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Climate change and viticulture - a quantitative analysis of a highly dynamic research field

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Summary

In this study, we analyzed the newly emerging research field of climate change in combination with viticulture. Our analyses have two objectives: First, the overall publication output and the growth of research on climate change and viticulture is presented and analyzed. We developed a sophisticated search query to cover the relevant literature as completely as possible and to exclude irrelevant literature. The time evolution of the publications of the research topic as well as the most contributing journals and countries of authors, and the major research areas are presented. Second, most important publications in the historical context of this field are identified. Both analyses are based on a carefully selected publication set of 1039 papers (articles, reviews, and conference proceedings) dealing with the implications of climate change for viticulture. The results reveal that the number of papers published per year dealing with climate change and viticulture shows a strong increase: Since around 2000, the number increased by a factor of ten, whereas in the same time period the overall number of papers increased by a factor of around two. We identified 14 citation classics which include fundamental early works of viticulture with a weak connection to climate change and more recent works with a stronger connection to climate change.

Key words: climate change; viticulture; citation analysis; RPYS.

Introduction

Climate change has gained strongly increasing attention in the natural sciences and more recently also in the social and political sciences. Scientists actively work to understand past climate and to predict future climate by using observations and theoretical models. Various subfields from physics, chemistry, meteorology, and geosciences are interlinked. The scientific community has contributed extensively with various data, discussions, and projections on the future climate as well as on the effects and risks of the expected climatic change (IPCC Synthesis Report 2014). Climate is one of the key controlling factors in wine production since grapevines (*Vitis vinifera*) are very responsive to their surrounding environment. The gradually rising average global temperature is anticipated to affect viticulture all over the world, having both positive and negative effects on the various wine regions. Winegrowers will have to adapt viticulture to climate change using suitable mitigation strategies. Consequently, research dealing with the implications of global warming for viticulture is among the many newly arising sub-fields of climate change research (e.g. impacts on food production or human health).

The analyses of this study have two objectives: First, the overall publication output and the growth of research on climate change and viticulture is presented and analyzed. We developed a sophisticated search query to cover the relevant literature as completely as possible (Haunschild *et al.* 2016), for example by excluding publications on climate and viticulture not relevant for the global warming issue. The time evolution of the publications of the research topic, the most contributing journals and countries of authors, and the major research areas are presented. Second, this study aims to answer the following questions: Which are the most frequently cited early works in climate change publications dealing with viticulture and thus are most important for the evolution of this field? On whose shoulders do the publishing authors stand and which are the origins or intellectual roots? Which are the most influential (most frequently cited) papers published in more recent years?

Method

Dataset used: The analyses of this study are based on a carefully selected publication set of 1039 papers (articles, reviews, and conference proceedings) which deal with the implications of climate change for viticulture. Papers published between 1974 and 2016 were searched in Clarivate Analytics (formerly Thomson Reuters) Web of Science (WoS) database (date of search: June 7, 2016). The WoS search query is given in the Appendix. The publications retrieved do not comprise the complete publication set covering any research paper relevant for the climate change and viticulture research field. There are presumably more papers which appeared in journals not covered by the WoS (e.g. books or book chapters). However, we assume that we have included by far most of the relevant publications

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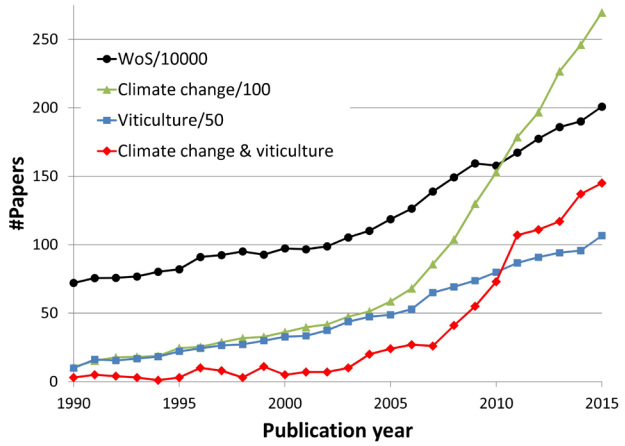

Fig. 1: Annual number of climate change and viticulture publications between 1990 and 2015 (only articles, reviews, and proceedings papers). 11 papers which appeared prior to 1990 and 65 papers which were indexed by the WoS in the first half of 2016 are not included in the graph. For comparison, the time evolution of the overall number of publications covered by the WoS as well as the number of publications dealing either with climate change or viticulture (each multiplied with appropriate factors) are included.

