elaborated by considering also time horizon when the trend is developing (Table 1).

Table 1. Characteristics of trend types depending on growth of patent and publication activity

Time horizon	**Trend type**	**Trend type characteristics**
Near horizon (5 years)	Steadily growing Mature	Patent activity exceeds publication activity. Still, the number of publications also steadily grows. This may imply there’s demand for new knowledge to solve emerging technological problems.
Medium horizon (10 years)	Mature Steadily growing	The number of patents is larger than the number of academic publications. The number of patents remains sufficiently high, indicating ongoing R&D in the field.
	Emerging	A surge of patent activity followed by a persistently high growth of the number of publications, combined with decreasing number of patents. This may be due to current problems with application, solving which requires generating new knowledge.
Remote horizon (25 years)	Emerging	A steady growth of publication activity coupled with a low level of patent activity (or a small number of patents), indicating ongoing R&D and generation of new knowledge.

Results

The main empirical result of the study is a structured (divided into 7 categories) list comprising global technology trends in the agricultural sector. Trend descriptions match specific technical requirements described above (regarding phraseology, syntax, and semantics).

In the *biotechnology* category there were identified the trends of: 1) substituting conventional varieties of major crops with genetically modified ones, more resistant to pests, diseases, droughts, herbicides (including emerging area of development and testing of technologies for creating industrial plantations of genetically modified trees) and 2) increased application of animal cloning for specific purposes (producing biologically active preparations, breeding extinct farm animal species) (including emerging area of development and testing of technologies for cloning and farming extinct animal species (mammoths, etc.).

In the *smart efficiency* category there were identified the trends in application of precision agriculture practices, including: 3) discontinuing flood irrigation in favour of drip underground irrigation, to significantly reduce water consumption; and the following junior areas:

4) Developing technologies for precision soil fertility diagnostics: discontinuing standardised uniform application of fertilisers in favour of dynamic one, differentiated to match specific nutrients content in soil, to deal with the water reservoirs' eutrophication problem.
5) Abandoning manually operated agricultural machinery in favour of driverless machines based on micro-geopositioning technologies and self-learning robots, including UAVs and "electronic shepherds" to pasture cattle without human involvement.
6) Developing composite capsular fertiliser technology to replace conventional fertilisers (capsules' shells degrade under specific weather conditions releasing layers containing various nutrients into the soil in line with plants' life cycle stages).
7) Developing technologies for detecting lack of microelements in crops' nutrients, in real time.
8) Developing technologies for monitoring health and specific needs of individual farm animals, in real time.

In the category of *substitution of chemical-based solutions with biological ones* there were identified the trends of: 9) increasingly large-scale substitution of agricultural chemicals with organic fertilisers – by-products of agricultural activities, leading to reduced costs and reduced adverse impact on the environment; as well as the following junior areas:

10) Emergence of integrated pest control technologies; abandoning pesticides in favour of biological weed and pest killers.
11) Discontinuing use of antibiotics in animal farming in favour of innovative immunomodulatory techniques.

In the *environmental sustainability* category there were identified the trends of: 12) developing technologies for integrated remote monitoring of agricultural production to ensure adherence to environmental standards, and technologies for tracking supply chains (including GPS/GLONASS tracking labels) to guarantee reliability of products' origins; 13) adding flexible water treatment modules to irrigation systems (capable of automatically adjusting parameters during operation), to reduce the risk of soil salination; 14) abandoning conventional mechanical-based agricultural waste water filtration technologies for removing organic compounds in favour of nanotechnology- and microbiology-based fine filtration solutions, for complete water treatment; 15) abandoning conventional ploughing techniques in favour of no-till farming and other soil conservation technologies; and 16) development of second-generation biofuel production technologies, in particular:

a. Production of solid biofuels from peat and timber (pellets, peat pellets, briquettes);
b. Production of gaseous fuels from organic materials (generator gas, controlled methane-based fermentation of organic materials, etc.);
c. Production of liquid organic fuels from cellulose (biodiesel from wood cellulose; biopetrol: butylene-based fermentation for subsequent production of isooctane).

It also includes two emerging areas of: 17) exploratory research for mass production of inexpensive low-energy algae fertilisers, to make third-generation biofuel production technologies competitive; and 18) application of microbiology-based technologies for recultivation of degraded and polluted soils, to make lands ruined by bad irrigation practices, overgrazing, and pollution by industrial and communal waste suitable for agricultural use again.

In the *intensification and compacting* category there were identified the trends of: 19) application of technologies for combining fisheries and agriculture (aquaponics), allowing to process fish excreta to make plant nutrients in situ, in the scope of a fully closed water cycle; and 20) development of a climate-independent agricultural infrastructure including closed artificial ecosystems for agricultural purposes; as well as the following junior areas:

21) Development of urban agriculture based on innovative technologies for super-intensive plant growing in artificial environments (vertical farms, aeroponics, hydroponics); growing farm animals' nutritious tissues in artificial nutrient solutions.
22) Building robotic hothouses in adverse climate areas, to reduce the impact of seasonal factor on the supply of a wide range of agricultural products.

In the category of *reduction of food industry waste* there were identified the trends of: 23) application of technologies for instant low-temperature (shock) freezing to replace conventional freezing technologies, to better preserve organoleptic and nutritious properties of agricultural products; and two emerging areas:

24) Application of new preserving agent types programmed to self-destruct after a certain period of time, for safer preservation of agricultural products.
25) Discontinuing the practice of food waste disposal at garbage dumps in favour of smart recycling technological solutions; application of food waste to generate energy and make biochemical products, including development of technologies and systemic organisational and information solutions for efficient use of vegetable oils for technological purposes, including collection and processing of used cooking oil (among other things to make biodiesel fuel).

