

Bibliometric and social network analysis in scientific research on precision agriculture

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Precision agriculture (PA) is used to improve agricultural processes. A better understanding of PA as well as the evolution of the research status through the available literature are reported and discussed in this study. The Web of Science (WoS) was used to obtain the research records under study. Indicators of scientific productivity, collaboration between countries and research impact were evaluated through a social network analysis. The keywords included in the publications and subject areas under which the research was published were also evaluated through subject analysis. A total of 2027 articles were analysed from 1994 to 2014. The most productive journals were 'Computers and Electronics in Agriculture' (n = 191) and 'Precision Agriculture' (n = 110). The most frequent keywords were 'management' (n = 243), 'yield' (n = 231), 'soil' (n = 198) and 'variability' (n = 190). The collaboration network showed the United States occupying a central position, in combination with some leading countries such as Brazil, Germany, People's Republic of China, Canada, Australia and Spain. A steady increase in PA research was identified during the last decade, which was even more sharp between 2010 and 2014. The increased importance of PA research has recently led to the birth of specific journals such as Precision Agriculture. The increasing number of journals that publish articles related to the topics included in the WoS must also be considered. The network analysis identified a number of developed countries in the hotspot of international collaboration.

Keywords: Bibliometrics, precision agriculture, research collaboration, scientific analysis, social network.

THE term 'precision agriculture' (PA) defines a farm management approach where the decision making relies on information-based knowledge. Each step of the production cycle is designed to improve the agricultural process using precision management techniques. Both agricultural production and profitability are optimized with the corresponding PA management approach. Cost-effectiveness and environmental benefits are achieved due to the reduced use of inputs (energy, water, machinery, fertilizers, etc.). Increased yields and better quality are thus more likely to be the source of profitability¹.

PA is also defined as an improved agricultural management production strategy. However, it also takes into

account the considerable variation (even within very short distances) that influences the potential productivity of agricultural activity^{2,3}. The development of PA is, for instance, in response to the variable intrinsic ability of an agricultural land to produce outputs^{4,5}. Recent available techniques are of major importance in PA, including a number of systems such as global positioning system (GPS), or geographical information systems (GIS), in combination with remote sensing and/or crop-yield monitoring.

Research and applications of PA in the sugarcane industry were undertaken in Australia during the second part of the 1990s (refs 6, 7). Unfortunately, collapse in the price of sugar worldwide, among other factors, led to a low adoption of the technology. In the meantime, a gain in growing experience through research has been accumulated⁵. In the specific case of Australia, apart from the predominant focus on the grain industry, an increasing interest in other related industries such as wine, cotton and other cropping industries was also noticed⁸.

Interesting reviews on the state-of-the-art of precision viticulture (PV) have been published^{2,9,10}. In the studies by Bramley and Hamilton^{11,12}, yield crop maps were collected from different vineyards sites and over a number of

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vintages. The authors reported stable patterns over time in the variation of grape yields despite clear vintage-to-vintage effect ascribed to yearly varying weather patterns.

In addition, a recent review of the current situation of broad PA worldwide has been published¹³. The application of PA in different industries, including potato, sugar beet, wheat, barley, corn, soybean, oats, rice, sorghum and cotton has been reported¹³. The commercial use of PA for winegrapes^{9,14}, citrus^{15,16}, banana¹⁷, tea and date palm¹⁸ production has also been extensively reported. Improvements in the management of the tobacco and olives¹⁹, tomato²⁰, apple²¹, kiwifruit²² and sugarcane^{7,23} have also been identified.

The profitability when PA management was applied has been the main focus of some economic studies²⁴. These studies identified a limited difference on the pay-offs despite a large deviation from the optimum agricultural decision²⁵. Also, it has been reported that the possible benefits of PA application in the UK cereal industry are defined by the interactions between a number of variables, including farm size, cost of PA equipment and increase in the annual yield required to balance these costs²⁶.

On the other hand, the use of remote imaging with the possibility of incorporating yield mapping has received the greatest attention in PV²⁷. The main factor here is the sequential harvesting strategy defined based on yield/quality criteria needed to account for the observed variation²⁸.

The use of published studies to analyse the research trends through bibliometric approaches is receiving increasing attention. This is because the main indicators of scientific research as well as its progression over time are evaluated²⁹. Even though research on PA is gaining public importance, scientometric studies based on published research on this topic are currently not available. The contribution to an extensive understanding of the scientific knowledge in PA, as well as the analysis of its evolution through published papers included in the Web of Science (WoS) database is thus the main aim of this study.

Methods

The Science Citation Index-Expanded (SCIE) database was used in this study. The search strategy included the terms 'precision agriculture' or 'precision farming'. We used these keywords as they gave more satisfactory results. For better comprehension of the results, the topic field was used to conduct the search. The title, abstract and keywords were thus included within the topic field. The inclusion of quotation marks was done to guarantee enhanced precision of the obtained records, e.g. all records containing the terms in the same order. An individual revision of the items was performed to ensure their relevance. The analysis was performed including the articles published in the period from 1994 to 2014 (21

years). Only original papers and reviews were selected as research contributions. Conference abstracts, book reviews, bibliographical articles, letters, editorials, news and reprints were therefore not included in the study.