Appendix

WoS Serch Query (date of searching: June 7, 2016)

# 7	1,039	#5 AND #4 **Refined by: DOCUMENT TYPES:** (ARTICLE OR PROCEEDINGS PAPER OR REVIEW) Indexes=SCI-EXPANDED, SSCI, A&HCI, CPCI-S, CPCI-SSH, BKCI-S, BKCI-SSH, ESCI, CCR-EXPANDED, IC Timespan=1900-2016
# 6	1,081	#5 AND #4 Indexes=SCI-EXPANDED, SSCI, A&HCI, CPCI-S, CPCI-SSH, BKCI-S, BKCI-SSH, ESCI, CCR-EXPANDED, IC Timespan=1900-2016
# 5	80,979	**TOPIC:** (enolog* OR grape OR grapes OR grapevine OR grapevines OR vine OR vines OR vineyard OR vineyards OR viniculture OR viticulture OR wine OR wines OR winegrape OR winegrapes OR winegrowing) Indexes=SCI-EXPANDED, SSCI, A&HCI, CPCI-S, CPCI-SSH, BKCI-S, BKCI-SSH, ESCI, CCR-EXPANDED, IC Timespan=1900-2016
# 4	258,145	#3 OR #2 OR #1 Indexes=SCI-EXPANDED, SSCI, A&HCI, CPCI-S, CPCI-SSH, BKCI-S, BKCI-SSH, ESCI, CCR-EXPANDED, IC Timespan=1900-2016
# 3	117,519	**TITLE:** (climat* OR paleoclimat* OR palaeoclimat*) Indexes=SCI-EXPANDED, SSCI, A&HCI, CPCI-S, CPCI-SSH, BKCI-S, BKCI-SSH, ESCI, CCR-EXPANDED, IC Timespan=1900-2016
# 2	66,848	**TOPIC:** („climate warming“ OR „climatic warming“ OR „global temperature*“ OR „global warming“ OR „greenhouse effect“ OR „greenhouse gas*“ OR „greenhouse warming“) Indexes=SCI-EXPANDED, SSCI, A&HCI, CPCI-S, CPCI-SSH, BKCI-S, BKCI-SSH, ESCI, CCR-EXPANDED, IC Timespan=1900-2016
# 1	150,970	**TOPIC:** („climate change“ OR „climate changes“ OR „climate changing“ OR „climatic change“ OR „climatic changes“ OR „climatic changing“) Indexes=SCI-EXPANDED, SSCI, A&HCI, CPCI-S, CPCI-SSH, BKCI-S, BKCI-SSH, ESCI, CCR-EXPANDED, IC Timespan=1900-2016

(*i.e.* journal-based publications), in particular the key papers dealing with research on climate change and viticulture. Since researchers in the sciences and engineering are (increasingly) publishing their research results in peer-reviewed journals which are covered by Clarivate Analytics in the WoS (Adams and Gumey 2014, Digital Science 2016), it is reasonable to use this database for our analysis.

Visualization of research topics: The method which we used for revealing the thematic content of our publication set is based on the analysis of the title words. We used the VOSviewer software package (Van Eck and Waltman 2010) for mapping the title words of the climate change research and viticulture literature (www.vosviewer.com). The title word map presented in this study is based on bibliographic coupling for positioning the nodes (in our case: the corresponding title words) on the map. The distance between two nodes (two words) is proportional to the similarity (relatedness) with regard to the references cited within the publications having these words in the title. Hence, title words of papers that cite similar literature are found closer to each other. The size of the nodes is proportional to the number of papers with a specific title word. The nodes on the map are assigned by VOSviewer to clusters based on a specific cluster algorithm (the clusters are highlighted in different colors). These clusters identify closely related nodes, where each node is assigned to only one cluster.