The *organisational and IT innovations* category comprises the following trends: 26) development of smart (flexible and automated) agricultural insurance technologies to protect producers from natural disasters, to replace conventional agricultural insurance business models with new ones, based on application of supercomputers for mesoscale climatic and weather forecasting; 27) moving agricultural territorial planning up to a new efficiency and response speed level, by applying integrated information systems to support management decision-making and connecting to global Big Data bases.

The most remarkable outcomes of the subsequent expert-based and quantitative validation of these trends were summarised in a comparative Table C.1 (there is no possibility to show properly all of them because of the limits of the paper). It consists of a brief description of trends development stage based on bibliometric and patent analysis as well as on expert polling. Of particular interest are the columns of the year when the trend is expected to peak (averaged-out expert estimates) and degree of conformity of results validation with detailed clarifications.

One of the main conclusions based on analysing the summarised results in the Table C.1 is that there is a clear positive correlation, at least on the qualitative level, between the trend's maturity (measured using objective bibliometric and patent indicators) and the expert community's perception of the trend's potential. On the whole, trends which, judging by relevant quantitative indicators, appear to be powerful and mature, are seen by experts as more important ones (at least on the nearest forecasting horizon). Trends weakly represented in quantitative indicators terms (i.e. insignificant or emerging ones) were usually seen by the experts as potentially important only on a remote forecasting horizon. Importantly, it should be noted that no bibliometric or patent analysis data was made available to the surveyed experts, in any form.

Of course establishing a more reliable connection between quantitative analysis and expert assessment results would require conducting larger-scale surveys covering a significantly larger number of study objects (i.e. trends), to calculate mathematical correlation between the two types of results. Also it would be very useful to link expert assessments to the experts' membership in particular qualification groups (experts could be grouped, for example, on the basis of their formal qualifications such as academic degree (PhD, Doctor of Science, Academician of the Russian Academy of Sciences), with possible introduction of a control group comprising non-experts, e.g. students of general-type universities).

Conclusions

Monitoring and precise interpretation of technology trend data is a key factor of obtaining competitive advantages in various sectors of the economy. Combination of qualitative (based on expert polling) and quantitative (based on Big Data analysis and text mining) techniques in our research allowed to detect global technology trends, formalise their criteria, and design automated data processing tools. Methodological results of the study comprise analytical decomposition of the "technology trend" concept, including trend attributes and major trend types. Proposed approach to analysing technology trends has a potential to increase predictive capability of futures studies. Empirical results were obtained for the agricultural sector – which was taken as an example – detected and validated global technology trends. These results can be applied by federal and regional authorities responsible for promoting development of the sectors to design relevant strategies and programmes, and by companies to set their long-term marketing and investment priorities.

There was demonstrated that depending on the objectives of technology development monitoring basic processing techniques for structured (bibliometric analysis) and unstructured (in-depth text mining) data can be applied in combination, and supplemented with various auxiliary methods such as network analysis, clustering, principal component analysis, analysis of probability distributions, ontological modelling, etc. Specific combinations of such techniques would help detect various kinds of trends (emerging technologies, research fronts, "invisible" research teams, prospective research areas, citation patterns, etc.), and extend the range of data sources based not just on academic publication and patent databases but also supplementary sources such as news media, business information resources, conference proceedings, etc.

We see two major areas for applying automated data retrieval and text mining techniques to global technology trend analysis. The first is obtaining various samples of the studied area in order to speed up and deepen experts' immersion in the subject field. Such samples can take the form of, e.g., lists of topics; ranked n-gram lists, semantic concept clusters, graphs illustrating interconnection between various actors (organisations and individuals), or extracts of specific contexts based on specially designed lexicographic and syntactic conditions.

The second area is supporting objective patent and bibliometric analysis; it mainly amounts to helping experts prepare lists of key words and phrases (further on, "keywords") for queries, and validating keywords suggested by experts. Obviously linking specific units – objects of study (e.g. technology trends) to specific data in patent and bibliometric databases on the basis of specially composed sets of relevant keywords is a very complex task. Biased keyword selection (too large or too small keyword lists, inclusion of irrelevant words), due to inevitably limited expert knowledge in certain areas, dictates the need to design an integrated methodology, and a set of "compensatory" tools. Otherwise results of patent or bibliometric validation searches could be easily questioned. Application of text mining techniques certainly does not solve all these issues. But applying computer algorithms to compose keyword lists using sufficiently large arrays of full-text data sources, including n-gram analysis, topic modelling, and semantic concept clustering makes the problem significantly less acute. These tools can be usefully applied both before experts draft the initial keyword lists and after that, to validate the lists before using them as search terms to search bibliometric/patent databases.

Validating expert assessments by quantitative methods helps to discover obscure evidence of technological changes, by analysing large volumes of data. However, application of expert-based techniques to validate results generated by smart data analysis systems has certain limitations. Assessments of reliability and applicability of analytics produced by automated analytical systems, leading experts in relevant fields, and supervisors of major S&T areas can be used only as additional, but not mainline criteria for quantitative assessment of reliability of results. Automated extraction, summarising, and interpretation of primary data (especially when huge volumes of it, i.e. Big Data, is processed) cannot be directly verified on the basis of generalised subjective expert opinions. Expert consensus is not a sufficiently reliable validation tool, due to inevitably high controversy and inconsistency of expert opinions. E.g. expert consensus in focus groups, surveys, and panels dealing with issues resolved through big data analysis, such as optimal classifications for particular subject areas, usually does not exceed 50-65%, while the accuracy of quantitative assessment of reliability of results produced by automated analytical systems may be as high as 80-90%.