The evolution of published papers per year and distribution of papers per journal, keywords, WoS subject categories and countries were considered as indicators of scientific productivity. The number of citations, ratio citations per article as well as impact factor and quartile in Journal Citation Reports (JCR) subject categories were evaluated as the main indicators of impact. The most cited papers were also reported. Only the citations extracted from the WoS database received by the articles and reviews during the period of analysis were taken into account. The 2014 edition of the JCR was consulted to obtain the impact factor data. The number of co-occurrences among countries was studied through a social network analysis (SNA). The relationships and flows among people, groups, organizations or countries were mapped measuring a pairwise combination among countries for each paper, which may also be present in other papers. The nodes in the network include people and groups, while the links establish relationships or flows between the nodes.

The assigned keywords and subject categories of journals included in the JCR were evaluated through subject analysis. The number of co-occurrences between keywords (cowords) was evaluated using SNA. A co-occurrence indicates combinations of keyword pairs found repeated within the papers obtained. The application of SNA to co-word analysis provides network graphs showing a visual representation of the strongest associations between the keywords and thus concepts included in the scientific papers³⁰. SNA has also been used to evaluate knowledge in other fields such as environmental science³¹, tsunamis³², wine and health³³, among others.

The software Pajek³⁴ was used to generate and graphically visualize the networks. The software VOSViewer was used to generate the international collaboration network of countries. A threshold or minimum of relations to appear in the networks was applied in order to correctly visualize the networks. Different thresholds were later specified based on the results obtained.

Results

The number of articles obtained from the WoS during the period of analysis was 2027. As can be observed in Figure 1, the number of scientific articles published has increased since 1994. The most prominent growth has been observed in the last decade, since 75.8% of the papers was published.

Table 1 presents journals publishing more than 20 papers. The table also includes the number of citations received and the ratio citations per paper as well as

impact factor, the WoS subject category, including quartile and ranking within the category. The journals with the highest productivity were *Computers and Electronics in Agriculture* ($n = 191$), *Precision Agriculture* ($n = 110$), *Applied Engineering in Agriculture* ($n = 80$) and *Agronomy Journal* ($n = 52$). When the number of citations was evaluated *Computers and Electronics in Agriculture* ($n = 3.730$) ranked first, followed by *Remote Sensing of Environment* ($n = 2.240$), *Geoderma* ($n = 1.516$) and *Agronomy Journal* ($n = 1389$). *Remote Sensing of Environment* had higher impact factor (IF = 5.103), followed by *European Journal of Agronomy* (IF = 2.800), *Agricultural Systems* (IF = 2.504), *Fields Crop Research* (IF = 2.4746), and *Soil and Tillage Research* (IF = 2.367). Majority of the above-mentioned journals are within the first or second quartile in the subject category of JCR, excluding *Applied Engineering in Agriculture*, *Communications in Soil Science and Plant Analysis*, *Transactions of the ASABE*, *Revista Brasileira de Ciencia do Solo* and *Spectroscopy and Spectral Analysis* that rank in the third or fourth quartile.

Table 2 shows the most common keywords as well as their annual evolution. The most frequent keywords are ‘management’ ($n = 243$), ‘yield’ ($n = 231$), ‘soil’ ($n = 198$) and ‘variability’ ($n = 190$). For the majority of the keywords an increase in the frequency of use was observed especially since the 2000s. Keywords that significantly increased in frequency were ‘systems’ and ‘vegetation indexes’. Others only appear during the period 2000–2007: ‘electrical conductivity’, ‘electromagnetic induction’, ‘management zones’, ‘leaf-area index’, ‘chlorophyll content’, ‘hyperspectral’ and ‘scale’.

Table 3 provides the number of research indicators, including the most productive subject categories, the most common keywords assigned to the articles and the most prolific journals per subject category. The subject category agriculture, ‘multidisciplinary’ ($n = 530$) appears first, where the most common keywords are ‘yield’ ($n = 76$), ‘management’ ($n = 63$) and ‘systems’ ($n = 54$).

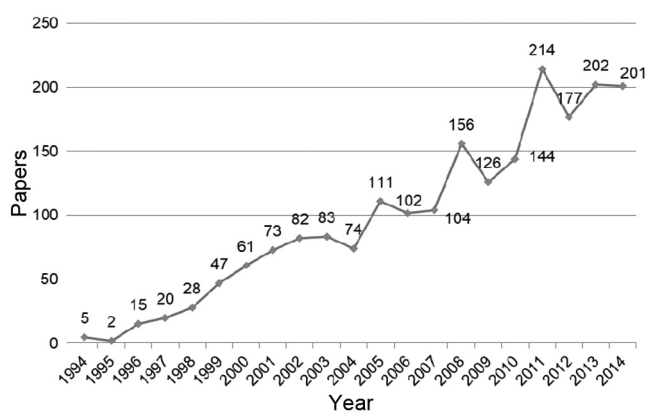


Figure 1. Annual evolution of published papers.