Cited reference analysis: Questions regarding the historical context of research fields or topics can be answered by using a bibliometric method called "Reference Publication Year Spectroscopy" (RPYS, Marx *et al.* 2014) in combination with a recently developed tool named CRExplorer (http://www.crexplorer.net, Thor *et al.* 2016). In this study, we determined which references have been most frequently cited by the papers in our publication set. The RPYS changes the perspective of citation analysis from a times cited to a cited reference analysis (Bornmann and Marx 2013).

The analysis of the publication years of the references cited by all the papers in a specific research field shows that (earlier) publication years are not equally represented. Some years occur particularly frequently among the cited references. The years appear as pronounced peaks in the distribution of the reference publication years (*i.e.* the spectrogram). The peaks are frequently based on single early publications which are highly cited compared to other early publications. The highly cited papers are – as a rule – of specific significance to the research field in question (here: climate change research and viticulture) and often represent its origins and intellectual roots (Marx *et al.* 2014). In recent years, several studies have been published, in which the RPYS was basically described and applied to examine the historical roots of research fields (Marx and Bornmann 2014, Leydesdorff *et al.* 2014, Comins and Hussey 2015a and b).

Recently, we applied RPYS to reveal which early works are cited most frequently in the overall climate change research literature (Marx *et al.* 2016). In this study, we present an analysis of climate change and viticulture as a more specific research topic. We performed the reference analysis by importing the climate change and viticulture publication data including the cited references (downloaded from the

WoS) into the CRExplorer. The first step in RPYS is to select the publications of a specific research field and to extract all references cited therein. The second step is to establish the distribution of the frequencies of the cited references over the reference publication years and to determine the early reference publication years cited rather frequently. The third step is to analyze these reference publication years for frequently cited publications.

For applying RPYS, all cited references (n = 34,792) have been selected from the papers of our publication set on climate change and viticulture (n = 1039). The cited reference publication years range from 1541 to 2016. We removed all references with reference publication years prior to 1900, resulting in 34,560 references (there are no references with reference counts above 2 published before 1900). The references were sorted according to the cited reference year and the number of cited references. The CRExplorer offers the possibility to cluster and merge variants of the same cited reference (Thor *et al.* 2016). These variants are a great problem in citation analyses, because there is the danger that the impact of single publications is distributed over several cited reference variants (Marx 2011).

We clustered and merged the associated reference variants in our dataset (which are mainly caused by misspelled references) using the corresponding CRExplorer module. Clustering the reference variants via volume and page numbers and subsequently merging aggregated 174 cited references (for more information on using the CRExplorer see "guide and datasets" at www.crexplorer.net). Due to the many possible errors in cited references, the automatic clustering and merging procedure of the CRExplorer may not unify all possible variants. Therefore, the CRExplorer offers the possibility to cluster cited references manually. The manual cleaning is only practicably manageable with low numbers of cited references. Thus, we applied it only to the references published prior to 2000. In our experience, older cited references are more prone to "mutation" and more reference variants can be found.

After clustering and merging we applied a further cutback: To focus the RPYS on the most-pronounced peaks, we removed all references with reference counts below 10 (resulting in a final number of 235 cited references) for the detection of the most frequently cited works. A minimum reference count of 10 has proved to be reasonable in particular for early references (Marx *et al.* 2014, Marx and Bornmann 2014).

Note that RPYS reveals the most frequently cited (referenced) papers within specific reference publication years. RPYS does not identify the most highly cited papers of the publication set under study (as usually done by bibliometric analyses in research evaluation). The RPYS analysis aims to mirror the knowledge base of the relevant research topic (here: climate change and viticulture). Readers who have access to the WoS and are interested in an in-depth analysis of the knowledge base (see the search query in the appendix) can use the CRExplorer interactively (http://www.crexplorer.net).