Validation of results generated by Big Data analytical systems is traditionally based not only on comparing these results with an etalon (the *ex-post* approach), but also on demonstrating mathematical validity of applied data processing tools (the *ex-ante* approach), combined with validation of data sources' reliability. Thus the expert validation method may be applied as a supplementary technique, to regularly monitor how well strategic industry-specific analytics produced by automated analytical systems match expectations and specialised knowledge of individual high-level experts – supervisors of major S&T areas. Application of relevant procedures would provide additional information to control the quality of, and measure demand for results produced by automated analytical systems.

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Table A.1 – Clustering of the often mentioned terms related to agriculture technologies (example)

Sentence	Frequency of occurrence[9]	Cluster of concepts associated with the sentence
Biotechnology	1,1260	agricultural biotechnology, plant biotechnology, animal biotechnology, crop biotechnology, microbiology biotechnology, ICT biotechnology, industrial biotechnology, nanotechnology biotechnology, pesticides biotechnology, food biotechnology, marine biotechnology, breeding biotechnology, environmental biotechnology, livestock biotechnology, active biotechnology, cotton biotechnology, ecological biotechnology, green biotechnology, Mendel biotechnology, Nelson biotechnology, Rozelle biotechnology, survival biotechnology, Zilberman agricultural biotechnology, bank agricultural biotechnology, agricultural biotechnology council, environmental threats biotechnology, perceived environmental threats biotechnology
Nanotechnology	0,2098	biotechnology nanotechnology, material nanotechnology, biology nanotechnology, communication nanotechnology, ICT nanotechnology, mechatronics nanotechnology, nanotechnology geotechnology, proteomics nanotechnology
Agrotechnology	0,0270	materials agrotechnology, agrotechnology sector, advanced agrotechnology
Agricultural technology	0,0150	fund agricultural technology, green agricultural technology
Communication technology, Information technology	0,0088	information-communication technology, global communication technology, information-telecommunication technology, computer information technology, information-communication nanotechnology, information guidance technology, agriculture contextual information, networks information technology, contextual information network, market information system, information communication technology ICT, insurance premiums ICT, technical regulations telecommunications, communications financial intermediation computer, premiums telecommunications energy export
Ecotechnology	0,0052	-
Irrigation technology	0,0044	irrigation water, irrigation systems, drip irrigation, irrigation drainage systems, irrigation infrastructure, irrigation schemes, on-farm irrigation, irrigation facilities, North Otago irrigation, irrigation equipment, fertiliser irrigation, irrigation acceleration fund, community irrigation, pressurised irrigation, community irrigation fund, irrigation canals, irrigation channels, irrigation networks, irrigation techniques, large-scale irrigation, plantations irrigation, roads irrigation, supplemental irrigation, flood irrigation, irrigation freshwater, effluent irrigation, groundwater irrigation, precision irrigation, small-scale irrigation, surface irrigation, crop irrigation, directed irrigation, irrigation electricity, irrigation fertilization, irrigation well, outlays irrigation, rehabilitation irrigation, tillage irrigation, excessive irrigation, inappropriate irrigation, participatory irrigation, transport irrigation, wastewater irrigation, micro irrigation, micro-irrigation systems, saving irrigation technology, mini-irrigation drip technology, water-conserving irrigation technology, water-saving irrigation technology, industrial drip irrigation, Otago irrigation company, water saving irrigation, irrigation drainage infrastructure, national irrigation commission
Agritechnology	0,0037	agritechnology exports
LEISA technology	0,0036	LEISA organic biotechnology, scaling LEISA approaches, adopt labour-intensive LEISA, difficulty scaling LEISA, farmers adopt LEISA, gm crops LEISA, inter-temporal impacts LEISA, labour-intensive LEISA approaches, large-scale adoption LEISA, LEISA technology liquidity, rapidly scaling LEISA, restrictive forms LEISA, strictly prohibited LEISA, sustainable agriculture LEISA
Microtechnology / micro-technology	0,0030	-
Nanobiotechnology	0,0022	-
Critical technology	0,0021	priorities critical technology, critical modern biotechnology, national critical technology, regional critical technology, Russian critical technology
Green technology	0,0022	green technological foresight, green technology promotion, green revolution technology, OECD green growth, green growth studies, green growth fisheries, green growth indicators, green growth strategy, green growth aquaculture, green growth blue, green growth initiatives, cap greening measures
Energy technology	0,0019	renewable energy technology, new energy technology, alternative energy technology, decentralised energy technology, renewable energy technology, solar energy technology, energy technology waste, energy technology platform
Environmental technology	0,0017	environmentally friendly technology, alternative environmentally acceptable technology, environmentally sound technology, environmentally sound infrastructure technology, environmental taxes, agrienvironmental public goods, externalities agrienvironmental policy, cost-effective agrienvironmental policy, environmental quality incentives, environmentally friendly farming, negative environmental impacts, environmental impact assessment, agrienvironmental footprint index, environmentally related taxes, monitoring environmental efficiency, negative environmental externalities, environmentally friendly agriculture, environmental effects dairy, evidence-based agrienvironmental policies, environmental cross compliance, environmental taxes tradeable, environmentally harmful subsidies, agrienvironmental public bads
Cloud technology	0,0016	internet cloud technology, internet things technology, cisco global cloud, cloud-enabled internet services, mobile internet cloud, cloud social impacts
Geotechnology	0,0015	nanotechnology geotechnology, geotechnology automation
Mitigation technology	0,0013	climate change mitigation technology, agricultural mitigation technology, adaptation mitigation technology, mitigation technology bioenergy
Processing technology	0,0013	food processing technology, grain circulating processing technology, ethanol processing technology, signal processing technology

[9] Calculated by proprietary algorithm, designed in the Institute for Statistical Studies and Economics of Knowledge of National Research University Higher School of Economics