The most prolific journals within this subject category were *Computers and Electronics in Agriculture* ($n = 191$), *Precision Agriculture* ($n = 110$) and *Biosystems Engineering* ($n = 32$). The second most frequent subject category was ‘agronomy’ ($n = 363$), whose most frequent keywords were ‘yield’ ($n = 54$), ‘management’ ($n = 52$) and ‘soil’ ($n = 52$). The most prolific journals were *Agronomy Journal*, *Fields Crop Research* and *European Journal of Agronomy*. Three other subject category with more than 100 records were ‘agricultural engineering’ ($n = 327$; with ‘sensors’, ‘yield’ and ‘global positioning system’ as the most frequent keywords), ‘soil science’ ($n = 298$, with keywords ‘spatial variability’, ‘management’ and ‘variability’) and ‘computer science interdisciplinary applications’ ($n = 194$, with keywords ‘systems’, ‘yield’ and ‘global positioning system’). Other significant subject categories with more than 100 published papers include ‘remote sensing’ ($n = 141$), with the most frequent keywords being ‘vegetation indexes’ ($n = 50$), ‘reflectance’ ($n = 30$) and ‘chlorophyll content’ ($n = 23$); ‘plant sciences’ ($n = 131$) and ‘environmental sciences’ ($n = 122$).

Table 4 shows 21 research publications that received more than 100 citations. The most cited article, ‘Hyperspectral vegetation indices and novel algorithms for predicting green LAI of crop canopies’ was published in *Remote Sensing of Environment* in 2004. This paper received 407 citations. The second paper with the highest number of citations ($n = 383$) was published in 2002 in the same journal. The third most cited paper, with more than 300 citations, was published by Cassman in 1999 in *Proceedings of the National Academy of Sciences of the United States of America*. Three other papers received more than 200 citations and 15 papers more than 100 citations. Almost 50% of the most cited papers was published in two journals: *Remote Sensing of Environment* and *Computers and Electronics in Agriculture*.

Figure 2 shows the network of collaboration among countries. The sphere size, number of publications, connecting lines and papers published in collaborations are proportional. A central position is occupied by the US with other leading countries such as Brazil, Germany, People’s Republic of China, Canada, Australia and Spain. Collaboration was particularly more among the US and People’s Republic of China ($n = 37$), Canada ($n = 28$), Germany ($n = 16$) and South Korea ($n = 15$). Other collaborations were established between Germany and China ($n = 20$), the US and Italy ($n = 14$) as well as Australia and Spain ($n = 12$).

Figure 3 shows the keywords most frequently associated with these countries. In this figure, the number of articles and the number of keywords in papers published by each country are proportional to the sphere size and thickness of lines connecting the spheres respectively. The US has a wide variety of keywords (yield, corn, management and models, among others) followed by Brazil

Table 1. Papers in most productive journals, ratio citation per paper, rate citations per article, impact factor, subject category and ranking in subject category

Journal	No. of papers	No. of citations	Citations/papers	Impact factor	Web of Science subject category	Quartile	Category ranking
<i>Computers and Electronics in Agriculture</i>	191	3730	19	1.766	Agriculture, multidisciplinary; computer science, interdisciplinary, applications	Q1-Q2	5/57-31/100
<i>Precision Agriculture</i>	110	775	7	1.728	Agriculture, multidisciplinary	Q1	8/57
<i>Applied Engineering in Agriculture</i>	80	556	6	0.571	Agricultural engineering	Q4	11/12
<i>Agronomy Journal</i>	52	1389	26	1.518	Agronomy	Q2	24/78
<i>Geoderma</i>	43	1516	35	2.345	Soil science	Q1	7/34
<i>Field Crops Research</i>	36	759	21	2.474	Agronomy	Q1	11/78
<i>European Journal of Agronomy</i>	33	573	17	2.800	Agronomy	Q1	7/78
<i>Soil Science Society of America Journal</i>	33	981	29	1.821	Soil science	Q2	15/34
<i>Communications in Soil Science and Plant Analysis</i>	32	214	6	0.420	Chemistry, analytical; agronomy; plant sciences; soil science	Q3-Q4-Q4-Q4	58/78-70/75-165/196-30/34
<i>Biosystems Engineering</i>	32	355	11	1.357	Agriculture, multidisciplinary; agricultural engineering	Q2-Q1	5/12-11/57
<i>Remote Sensing of Environment</i>	32	2240	70	5.103	Environmental sciences; remote sensing; imaging science and photographic technology	Q1-Q1-Q1	9/210-1/23-1/27
<i>Sensors</i>	31	267	8	1.953	Chemistry, analytical; electrochemistry; instruments and instrumentation	Q3-Q3-Q1	38/75-15/26 -8/57
<i>Journal of Soil and Water Conservation</i>	27	504	18	1.722	Soil science; water resources; ecology	Q3-Q2-Q2	76/136-16/34-28/80
<i>International Journal of Remote Sensing</i>	23	352	15	1.138	Remote sensing; imaging science and photographic technology	Q2-Q3	10/23-16/27
<i>Revista Brasileira de Ciencia do Solo</i>	23	192	8	0.733	Soil science	Q4	27/34
<i>Soil and Tillage Research</i>	23	368	16	2.367	Soil science	Q1	6/34
<i>Transactions of the ASABE</i>	22	53	2	0.974	Agricultural engineering	Q3	8/12
<i>Remote Sensing</i>	21	109	5	2.101	Remote sensing	Q2	7/27
<i>Agricultural Systems</i>	18	305	16	2.504	Agriculture, multidisciplinary	Q1	3/57
<i>Spectroscopy and Spectral Analysis</i>	17	29	1	0.293	Spectroscopy	Q4	43/43

Table 2. Total number of published articles, including the most frequent keywords by time period