Table 1

The top-10 journals of papers dealing with climate change and viticulture

Journal	# Papers	% Papers
Acta Horticulturae	66	6.4
Australian Journal of Grape and Wine Research	46	4.4
American Journal of Enology and Viticulture	39	3.8
Journal International des Sciences de la Vigne et du Vin	24	2.3
Agriculture Ecosystems Environment	20	1.9
International Journal of Biometeorology	20	1.9
Agricultural and Forest Meteorology	19	1.8
Climatic Change	18	1.7
Climate Research	16	1.5
VITIS – Journal of Grapevine Research	16	1.5

Results

Publication output and growth of the research field: To provide an overview of the development of the research field dealing with climate change and viticulture, the time evolution of the publication productivity (output) has been analyzed measured as numbers of papers published per year. Fig. 1 shows the annual number of papers covered by the WoS database. Based on our experience with the WoS, we assume that at the date of searching (June 7, 2016) the publications from 2015 have been (almost) completely covered.

According to Fig. 1, the number of papers published per year dealing with climate change and viticulture shows a strong increase: Since around 2000, the number increased by a factor of ten, whereas in the same time period the overall number of papers covered by the WoS databases increased by a factor of around two (Bornmann and Mutz 2015). Fig. 1 exhibits a doubling of the climate change and viticulture papers every five years. This corresponds roughly to the growth of the overall climate change research field (Haunschild *et al.* 2016).

The exponential growth of climate change relevant literature correlates with the increasing influence of the IPCC Assessment Reports (https://www.ipcc.ch). These reports eventually made climate change research a hot topic. The reports revealed the strong need of further research for a better understanding of the earth's climate system and for improved predictions of the future climate. Furthermore, the effects, impacts, and risks of climate change became increasingly obvious and more concrete. The discussion of the human induced climate change as a real phenomenon (at least for the vast majority of the scientific community, Anderegg 2010) presumably stimulated also research on future pathways for adaptation and mitigation of viticulture.

Tab. 1 shows the top-10 journals ordered by the number of papers in our dataset. The papers are distributed across many different journals: Only 27.2 % of the papers are included in the top-10 journals in Tab. 1. About 6 % of the papers appeared in "Acta Horticulturae" that is a peer reviewed journal publishing mainly the proceedings of ISHS Symposia and the International Horticultural Congress (http://www.ishs.org/acta-horticulturae). The journal "Australian Journal of Grape and Wine Research" published about 4 % of the papers. The journal is intended

to provide a forum for the exchange of information about research in viticulture and oenology (http://onlinelibrary.wiley.com/journal/10.1111/%28ISSN%291755-0238/homepage/ProductInformation.html). The "American Journal of Enology and Viticulture" appears on rank three. It is the official journal of the American Society for Enology and Viticulture (ASEV) and is dedicated to scientific research on winemaking and grapegrowing.

The most active countries in research on climate change and viticulture are presented in Tab. 2. The results in the table are based on the country information in the affiliation of the authors (papers with multiple affiliations occur multiple times in Tab. 2). About 20 % of the papers in our publication set are from authors located in the US, further 15 % and 13 % in Spain and Italy, respectively. Besides the US as the leading scientific country in general, the countries where viticulture is already negatively affected by climate change are most active in research.

Table 2

The top-10 countries affiliated with the papers dealing with climate change and viticulture (the affiliations of all authors and not only the first-authors are considered)

Country of author	# Papers	% Papers
USA	207	19.9
Spain	154	14.8
Italy	138	13.3
Australia	114	11.0
France	103	9.9
Germany	81	7.8
Portugal	57	5.5
UK	54	4.1
Canada	39	3.8
China	38	3.7

To give a rough impression of the subject-specific orientation of our publication set, Tab. 3 lists the top-10 WoS research areas assigned to the papers dealing with climate change and viticulture. The major research area is "Agriculture" (about 44 %). Since about 18.500 papers (7 %) of the overall literature on climate change research have been assigned to the same research area, our publication set comprises only about 3 % of the overall publications on climate change within this area. In Tab. 3, further research areas besides "Agriculture" are "Environmental Sciences and Ecology" (about 25 %) and "Food Science Technology" (about 20 %).