Sentence	Frequency of occurrence[9]	Cluster of concepts associated with the sentence
Sensor technology	0,0013	sensor robotics, biosensor technology, sensors actuators, sensor systems, sensor data, sensor types, sensors GPS satellites, remote sensors, satellite sensors, sensor-based systems, onboard yield sensors, wide field-of-view sensor, implanted sensors, infrared sensors, artificial intelligence sensors, low-cost sensors, multiple sensors, nanosensors nanofluidics, pervasive sensors, electrical resistance sensors, sensor networks, sensors greenhouse gases, sensors greenhouse equipment, tactile sensors, thermo sensors, Norias thermo sensors, sensors monitor temperature, sensor online assessment, machine vision sensors, sensor technology foresight, hidden features sensors, computer systems interrogate sensors, sensors Samsung Galaxy
Food technology	0,0012	Guelph food technology centre, food technology centre GFTC
Conservation technology	0,0011	soil conservation technology, water conservation technology, soil water conservation technology
Farming technology	0,0011	varieties farming technology, labour-saving farming technology, farming technology farm size
Saving technology	0,0011	energy saving technology, moisture-saving technology, water saving technology, moisture water saving technology, farms USDA moisture-saving technology, labour-saving technology, labour time-saving technology, irrigation water-saving technology, irrigation water-saving technology desalination, water-saving technology desalinisation conservation, river extension water-saving technology, sprinkler systems water-saving technology, moisture-saving technology reduced tillage, promote cost-saving technological innovations
Sustainable technology	0,0010	environmentally sustainable biotechnology, maximum sustainable yield MSY, sustainable agricultural productivity, sustainable productivity growth, sustainable forest management, sustainable farming fund SFF, sustainable land use, sustainable land management, sustainable crop protection, sustainable rural development, sustainable fisheries aquaculture, sustainable farming practices, smart sustainable inclusive growth, sustainable natural resource management, sustainable management water resources, discontinued sustainable development technology, genetically modified plants sustainable, low external input sustainable agriculture LEISA, sustainable exploitation fisheries resources, sustainable water quality management, act RMA sustainable farming, RMA sustainable farming fund
RAS technology	0,0009	recirculation aquaculture systems RAS
Fuel technology	0,0008	fuel tax exemptions, fertiliser biofuel policies, advanced biofuels technology, fuel cell technology, biofuel support policies, renewable fuel standard, biofuel budgetary support, fuel tax concessions, first generation biofuels, fuel standard RFS, second generation biofuels, renewable fuels standard, advanced biofuel mandate, fuel excise tax exemption, flex fuel vehicles, abolishing biofuel mandates, hydrous ethanol fuel, biofuel blending mandates, biofuels produced lignocellulosic biomass, advanced cellulosic biofuel mandates, agriculture food fiber fuel, biofuel mandate subsidy equivalent, biofuel mandates EISA EPA, biofuel production limited feedstock, low carbon fuel standard, water implications biofuels production, market assessment biofuels cereals
Genetic technology	0,0008	genetically modified plants, genetically modified crops, genetically modified organisms, genetically modified foods, inheritance genetic stability, plant genetic systems, genetically engineered organisms, crop genetic improvement, genetically engineered crops, genetically modified cotton, forest genetics council, genetically engineered animals, genetically engineered varieties, unintended effects genetic modification, genetically modified rice, genetically modified corn, genetically modified microorganisms, genetic resource base, genetically modified feedstuffs, inbreeding depression genetic load, Enviropig TM genetic technology meeting
CDR technology	0,0005	carbon dioxide removal CDR, dioxide removal CDR technology
Cultivation technology	0,0005	crop cultivation technology, wheat cultivation technology, maize wheat cultivation technology, paddy rice cultivation, market gardening flower cultivation, green houses vegetable cultivation, scientifically established cultivation technology, intensive rice cultivation, upland crop cultivation, low-intensive cultivation, oil seeds cultivation, cultivation rain-fed crops, cultivation rape seed vegetable oil, cultivation staples small-holdings, cultivation using animal traction, wine cultivation steep slopes, cultivation far southern steppes, soil water conserving cultivation, water conserving cultivation practices, cultivation higher rain fall areas, cultivation marginal land, cultivation using motorized mechanization

Annex B

Table B.1 – Agriculture expert survey results: assessment of development prospects and the nature of global technological trends impact on Russia within the closed questions format, distribution of answers

Trend name	Trend period					Opportunities: 1 - significant, 2 - moderate, 3 - minor			Threats: 1 - significant, 2 - moderate, 3 - minor			The trend influence is insignificant in all aspects
	2016-2020	2021-2025	2026-2030	2031-2035	after 2035	1	2	3	1	2	3	
1	2	3	4	5	6	7	8	9	10	11	12	13
Substitution of traditional varieties of basic crops with genetically modified, more resistant to pests, diseases, droughts, herbicides; as well as the involvement in the economic circulation of wild plants and wild animals for breeding thus of new varieties and breeds (highy-yielding varietal technology; hybrid maize technology; soybean varieties technologies)	21	83	42	14	23	59	37	83	89	52	52	18
The replacement of traditional forest plantations with fast-growing genetically modified trees plantations	2	17	32	36	82	35	23	118	85	36	69	42
Increased use of animal cloning for specific tasks (production of biologically active drugs, veterinary research, etc.) (animal cloning breeding technologies; recombinant DNA technology)	20	45	43	38	35	65	42	70	44	48	96	39
The growing number of high-tech scientific projects on extinct animals cloning and mass reproduction (mammoth, etc.)	6	14	39	33	83	36	32	110	41	34	112	64
Replacement of continuous irrigation by point-wise underground irrigation, which allows to save water resources significantly (drip irrigation technology; farm irrigation technology; water conservation technologies)	40	70	38	16	23	123	30	28	13	26	154	18
Growth of demand from business for high-tech solutions in the field of precise soil fertility diagnostics for the transition from the normative uniform fertilizers application to the dynamic nutrient-differentiated soil saturation index	72	62	43	12	8	128	27	26	8	22	163	15
The turn from manually operated agricultural machinery to an autopilot based on micro-geo and self-learning robots, including the introduction of monitoring unmanned aerial vehicles and "electronic shepherds" for unmanned grazing	23	66	58	27	23	103	42	36	13	26	153	28
The displacement of traditional fertilizers with composite capsular fertilizers (the capsule shell is destroyed under certain weather conditions, after which the capsule layers containing various nutrients are transferred to the soil in relation to the plant life cycle stages)	41	70	47	13	12	118	37	25	9	30	153	20
Entering the stage of commercialization of technologies for real time diagnosing nutrient deficiencies (macro and trace elements) in the agricultural plants nutrition	35	58	55	21	14	96	52	32	13	21	158	24
Entering the stage of commercialization of technologies for real time monitoring the health status and specific needs of individual animals	42	62	52	23	12	104	41	35	8	27	158	20
Increasingly widespread replacement of agrochemicals with organic fertilizers - by-products of agricultural activities, leading to a reduction in costs and a reduction in the negative impact on the environment (manure spreading technology; local conditions technology)	53	63	43	10	16	110	42	28	8	28	154	25
Increasingly widespread practice of "integrated protection against pests", the replacement of pesticides with biological plant protection products	49	61	47	18	12	118	41	22	12	30	151	14
Substitution of antibiotics in animal husbandry with new immunomodulation methods	39	59	47	22	21	102	43	36	12	30	150	15