Keyword	1994–2000	2000–2007	2008–2014	Total
Management	18	70	155	243
Yield	16	72	143	231
Soil	20	76	102	198
Variability	4	67	119	190
Wheat	8	52	120	180
Spatial variability	16	55	103	174
Nitrogen	11	65	90	166
Systems	7	35	118	160
Models	10	54	90	154
Corn	12	54	86	152
Remote sensing	11	48	93	152
Vegetation indexes	3	24	97	124
Field	10	35	73	118
Reflectance	3	40	74	117
Geostatistics	9	41	60	110
Crops	1	36	68	105
Sensors	4	28	65	97
Classification	4	31	52	87
Soil properties	5	28	51	84
Global positioning system	16	26	36	78
Prediction	2	23	52	77
Growth	3	32	41	76
Electrical conductivity		22	53	75
Site-specific management	6	23	43	72
Water	4	30	37	71
Geographic information system	13	23	34	70
Electromagnetic induction		26	38	64
Management zones		18	45	63
Leaf-area index		16	45	61
Spectral reflectance	2	15	44	61
Quality	2	17	41	60
Water content	1	25	33	59
Phosphorus	3	17	33	53
Soil electrical conductivity	1	18	34	53
Chlorophyll content		9	43	52
Vegetation	2	12	38	52
Hyperspectral		9	42	51
Canopy	1	13	36	50
Canopy reflectance	1	12	36	49
Kriging	5	16	26	47
Scale		16	31	47
Simulation	6	15	26	47
Fertilizers	4	22	20	46
Grain-yield	2	13	30	45
Tillage	4	26	15	45
Cotton	1	18	25	44
Leaves	2	13	29	44
Plants	3	12	29	44
Moisture	3	13	26	42

(geostatics and yield), People's Republic of China and Spain (vegetation indexes and remote sensing) and Canada (yield and management).

Figure 4 shows the evolution of the network of co-words over three periods. The proportionality between the sphere sizes and the articles, including the keywords also applies to this figure. The same proportionality criterion is maintained for the thickness of the connecting lines and the number of publications with two keywords. In the first period (1994–2000), a threshold of two co-

occurrences was applied, thus consisting of a network with 54 keywords. The keyword 'soil' is centrally located and associated with 16 other keywords. Other words that act as intermediaries with less intensity (in partnership with five other keywords) are 'geostatics', 'spatial variability', 'management', 'global positioning system' and 'geographic information system'. In the second period (2000–2007), applying a threshold of 5 co-occurrences, the network contained 57 keywords with several of them having central roles and intermediation. These are

Table 3. Number of articles published per main subject areas, keyword and the most productive journals

Subject area	Main keywords						Most productive journals						
	<i>n</i>	Keyword 1	<i>n</i>	Keyword 2	<i>n</i>	Keyword 3	<i>n</i>	Journal 1	<i>n</i>	Journal 2	<i>n</i>	Journal 3	<i>n</i>
Agriculture, multidisciplinary	530	Yield	76	Management	63	Systems	54	<i>Computers and Electronics in Agriculture</i>	191	<i>Precision Agriculture</i>	110	<i>Biosystems Engineering</i>	32
Agronomy	363	Yield	54	Management	52	Soil	52	<i>Agronomy Journal</i>	52	<i>Field Crops Research</i>	26	<i>European Journal of Agronomy</i>	33
Agricultural engineering	327	Sensors	35	Yield	29	Global positioning system	28	<i>Transactions of the ASABE</i>	129	<i>Applied Engineering in Agriculture</i>	80	<i>Biosystems Engineering</i>	32
Soil science	298	Spatial variability	53	Management	52	Variability	50	<i>Geoderma</i>	43	<i>Soil Science Society of America Journal</i>	33	<i>Communications in Soil Science and Plant Analysis</i>	32
Computer science, Interdisciplinary applications	194	Systems	29	Yield	22	Global positioning system	18	<i>Computers and Electronics in Agriculture</i>	191	<i>Mathematical Geology</i>	2	<i>Mathematical Geosciences</i>	1
Remote sensing	141	Vegetation indexes	50	Reflectance	30	Chlorophyll content	23	<i>Remote Sensing of Environment</i>	32	<i>International Journal of Remote Sensing</i>	23	<i>Remote Sensing</i>	21
Plant sciences	134	Soil	27	Management	20	Corn	19	<i>Communications in Soil Science and Plant Analysis</i>	32	<i>Weed Science</i>	15	<i>Journal of Plant Nutrition and Soil Science</i>	12
Environmental sciences	122	Vegetation indexes	18	Hyperspectral	14	Management	13	<i>Remote Sensing of Environment</i>	32	<i>Journal of Applied Remote Sensing</i>	10	<i>Journal of Environmental Quality</i>	7
Chemistry, analytical	78	Soil	11	Nitrogen	9	Management	8	<i>Communications in Soil Science and Plant Analysis</i>	32	<i>Sensors</i>	31	<i>Sensor Letters</i>	9
Imaging science and photographic technology	71	Vegetation indexes	23	Reflectance	15	Canopy	12	<i>International Journal of Remote Sensing</i>	23	<i>Photogrammetric Engineering and Remote Sensing</i>	13	<i>IEEE Transactions on Geoscience and Remote Sensing</i>	9

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Table 3. (Contd)