Table 3

The top-10 WoS research areas assigned to the papers dealing with climate change and viticulture. Note that many papers are assigned to more than one research area, leading to a substantial overlap

Research area (WoS)	# Papers	% Papers
Agriculture	461	44.4
Environmental Sciences & Ecology	262	25.2
Food Science Technology	196	18.9
Plant Sciences	127	12.2
Meteorology & Atmospheric Sciences	124	11.9
Biotechnology & Applied Microbiology	68	6.5
Engineering	56	5.4
Science Technology & Other Topics	50	4.8
Geology	48	4.6
Water Resources	44	4.2

The title word map produced with the VOSviewer is presented in Fig. 2. As expected, our basic search terms (see the appendix) appear in the map as the most pronounced title words: "climate" (center), "climate change", and "wine". Beside these keywords, the terms "effect", "impact", and (less pronounced) "adaptation" are major title words and point to research dealing with the various risks of climate change for viticulture. Finally, many wine producing countries and grapevine names appear as less pronounced title words. The node "effect" appears in the center of an own cluster (green), whereas the node "impact" is closely related to the central node "climate" (red) and "adaptation" is close to "climate change" (yellow).

Spectrogram of the cited references: Fig. 3 shows the results of the RPYS performed with the CRExplorer. The spectrogram presents the distribution of the number of cited references across their publication years within the time period 1940-2015.The earliest reference publication year appearing in Fig. 3 is 1944. This is a consequence of the selection of references with a minimum reference count of 10 (see method section).

The red line in Fig. 3 visualizes the number of cited references per reference publication year. In order to identify those publication years with significantly more cited references than other years, the (absolute) deviation of the number of cited references in each year from the median of the number of cited references in the two previous, the current, and the two following years (t – 2; t – 1; t ; t + 1; t + 2) is also visualized (blue line). This deviation from the five-year median provides a curve smoother than the one in terms of absolute numbers. We used both curves for the identification of the peak papers.

According to Fig. 3, there are about 14 (more or less) pronounced peaks in the following reference publication years: 1944, 1974, 1978, 1992, 1998, 2000, 2002, 2004, 2005, 2006, 2007, 2010, and 2013. CRExplorer enables the identification of highly cited references via the table of references presented alongside the spectrogram. The references which are mainly responsible for the peaks are listed in Tab. 4.

The corresponding papers of the references presented in Tab. 4 have been published throughout a large time period (1944-2013) and thus within quite different publication and citation cultures. Therefore, the reference counts in the table from different time periods are not comparable with each other (Marx *et al.* 2010).

The most frequently cited references: According to Estreicher (2006), the Swiss/French botanist Alphonse de Candolle published the first serious study of viticultural climates in 1855. De Candolle noticed that wines start active growth in the spring when air temperatures exceed 50 °F (10 °C) and proposed criteria for the suitability of specific regions for viticulture. This early work of a forerunner is barely cited and does not appear at all in our spectrogram and in "References". Maynard A. Amerine and Albert J. Winkler (Amerine and Winkler 1944) applied the