Trend name	Trend period					Opportunities: 1 - significant, 2 - moderate, 3 - minor			Threats: 1 - significant, 2 - moderate, 3 - minor			The trend influence is insignificant in all aspects
	2016-2020	2021-2025	2026-2030	2031-2035	after 2035	1	2	3	1	2	3	
1	2	3	4	5	6	7	8	9	10	11	12	13
The growing demand of agribusiness and environmentally responsible consumers for technological solutions in the field of integrated remote conformity control of agricultural production to environmental requirements and tracking the supply chain of products (including GPS / GLONASS marking)	52	67	41	26	6	102	44	31	9	22	161	21
The increasingly widespread use of filtration and water pretreatment in irrigation systems, which effectively prevents salinization of soils	41	64	40	23	10	91	51	31	10	22	160	18
Substitution of traditional mechanical methods for of agricultural effluents filtration from organic compounds by a complex of interrelated nanotechnological and microbiological solutions for precision filtration providing full purification	23	78	47	20	24	94	53	34	9	29	154	25
Addition of agricultural land plowing traditional methods with technologies of landless farming and other soil-saving technologies (soil conservation technologies; no-till farming).	79	64	22	7	10	98	42	40	15	30	147	24
Formation of technological solutions and equipment complexes allowing to develop artificial agrobiocenoses on an industrial scale (forestry-pasture and forestry, agricultural-pasture)	14	41	60	30	32	80	60	40	11	34	145	30
Stable and rapid reduction in the cost of technological solutions that allow producing second-generation biofuels on an industrial scale, including production of gaseous fuels from organic raw materials (generator gas, controlled methane digestion of organic materials, etc.), production of liquid organic fuels from cellulose raw materials (biodiesel, biobenzene: butylene digestion with further obtaining of isooctane)	18	44	61	35	25	87	49	45	13	34	145	32
The research intensification in the field of creating cheap, non-energy-intensive mass fertilizers for algae, which can make the technologies of third generation biofuel production competitive.	10	37	51	39	43	64	60	57	12	28	152	39
Growth of demand (both in developed and developing countries) for the degraded and contaminated soils microbiological reclamation technologies that allow the return to farming of farmland, rendered inoperable by irrational practices of irrigation, overgrazing, pollution by industrial, domestic and radioactive waste (soil conservation technology; soil erosion technology; soil protection technologies)	29	57	58	26	21	94	52	35	15	24	154	30
Intensive introduction by advanced aquaculture holdings of fish and agriculture (aquaponics) combining technologies that enable the fish waste processing in plant nutrients directly at the production site (in situ) within the framework of a completely closed water cycle	26	81	46	13	25	84	57	39	7	28	156	33
Substitution of food products traditional packaging with a nanocellulose with bactericidal properties package	46	76	46	14	10	87	54	40	5	30	157	33
Increasing the effectiveness of aquaculture technologies in fresh and marine waters (fish farming, shellfish and crustacean cultivation), displacement of aquaculture by fisheries	28	56	46	29	25	76	48	56	17	43	131	22
Developing of a climate-independent agricultural infrastructure, including closed artificial ecosystems for agricultural purposes	14	26	40	41	68	96	43	42	18	30	143	24

Trend name	Trend period					Opportunities: 1 - significant, 2 - moderate, 3 - minor			Threats: 1 - significant, 2 - moderate, 3 - minor			The trend influence is insignificant in all aspects
	2016-2020	**2021-2025**	**2026-2030**	**2031-2035**	**after 2035**	**1**	**2**	**3**	**1**	**2**	**3**	
1	2	3	4	5	6	7	8	9	10	11	12	13
Wide spreading of commercial solutions in the field of over-intensive plant cultivation based on hydroponics, aeroponics, robotization and "verticalization" (vertical farms)	22	49	50	32	30	79	59	42	17	26	148	25
The turn of technologies for agricultural animals nutrient tissues growing in artificial nutrient solutions from the elaborating concept stage to the demonstration of realizability stage	6	23	41	40	73	51	47	80	26	37	126	43
The growth in the number of projects in the field of robotic greenhouses in climatically unfavorable areas	29	52	48	29	27	101	48	32	7	26	160	24
The replacement of traditional technologies of food products safety ensuring with instant low-temperature (shock) freezing technologies, which allows to ensure better preservation of agricultural products organoleptic and nutritional properties	74	73	28	9	10	111	43	27	8	28	157	19
The introduction of new types of preservatives programmed for self-destruction within a certain period, making it safer to prevent agricultural products damage	26	76	48	20	19	97	44	40	20	36	136	25
Repression of practices of storing food waste in landfills with technological solutions in the field of smart recycling, energy and food waste biochemical conversion	35	50	60	22	25	124	27	29	9	29	153	22