Subject area	Main keywords						Most productive journals						
	<i>n</i>	Keyword 1	<i>n</i>	Keyword 2	<i>n</i>	Keyword 3	<i>n</i>	Journal 1	<i>n</i>	Journal 2	<i>n</i>	Journal 3	<i>n</i>
Water resources	61	Management	12	Variability	11	Soil	9	<i>Journal of Soil and Water Conservation</i>	27	<i>Agricultural Water Management</i>	7	<i>Journal of Hydrology</i>	5
Instruments and instrumentation	58	Systems	10	Sensors	8	Nitrogen	7	<i>Sensors</i>	31	<i>Sensor Letters</i>	9	<i>IEEE Sensors Journal</i>	5
Geosciences, multidisciplinary	51	Soil	9	Management	6	Spatial variability	6	<i>Photogrammetric Engineering and Remote Sensing</i>	13	<i>ISPRS Journal of Photogrammetry and Remote Sensing</i>	6	<i>Journal of Hydrology</i>	5
Technology	45	Vegetation indexes	17	Reflectance	13	Hyperspectral	12	<i>Remote Sensing of Environment</i>	32	<i>Journal of Applied Remote Sensing</i>	10	<i>Journal of Agricultural and Food Chemistry</i>	2
Engineering electrical and electronics	44	Vegetation indexes	8	Reflectance	7	Canopy	6	<i>IEEE Transactions on Geoscience and Remote Sensing</i>	9	<i>IEEE Geoscience and Remote Sensing Letters</i>	7	<i>IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing</i>	7
Ecology	42	Management	10	Soil	6	Spatial variability	6	<i>Journal of Soil and Water Conservation</i>	27	<i>Agriculture Ecosystems and Environment</i>	5	<i>Ecological Modelling</i>	3
Food science and technology	42	Yield	8	Remote sensing	5	Management	4	<i>Journal of Food Agriculture and Environment</i>	11	<i>International Sugar Journal</i>	9	<i>Australian Journal of Grape and Wine Research</i>	3
Imaging science and photographic electrochemistry	42	Vegetation indexes	17	Hyperspectral	12	Reflectance	12	<i>Remote Sensing of Environment</i>	32	<i>Journal of Applied Remote Sensing</i>	10		
	40	Systems	7	Sensors	6	Nitrogen	5	<i>Sensors</i>	31	<i>Sensor Letters</i>	9		

Table 4. Most cited papers

Authors	Title	Reference	Citation
Haboudane, D., Miller, J. R., Pattey, E., Zarco-Tejada, P. J. and Strachan, I. B.	Hyperspectral vegetation indices and novel algorithms for predicting green LAI of crop canopies: modelling and validation in the context of precision agriculture.	<i>Remote Sensing Environ.</i> , 2004, 90 , 337–352	407
Haboudane, D., Miller, J. R., Tremblay, N., Zarco-Tejada, P. J. and Dextraze, L.	Integrated narrow-band vegetation indices for prediction of crop chlorophyll content for application to precision agriculture.	<i>Remote Sensing Environ.</i> , 2002, 81 , 416–426	383
Cassman, K. G.	Ecological intensification of cereal production systems: yield potential, soil quality and precision agriculture.	<i>Proc. Natl. Acad. Sci. USA</i> , 1999, 96 , 5952–5959	343
Rossel, R. A. V., Walvoort, D. J. J., McBratney, A. B., Janik, L. J. and Skjemstad, J. O.	Visible, near infrared, mid infrared or combined diffuse reflectance spectroscopy for simultaneous assessment of various soil properties.	<i>Geoderma</i> , 2006, 131 , 59–75	279
Wang, N., Zhang, N. Q. and Wang, M. H.	Wireless sensors in agriculture and food industry – recent development and future perspective.	<i>Comput. Electron. Agric.</i> , 2006, 50 , 1–14	238
Brown, D. J., Shepherd, K. D., Walsh, M. G., Mays, M. D. and Reinseh, T. G.	Global soil characterization with VNIR diffuse reflectance spectroscopy.	<i>Geoderma</i> , 2006, 132 , 273–290	221
Corwin, D. L. and Lesch, S. M.	Apparent soil electrical conductivity measurements in agriculture.	<i>Comput. Electron. Agric.</i> , 2005, 46 , 11–43	180
Lal, R.	Soil carbon dynamics in cropland and rangeland.	<i>Environ Pollut.</i> , 2002, 116 , 353–362	177
Di, H. J. and Cameron, K. C.	Nitrate leaching in temperate agroecosystems: sources, factors and mitigating strategies.	<i>Nutr. Cycl. Agroecosyst.</i> , 2002, 64 , 237–256	172
Gitelson, A. A.	Wide dynamic range vegetation index for remote quantification of biophysical characteristics of vegetation.	<i>J. Plant Physiol.</i> , 2004, 161 , 165–173	168
Corwin, D. L. and Lesch, S. M.	Application of soil electrical conductivity to precision agriculture: theory, principles, and guidelines.	<i>Agron. J.</i> , 2003, 95 , 455–471	167
Jacquemoud, S., Bacour, C., Poilve, H. and Frangi, J. P.	Comparison of four radiative transfer models to simulate plant canopies reflectance: direct and inverse mode.	<i>Remote Sensing Environ.</i> , 2000, 74 , 471–481	163
Stone, M. L., Solie, J. B., Raun, W. R., Whitney, R. W., Taylor, S. L. and Ringer, J. D.	Use of spectral radiance for correcting in-season fertilizer nitrogen deficiencies in winter wheat.	<i>Trans. ASABE</i> , 1996, 39 , 1623–1631	151