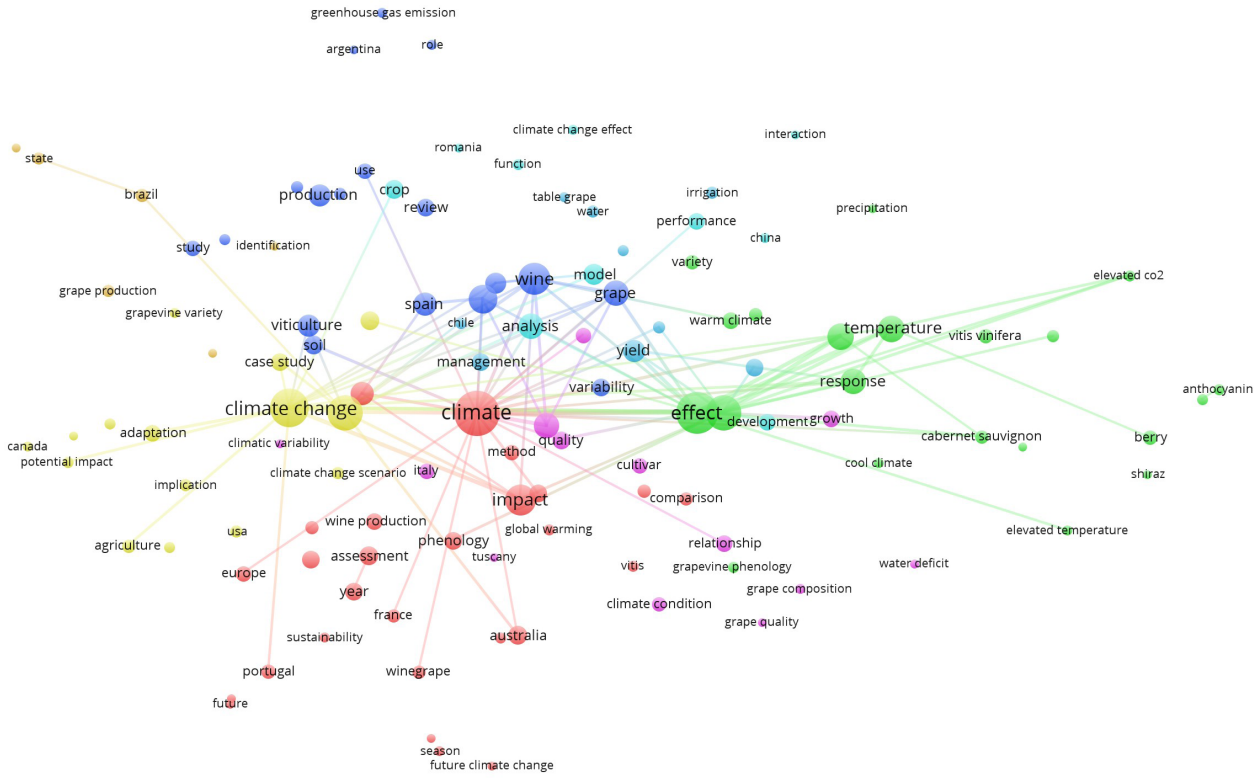

Fig. 2: Co-occurrence network of title words of climate change and viticulture papers based on bibliographic coupling of cited references (the minimum number of papers containing a specific title word is five).

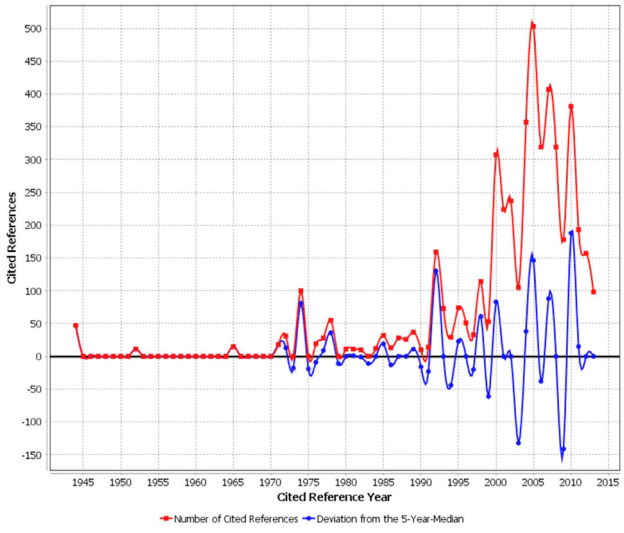

Fig. 3: Annual distribution of the references cited in climate change and viticulture papers across their reference publication years 1940-2015. Only references with a minimum reference count of 10 are considered.

ideas of de Candolle in their publication entitled "Composition and quality of musts and wines of California grapes". The paper by Amerine and Winkler (1944) corresponds to the first distinct peak in the spectrogram of Fig. 3. It appeared in "Hilgardia" which was the primary technical journal of the University of California, Division of Agriculture and Natural Resources over 70 years (between 1925 and 1995).

Amerine and Winkler (1944) stated that "the utility of a given variety of grapes for wine making depends upon several factors. These include production factors such as scion-stock interrelationship, susceptibility to disease, inherent vigor of the vine, resistance to frost…, and the yield and composition of the grapes under various soil and climatic conditions" (p. 493). The authors defined five viticultural regions (partly on the basis of climatic conditions) which served as a guide for replanting California after World War II. Thus, the paper had a significant impact on the recovery of the US wine production.

The second pronounced peak in the spectrogram of Fig. 3 can be assigned to a book published by Winkler *et al.* (1974) with the title "General viticulture" (710 pages). In chapter 4 of this book the yield and composition of the grapes under various soil and climatic conditions are discussed.