Table B.2 – Agriculture experts survey results: additional global technological trends, initiatively indicated by interviewed experts within the open questions format

Trend name	Trend period					Opportunities: 1 - significant, 2 - moderate, 3 - minor			Threats: 1 - significant, 2 - moderate, 3 - minor			Does it meet the proposed concept of the technological trend in terms of formal naming rules
	2016 - 2020	2021 - 2025	2026 - 2030	2031 - 2035	after 2035	1	2	3	1	2	3	
1	2	3	4	5	6	7	8	9	10	11	12	13
Increase of agricultural plants energy potential and of its use efficiency, as a strategic goal in selection field in order to import substitution and food security in Russia	V	V	V	V	V	1				1		Partly (excluding the normative context)
Organizational and economic mechanism of Russia's agriculture technical and technological modernization in conditions of import substitution, ensuring food security and the WTO and the Unified Energy System international integration processes	V	V	V	V	V	1			1			No (institute)
Biological methods for obtaining environmentally safe soybean grain in conditions of land reclamation	V	V	V			1				1		No (technology)
Artificial photosynthesis, allowing to become one of the alternative natural sun energy source				V		1				1		No (technology)
Development of agrometeorological technologies for predicting impact of weather and climate on crops, rangelands, farm animals, and performing various agricultural activities		V				1					1	Partly (excluding the normative context)
Formation and development of bioeconomics branches based on the new science architecture - NBIC convergence, for example:			V			1				1		Yes
- medical agrobiology development based on genetic engineering and the GMOs use with prescribed properties useful for health and disease treatment;			V			1				1		Yes
- development and expanded introduction of information and communication technologies that allow to create smart agriculture: RFID tags for cattle, GPS + GIS monitoring (field monitoring, sensor moisture sensors, etc.), monitoring and diagnostics (eg manure utilization), integrated databases for the entire farm infrastructure (including all artificial and living systems), the use of GNSS, a hybrid information communications architecture, the development of ultrasound diagnostics, a 4D camcorder, development of special web-applications and the cloud capabilities use, a virtual market of agricultural products (direct contact - producer and consumer), online consulting services, including education and more.			V			1				1		Yes
Restoration of natural ecosystems on the territories free from production, with the aim of increasing the territories stability to the natural and technogenic negative factors impact	V					1					1	Partly (excluding the normative context)
Comprehensive microbiological biological preparations considering agricultural crops individual features and based on metagenomic analysis of microflora of various parts of plants												Partly (excluding the normative context)
Intensive introduction of adapted land-security systems that allow full and year-round wastes utilization and land resources saving in order to improve the agricultural production efficiency	V					1					1	Partly (excluding the normative context)
Comprehensive use of secondary raw materials for the pectin and pectin goods production		V				1					1	No (normative priority)
More complete non-traditional, highly productive field crops use with the valuable raw materials integrated use (aboveground + groundwater), such as Jerusalem artichoke, for biologically active substances production (inulin, etc.) in order to improve the population health, increase the animal feed production and	V					1					1	No (normative priority)

Trend name	Trend period					Opportunities: 1 - significant, 2 - moderate, 3 - minor			Threats: 1 - significant, 2 - moderate, 3 - minor			Does it meet the proposed concept of the technological trend in terms of formal naming rules
	2016 - 2020	2021 - 2025	2026 - 2030	2031 - 2035	after 2035	1	2	3	1	2	3	
1	2	3	4	5	6	7	8	9	10	11	12	13
produce renewable energy												
Expanded production technologies introduction for biologically (ecologically) crop production based on the organic farming introduction	V					1					1	Partly (excluding the normative context)
Adaptive strategy of agroindustrial complex sustainable development (the author is the Russian Academy of Sciences academician – A.A. Zhuchenko). A significant part of the above trends is an integral part of this trend.			V			1					1	No (concept)
Introduction of non-tractor technologies in plant growing (using of agro-bridges - stationary installations, able to perform around the clock according to a set program, without human presence, like program control machine)					V	1				1		Partly (excluding the normative context)
Introduction of 3D printing technologies for food products or ready meals			V			1				1		Yes
Introduction of 3D printing technologies for animal organs production				V		1			1			Yes
Production of raw milk using large robotic dairy farms		V				1					1	No (technology)
GIS systems in monitoring the assessment of agricultural land and arable land use	V					1					1	No (technology)
Expansion of types and ways of crop production processing and conservation, expanding the possibilities of preserving products without consumer qualities loss		V				1				1		Yes
Development of decision-making support systems based on agroecologically improvement fertilizer efficiency use	V					1						Partly (excluding the normative context)
Development of smart systems for the agriculture adaptive systems and agro-technologies flexible design	V					1						Yes
Development of smart systems for the climate-adapted agriculture and land use design		V				1						Yes
Development of smart systems of organic products level certification	V					1						Yes
Development of smart agroecological monitoring systems with operational control of soils, agrotechnologies and products functional quality		V				1						Yes
Development of smart systems for organic residues with biofuel and organic fertilizers utilization		V				1						Yes
Development of smart technologies for the degraded and contaminated soils functional quality restoration		V				1						Partly (excluding the normative context)
Development of sustainable soil structures for various functional urban ecosystems		V				1						Partly (excluding the normative context)
Development of smart agricultural planning systems with therapeutic corrective properties			V			1				1		Yes