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Table 4. (Contd)

Authors	Title	Reference	Citation
Sudduth, K. A., Drummond, S. T. and Kitchen, N. R.	Accuracy issues in electromagnetic induction sensing of soil electrical conductivity for precision agriculture.	<i>Comput. Electron. Agric.</i> , 2001, 31 , 239–264	150
Zhang, N. Q., Wang, M. H. and Wang, N.	Precision agriculture – a worldwide overview.	<i>Comput. Electron. Agric.</i> , 2002, 36 , 113–132	147
Pierce, F. J. and Nowak, P.	Aspects of precision agriculture.	<i>Adv. Agron.</i> , 1999, 67 , 1–85	147
Adamchuk, V. I., Hummel, J. W., Morgan, M. T. and Upadhyaya, S. K.	On-the-go soil sensors for precision agriculture.	<i>Comput. Electron. Agric.</i> , 2004, 44 , 71–91	146
Zarco-Tejada, P. J. <i>et al.</i>	Assessing vineyard condition with hyperspectral indices: leaf and canopy reflectance simulation in a row-structured discontinuous canopy.	<i>Remote Sensing Environ.</i> , 2005, 99 , 271–287	145
Schroder, J. J., Neeteson, J. J., Oenema, O., and Struik, P. C.	Does the crop or the soil indicate how to save nitrogen in maize production? Reviewing the state of the art.	<i>Fields Crop Res.</i> , 2000, 66 , 151–164	142
Berni, J. A. J., Zarco-Tejada, P. J., Suarez, L. and Fereres, E.	Thermal and narrowband multispectral remote sensing for vegetation monitoring from an unmanned aerial vehicle.	<i>IEEE Trans. Geosci Remote Sensing</i> , 2009, 47 , 722–738	129
Colombo, R., Bellingeri, D., Fasolini, D. and Marino, C. M.	Retrieval of leaf area index in different vegetation types using high resolution satellite data.	<i>Remote Sensing Environ.</i> , 2003, 86 , 120–131	129

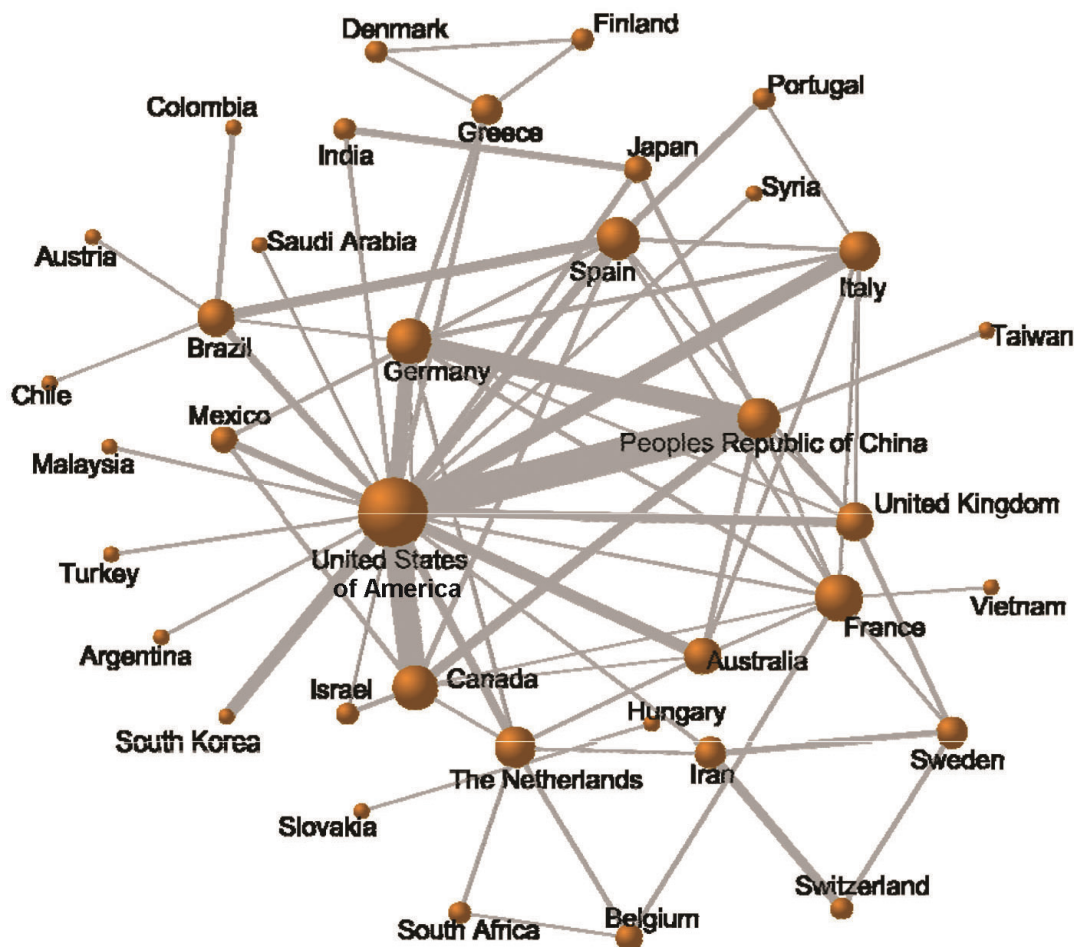


Figure 2. Network of collaboration among countries. The size of the spheres is proportional to the number of published papers per country. Only countries with five or more papers are represented.