The next comparatively highly cited reference which is responsible for the peak in the spectrogram four years later refers to the fundamental work of Pierre Huglin, who invented the so-called Huglin Index (Huglin 1978). The index estimates the heliothermal potential of a specific climatic condition and is based on the half sum of daily maximum and daily average temperatures from 1 April to 30 September (in the Northern Hemisphere). The Huglin index is based on aggregated growing season temperature measures which form the basis of most viticulture classification schemes. The publications of Amerine and Winkler (1944), Winkler (1974), and Huglin (1978) indicate the importance of growing degree day derived measures of climate suitability for viticulture. The Huglin index, originally introduced as a measure of the impact of climate on viticulture in general, is one of several indices that have become most important to measure the implications of global warming for viti-

Table 4

The most frequently cited references from specific reference publication years cited by papers dealing with climate change and viticulture. For each reference, the corresponding reference publication year (RPY) and the number of cited references (NCR) within the climate change and viticulture publication set are listed

RPY	Reference	NCR
1944	Amerine, M. A.; Winkler, A. J.; 1944: Composition and quality of musts and wines of California grapes. Hilgardia **15** (6), 493-675.	47
1974	Winkler, A. J. *et al*.; 1974: General Viticulture. University of California Press.	78/87
1978	Huglin, P.; 1978: Nouveau mode d'évaluation des possibilités hélio-thermique d'un milieu viticole, 1117-1126. Comptes Rendus de l'Académie d'Agriculture de France.	45
1992	Gladstones, J.; 1992: Viticulture and Environment - A Study of the Effects of Environment on Grapegrowing and Wine Qualities, with Emphasis on Present and Future Areas for Growing Winegrapes in Australia. Winetitles, Australia.	55
1998	Allen, R. G. *et al.*; 1998: Crop evapotranspiration - Guidelines for computing crop water requirements. FAO Irrigation and Drainage Paper 56FAO 56.	20/65
2000	Jones, G. V.; Davis, R. E.; 2000: Climate influences on grapevine phenology, grape composition, and wine production and quality for Bordeaux, France. Am. J. Enol. Vitic. **51** (3), 249-261.	117
2002	Spayd, S. E.; Tarara, J. M.; Mee, D. L.; Ferguson, J. C.; 2002: Separation of sunlight and temperature effects on the composition of *Vitis vinifera* cv. Merlot berries. Am. J. Enol. Vitic. **53** (3), 171-182.	63
2004	Tonietto, J.; Carbonneau, A.; 2004: A multicriteria climatic classification system for grape-growing regions worldwide. Agric. Forest Meteorol. **124** (1-2), 81-97.	72
2005	Jones, G. V..; White, M. A.; Cooper, O. R.; Storchmann, K.; 2005: Climate change and global wine quality. Climat. Change **73**, 319-343.	193
2006	White, M. A.; Diffenbaugh, N. S.; Jones, G. V.; Pal, J. S.; Giorgi, F.; 2006: Extreme heat reduces and shifts United States premium wine production in the 21st century. Proc. Nat. Acad. Sci. USA (PNAS) **103** (30), 11217-11222.	54
2007	Webb, L. B.; Whetton, P. H.; Barlow, E. W. R.; 2007: Modelled impact of future climate change on the phenology of winegrapes in Australia. Aust. J. Grape .Wine Res. **13** (3), 165-175.	74
2010	Duchene, E.; Huard, F.; Dumas, V.; Schneider, C.; Merdinoglu, D.; 2010: The challenge of adapting grapevine varieties to climate change. Clim. Res. **41** (3), 193-204.	36
2010	Keller, M.; 2010: Managing grapevines to optimise fruit development in a challenging environment: a climate change primer for viticulturists. Aust. J. Grape .Wine Res. **16** (1), 56-69.	34
2013	Hannah, L. *et al*.; 2013: Climate change, wine, and conservation. Proc. Nat. Acad. Sci. USA (PNAS) **10** (17), 6907-6912.	40