Trend name	Trend period					Opportunities: 1 - significant, 2 - moderate, 3 - minor			Threats: 1 - significant, 2 - moderate, 3 - minor			Does it meet the proposed concept of the technological trend in terms of formal naming rules
	2016 - 2020	2021 - 2025	2026 - 2030	2031 - 2035	after 2035	1	2	3	1	2	3	
1	2	3	4	5	6	7	8	9	10	11	12	13
The GMOs use prohibition in agriculture of the Russian Federation can increase the backlog in the agricultural goods production and genetics, and in 10-15 years will make it completely dependent on developed countries of genetic material supply	V					1			1			No (expert thesis, postulate, opinion)

Annex C

Table C.1 – Brief comparison of qualitative and expert-based validation results of fourteen major global technology trends in the agricultural sector

№	Trend name	Brief trend description based on...		Year the trend is expected to peak (averaged-out expert estimates)	Conformity of validation results (+: high, +/-: average, -: low)	Detailed explanation
		...quantitative validation (bibliometric and patent analysis)	…expert validation (expert polling)			
1	**2**	**3**	**4**[10]	**5**	**6**	**7**

[10] When columns 4 and 5 are compared, column 5 has priority (mathematically averaged-out year when the trend is expected to peak).

1	2	3	4[10]	5	6	7
1.	Substituting conventional mainline crop varieties with genetically modified ones, more resistant to pests, diseases, droughts, herbicides.	Powerful, steadily growing trend	Relevant already in the near horizon of the forecast (no later than the early- to mid-2020s)	2025	+	The number of patents exceeds the number of academic publications, except for two keywords: - new crop varieties - yield-increasing AND cost-reducing AND technologies Here the opposite is true: a steady growth of publications coupled with a very low level of patent activity. This may indicate that these keywords refer to areas where creation of new knowledge is taking place, and new technologies are being developed. On the whole, this trend may be assessed as steadily growing, being at the stage where applied technological solutions and business ideas are developed, which is evidenced by high patent activity steadily growing since 1998.
2.	Development and testing of technologies for creating industrial plantations of genetically modified trees.	Mature trend	May become relevant in the far horizon of the forecast (after 2030)	2031	-	The number of patents exceeds the number of academic publications, except for two keywords: - genetically modified OR gm AND trees - genetically modified OR gm AND tree AND plantations A sharp and steady growth of publication activity, combined with a low level of patent activity. This may indicate that these keywords refer to areas where creation of new knowledge is taking place, and new technologies are being developed. The mismatch between expert-based and quantitative validation results is due to the fact that more general keywords were selected for the trend, which also relate to genetically modified plants. Technologies for producing genetically modified plants have found wide application, so now the trend's development is at the stage of technology improvement and innovation, and the number of technologies and innovations is not that big compared with the early development stage. The experts specifically referred to genetically modified plants and their plantations. According to the quantitative validation, this trend is at the emergence stage (see above).

1	2	3	4[10]	5	6	7
3.	Increased application of animal cloning for specific purposes (producing biologically active preparations, breeding extinct farm animal species).	Mature trend	Will become relevant in the medium horizon of the forecast (not before the mid-2020s)	2027	+	The number of patents exceeds the number of academic publications for all keywords describing this trend. Publication activity remains very low compared with the number of patents, and is not visibly growing except for three keywords: - animal cloning - animal AND genome sequencing - artificial wombs This may indicate that creation of new knowledge here is prompted not by the need to solve agricultural problems but by other scientific interests. Generally, the trend is at the maturity stage when relevant technologies are widely applied. Since 2011 there were signs of declining patent activity, but the number of patents remains sufficiently high – which is evidence of R&D in this field still being carried out.
4.	Development and testing of technologies for cloning and farming extinct animal species (mammoths, etc.).	Emerging trend	May become relevant in the far horizon of the forecast (after 2030)	2031	+	The number of patents matching the keywords is much higher than the number of publications; until 2002-2004 a steady growth was noted, followed by a more linear development and then decline, which indicates the technologies have reached maturity: - cloning AND extinct animals - de-extinction For the keywords “animal” AND “genome sequencing” the situation is similar, with a single difference: the number of publications started to steadily increase since 1998, which is evidence of continuing R&D and new knowledge creation. CRISP dynamics stand out of the general trend. The publication activity started to sharply grow since 2010 while the first patents were filed only in 2013. This is a signal of a newly emerging trend for application of this technology. Finally, the dynamics of keywords “cloning” AND “woolly mammoth” do not allow to identify a specific trend, including for numbers of publications and patents: there were no more than 6 in each year of the period under consideration.

1	2	3	4[10]	5	6	7
5.	Development of technologies for detecting lack of microelements in crops' nutrients, in real time.	Mature trend	Relevant already in the near horizon of the forecast (no later than the early- to mid-2020s)	2025	+	Patent activity exceeds publication activity. However, the number of publications was also steadily growing during the period in question. This may be evidence of the trend's having reached a certain maturity, with a drop in patent activity but a growth of publication activity. It may be evidence of demand for new knowledge required to deal with emerging technological problems.
6.	Development of technologies for monitoring health and specific needs of individual farm animals, in real time.	Relatively young, erratically developing trend	Relevant already in the near horizon of the forecast (no later than the early- to mid-2020s)	2025	-	A significant patent activity related with this trend noted during the period under consideration was accompanied by an almost zero publication activity. This is due to the fact that relevant technologies are largely based on specific applied solutions, with no demand for new knowledge.
7.	Increasingly large-scale substitution of agricultural chemicals with organic fertilisers – by-products of agricultural activities, leading to reduced costs and reduced adverse impact on the environment.	Mature, steadily growing trend	Relevant already in the near horizon of the forecast (no later than the early- to mid-2020s)	2024	+/-	Patent activity exceeds publication activity. The number of publications is growing (and is close to the number of patents) only for two keywords: - organic AND farming - fertiliser AND application AND technologies This may signal that following the decline of patent activity after 2010, new knowledge related to these technologies is required to deal with emerging application-related problems. On the whole the trend seems to be growing, and approaching the maturity stage.
8.	Emergence of integrated pest control technologies; abandoning pesticides in favour of biological weed and pest killers.	Steadily growing trend	Relevant already in the near horizon of the forecast (no later than the early- to mid-2020s)	2024	+/-	Patent activity exceeds publication activity, except for the keywords "pest" AND "management" AND "ipm". Here the number of publications is growing faster. This may be evidence of the technologies being at the emergence stage.