‘variability’, ‘spatial variability’, ‘nitrogen’, ‘yield’ and ‘corn’, among others. In the third period (2008–2014), with a threshold of 10 co-occurrences, the network of co-words included 48 keywords; new terms occurred with central position such as ‘system’ and ‘reflectance’.

Discussion

The annual evolution of scientific articles, as well as the most productive journals, subject categories, productive countries and their international collaboration and also the most cited papers are reported in this study. The evolution of scientific knowledge on the topic through the most frequently used keywords and the co-words SNA is also shown. Through this study an enhanced level of cooperation between international communities is promoted due to the availability of information on PA with the establishment of a favourable environment for research networking, collaboration and debate.

Several studies are available in the literature that has used scientometric approaches to evaluate the knowledge

status of a particular field or scientific topic. Some examples are: plant genetic resources³⁵, biotechnology^{36,37}, food and feed safety²⁹, flow cytometry³⁸, environmental marketing³⁹, production of bioenergy from biomass⁴⁰, the effects of wine on health³³ and soil contamination⁴¹. However, we found only one paper from Portugal using SNA to measure and map scientific knowledge in PA⁴². A number of databases are available nowadays, which have helped researchers perform studies on a wide variety of disciplines and topics. For example, in the WoS, using the WoS database, it is possible to perform bibliometric analysis taking into account citations received and journal impact factors. On the other hand, several software programs allow the visualization of the relationship among data by means of exploring portions of the articles like titles, keywords and abstracts⁴³.

The annual evolution of the number of published articles shows three well-differentiated periods. The first one extends to early 2000, with a moderate increased production of 41 papers on an average per year. In 1994, only one paper was published with near 100 papers per year in 2000. The second period is from 2001 to 2007 with

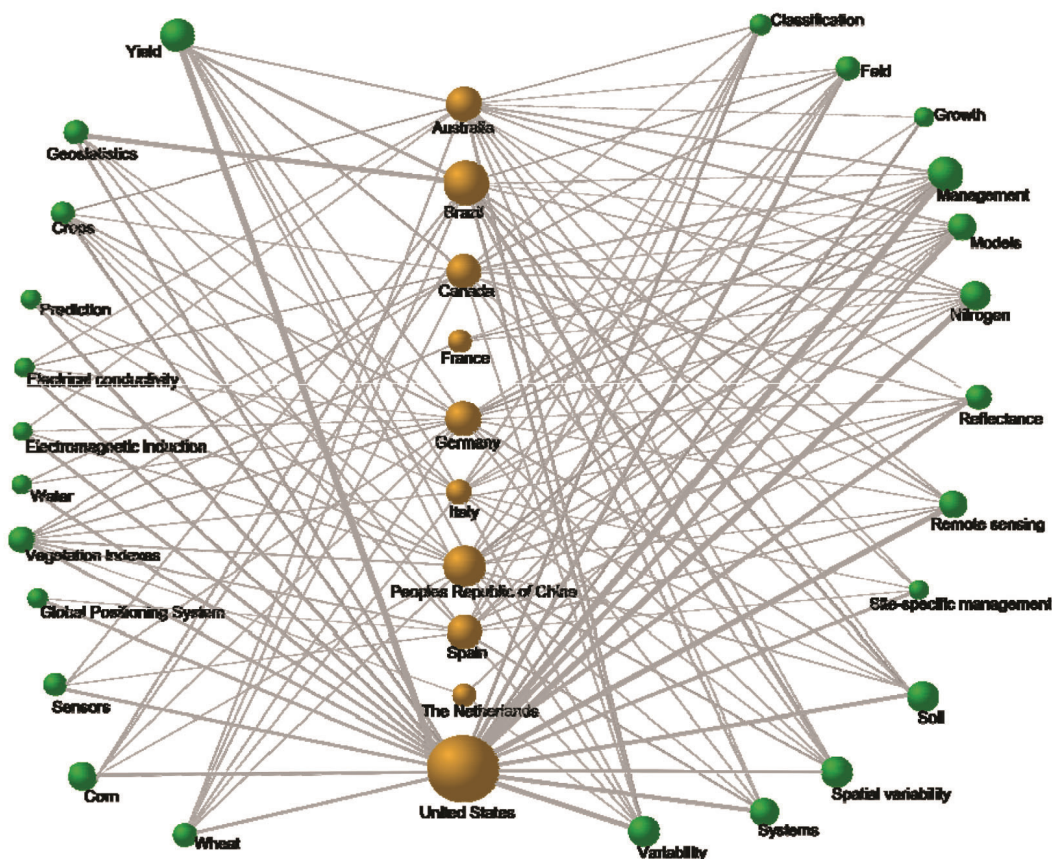


Figure 3. Network of main productive countries and most frequent keywords. The size of the spheres is proportional to the number of papers published including the keywords by each countries and to the number of papers published per keyword.

similar growth, and with an average of 185 papers per year. It is in the third period (2008–2014) where maximum growth is seen, reaching 540 articles in 2014, with an average of 435 papers per year. The increased productivity observed on PA is supported by the overall number of publications identified in this study. This growth has also been observed, from the bibliometric point of view, in other research areas such as agro-ecology⁴⁴, soil contamination⁴¹ and wine and health³³.