1	2	3	4[10]	5	6	7
9.	Discontinuing use of antibiotics in animal farming in favour of innovative immunomodulatory techniques.	Steadily growing trend	Relevant already in the near horizon of the forecast (no later than the early- to mid-2020s)	2025	+	The number of patents is small but exceeds the number of publications, and shows a tendency to grow: - livestock AND antimicrobial AND resistance - animal AND beneficial AND microbes - nontherapeutic AND uses AND antibiotics AND animals In the latter case it is not possible to detect a trend because the patent and publication indicators alike are too disparate. The dynamics of “animal” AND “microbiome” keywords seem to suggest an emerging trend. This is evidenced by a sharp increase of the number of publications after 2008 (from zero), and the small catch-up growth of the number of patents which has begun a few years later.
10.	Development of second-generation biofuel production technologies, including for production of gaseous fuels from organic materials (generator gas, controlled methane-based fermentation of organic materials, etc.), and production of liquid organic fuels from cellulose (biodiesel; biopetrol: butylene-based fermentation for subsequent production of isooctane).	Emerging trend	Will become relevant in the medium horizon of the forecast (not before the mid-2020s)	2027	+/-	The trend displays a sharp growth of publication activity since 2007, with a low growth of the number of patents afterwards. The only exception are the keywords “ethanol” AND “production” which describe an already mature technology, but after 2013 we can see a sharp decline of patent activity coupled with a sharp growth of the number of relevant academic publications. This may be due to a new round of the technology’s development, moving on to a higher level of innovation activity. The technology described by the keywords “energy” AND “vegetable” AND “oils” can also be considered as mature, because the number of patents and publications stopped growing in 2011, and then started to sharply decline afterwards.
11.	Stepping up exploratory research for mass production of inexpensive low-energy algae fertilisers, to make third-generation biofuel production technologies competitive.	Emerging trend	Will become relevant in the medium horizon of the forecast (not before the mid-2020s)	2028	+/-	Initially the trend displayed an explosive growth of patent activity (after 2006), followed by a steadily high growth of the number of publications and a declining number of patents. This may be due to emergence of application-related problems at this stage, solving which required new knowledge. Dynamics for the keywords “algae” AND “fertiliser” stand out. The numbers of relevant publications and patents took turns to grow, but the total never exceeded even 50.

1	**2**	**3**	**4**[10]	**5**	**6**	**7**
12.	Application of microbiology-based technologies for recultivation of degraded and polluted soils, to make lands ruined by bad irrigation practices, overgrazing, and pollution by industrial and communal waste suitable for agricultural use again.	Steadily growing trend	Will become relevant in the medium horizon of the forecast (not before the mid-2020s)	2026	+	The trend displays a high patent activity with a sufficiently small number of academic publications. The following keywords are exceptions: - land AND degradation - arable AND land Here the number of publications is far higher than the number of patents, which may be explained by the wide coverage of the keywords and by a demand for new knowledge. Patent and publication activities' dynamics for the keywords "soil" AND "erosion" AND "technology" particularly stand out: here the growth of patents is accompanied by a decline of publication activity, and vice versa. Still, the overall trend is a steady growth of both. Generally, this technology is well-developed in application terms, and may soon reach maturity.
13.	Application of technologies for combining fisheries and agriculture (aquaponics), allowing to process fish excreta to make plant nutrients in situ, in the scope of a fully closed water cycle.	Emerging trend	Relevant already in the near horizon of the forecast (no later than the early- to mid-2020s)	2025	+/-	This trend displays a growth of patent activity since 2002, and a growing number of publications since 2004. Subsequently the number of patents exceeded the number of academic publications, and kept growing (even given the delayed updating of the databases). This may indicate the applied nature of the technology development, with no fundamental new advances. The small number of patents (less than 35) suggests the technology remains at the early development stage. The mismatch between the results of quantitative and expert validation is due to the fact that the experts gave a medium-term prognosis while the technologies are only beginning to find wide application – which suggests rather more long-term prospects.

1	2	3	4[10]	5	6	7
14.	Development of urban agriculture based on innovative technologies for super-intensive plant growing in artificial environments (vertical farms, aeroponics, hydroponics); growing farm animals' nutritious tissues in artificial nutrient solutions.	Emerging trend	Will become relevant in the medium horizon of the forecast (not before the mid-2020s)	2026	+	A steady growth of the number of publications combined with a relatively low patent activity were observed for the keywords "urban" AND "agriculture" throughout the period under consideration. This may indicate that the technology remains at the conceptual development stage. A higher (and steadily growing) number of patents than the number of academic publications was discovered for the keywords: - applications AND hydroponic AND technology - hydroponics The number of patents started to steadily grow after 1995. It may mean the technology has reached maturity because after 2010 a small decline was noted, followed by linear development. At the same time publication activity was steadily growing, albeit at a lower rate. Technologies described by the following keywords may be classified as emerging trends: - vertical farms - aeroponics - home AND aeroponics - home AND hydroponics An upsurge of patent activity was noted after 2006, though initially an increase of the number of publications was only observed for "vertical farms". Also, by 2015 the average number of patents did not exceed 60, which implies these technologies are just emerging.