From its origins in the late 1980s, PA was developed in contrast to mainstream agriculture and to traditional agricultural institutions and policies. In the nineties, the EU completely changed this situation with the introduction of organic farming support schemes, regulations and increasing involvement of state authorities on this topic (e.g. training, education, advice, information, research)⁴⁵. In June 2014, the Joint Research Centre of the European Commission published a report entitled ‘precision agriculture: an opportunity for EU farmers 2004–2020’, where experts on the topic suggested the need to develop appropriate guidelines and implementation assistance, also highlighting that this should go together with the corresponding research and development studies that have to define, monitor and evaluate specific programmes

and measurements. Sharing the acquired knowledge and expertise is thus encouraged and the state members are required to provide conclusions, advice and identify research gaps within this topic. In the US, the Alternative Farming Systems Information Center (AFSIC) is specialized in identifying resources regarding sustainable food systems and practices, and is supported by the United States Department of Agriculture with the objective of ensuring a sustainable future in agricultural practices and farming.

The increased importance of PA research in recent times has given birth to specific journals such as *Precision Agriculture* (Springer), available since 1999, but only included in the WoS from 2006. Before the foundation of *Precision Agriculture*, the European Conference on Precision Agriculture had been organized every alternate year and its proceedings have played a key role in documenting and communicating research results. In addition to the existing journals, the increasing number of journals that publish articles related to the topic included in the WoS must also be considered. For example, the number of journals included in the ‘agriculture multidisciplinary’ subject category has increased from 35 in 2008 to 56 in 2013. To this subject category belongs the journal in

deposits^{40,47}, mining geochemical exploration⁴⁸, evaluation of solar resource⁴⁹ and for assessing the effects of air contaminants on human health in industrialized areas⁵⁰.

Considering at the subject categories (areas of research) and in accordance with the previous results, articles published in non-specific areas of agriculture, such as agriculture multidisciplinary, agronomy, agricultural engineering, soil science and plant science and in technological areas such as computer science, remote sensing, imaging science, photographic technology, among others, were identified. Thus technology plays an important role in the development of precision farming. There are several studies focusing on areas such as electronics, ecology, food science and technology and imaging and photographic sciences. This spread in subject categories suggests that PA is a research topic that further requires collaboration of other scientific areas from alternative disciplines.

The analysis of collaboration between countries shows that research on the topic is mainly performed in developed countries such as the US, Canada, Germany, Italy and Spain. There is noteworthy collaboration between the US and China, and partnership among developing countries such as South American and Asian countries. This geographical and economical distribution has also been noticed in topics such as agro-ecology⁴⁴, soil contamination⁴¹, and production of bioenergy from biomass⁵¹.

In terms of papers with more citations, a number of findings need to be highlighted. First, a large part of them deal with several aspects of soil (quality, conductivity, sensors, properties, carbon dynamics, etc.), vegetation indices and spectroscopy, among others. Secondly, the multidisciplinary nature of the journals publishing research studies on this topic has been identified. Finally, the importance of related issues to the environment, ecology, sensors, computers and electronics has also been observed.

Conclusion

Helpful insights in precision farming research have been identified in this study. Many themes such as the most promising subject areas, journals, topics and collaboration between countries have been evaluated and further discussed. On the basis of the research findings, some conclusions and recommendations for the key network players could be drawn. The research on PA had markedly increased during the last decade, more sharply between 2010 and 2014. The scientometric and SNA has the ability to provide useful information on the research direction in the field, similar to that observed in other new emerging fields, i.e. emerging technologies and processes. Therefore, addition of scientometric studies to the content analysis studies as well as literature reviews increases knowledge in the area. SNA enables us to identify the main traits on the evolution of PA using a net-

work of co-words, as well as the leader countries in the area and their network of collaboration, and finally the main topics dealt with by each country.

Although estimating the importance of PA has not been widely reported in the past, we believe that such a study will have a great impact on the present and future discussions on PA. First, the status of PA research needs to be known in order to establish adequate policy practices by the policy-makers. It is also important to be aware of the current research in order for the private sector firms to position themselves against their competitors⁵².

Limitations

Our study has some limitations that need be addressed. First, bibliometric analysis was performed based on articles archived in WoS. The reason for using WoS instead of Scopus or Google Scholar was based on conclusions drawn in studies reported in the literature^{52,53}. Second, in the early nineties, when PA had developed as a topic for scientific study, proceedings of the major PA conferences held in the US and Europe were an important source of research information. However, these have not been included in the present study because the ideas reported are often published in scientific journals. However, it is possible that many of these papers were never published in refereed journals because of the lack of viable venues for publication and, therefore, such research has not been analysed in our study. Third, also in the early nineties, there were other terms used for PA research, as 'site-specific farming', 'spatial soil management' or 'smart farming'; so we could have missed a few records. Nevertheless, the terms used in our search have ensured greater accuracy in the obtained records.

Future directions

Future research could identify the networks of collaboration between researchers and institutions, allowing for the identification of groups of authors and/or institutions that currently make up the research front in this area and its main research topics, information that would be useful both to strengthen collaboration networks between the research teams working on similar or related topics, which indicates that newcomers can make contact and be integrated into the networks. Bullock *et al.*⁵⁴ have highlighted the importance of multidisciplinary teams. Moreover, they emphasize the importance of providing rewards for teams participating in multidisciplinary research.

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