culture worldwide. The next peak of Fig. 3 appearing in the reference publication year 1992 can be assigned to the book "Viticulture and environment" (Gladstones 1992). This is the first highly-cited work that discussed viticulture in the context of climate change (in the sense of global warming). The subtitle is more specific: "A study of the effects of environment on grapegrowing and wine qualities, with emphasis on present and future areas for growing winegrapes in Australia". Darby Higgs, a Melbourne based wine writer and enthusiast, comments the book as follows: "Viticulture and Environment begins with a chapter on the history of climate selection for Australian viticulture. This includes a discussion on the various methods of classifying climatic data. He then discusses in considerable detail the influence of individual climatic factors on grape quality… The book is concluded with a discussion of climate change and viticulture… The practical significance of this book is enormous… John Gladstones 'Viticulture and Environment' was awarded Special Distinction in Viticulture by the Office International de Vigne et du Vin in Paris 1994" (http://www.vinodiversity.com/index.html).

The less pronounced reference publication year 1998 is dominated by a more technical contribution by Allen *et al.* (1998) entitled "Crop evapotranspiration - Guidelines for computing crop water requirements". Evapotranspiration is referred to as the combination of two separate processes whereby water is lost on the one hand from the soil surface by evaporation and on the other hand from the crop by transpiration. The peak of reference publication year 2000 can be assigned to a paper by Gregory V. Jones and Robert E. Davis (Jones and Davis 2000). The paper discusses a long-term climatology based on reference vineyard observations in Bordeaux, France. It states that "over the last two decades, the phenology of grapevines in Bordeaux has tended towards earlier phenological events, a shortening of phenological intervals, and a lengthening of the growing season… The composition and quality trends were mostly described by increases in the number of warm days during floraison and veraison and a reduction in precipitation during maturation… By variety, the relationships between phenology, climate, and composition… could be an indication that, in Bordeaux, 'Merlot' is more phenologically and climatologically sensitive… This indicates that the wine industry in Bordeaux is more dependent on 'Cabernet Sauvignon' for good vintages than on 'Merlot'" (p. 249).

The peak of reference publication year 2000 is closely followed by a peak in 2002 which can be traced back to a paper by Spayd *et al.* (2002) that discusses the "Separation of sunlight and temperature effects on the composition of *Vitis vinifera* 'Merlot' berries" in the Yakima Valley of Washington. Again, there are some consecutively following peaks in the time period 2004-2007. The 2004 peak is based on a paper by Tonietto and Carbonneau (2004): "A multicriteria climatic classification system for grape-growing regions worldwide". Jorge Tonietto and Alain Carbonneau formulated a climatic classification system (Géoviticulture MCC System) for the grape-growing regions worldwide based on three viticultural climate indices: (1) the dryness

index (DI) as an indicator for the potential water balance of the soil over the growing cycle, (2) the heliothermal index (HI) (which corresponds to the Huglin index) as an indicator for the heliothermal conditions over the growing cycle, and (3) the cool night index (CI) as an indicator for night temperature during maturation. The application of the MCC System is presented for 97 grape-growing regions in 29 countries.

The most pronounced peak of the spectrogram in Fig. 3 corresponds to the reference publication year 2005. It is mainly caused by a paper by Jones *et al.* (2005) published in "Climatic Change", a prestigious journal of the climate change research community. This is the first paper in Tab. 4 with the terms "climate change" and "wine" concurrently appearing in the title: "Climate change and global wine quality". The authors report that "from 1950 to 1999 the majority of the world's highest quality wine-producing regions experienced growing season warming trends… This study revealed that the impacts of climate change are not likely to be uniform across all varieties and regions. Currently, many European regions appear to be at or near their optimum growing season temperatures, while the relationships are less defined in the New World viticulture regions… For regions producing high quality grapes at the margins of their climatic limits, these results suggest that future climate change will exceed a climatic threshold such that the ripening of balanced fruit required for existing varieties and wine styles will become progressively more difficult. In other regions, historical and predicted climate changes could push some regions into more optimal climatic regimes for the production of current varietals" (p. 319).

The 2006 peak corresponds to a paper by White *et al.* (2006) published in the "Proceedings of the National Academy of Sciences of the United States of America (PNAS)". The title of this paper is "Extreme heat reduces and shifts United States premium wine production in the 21st century". The authors report: "Here, by using a high-resolution regional climate model forced by the Intergovernmental Panel on Climate Change Special Report on Emission Scenarios A2 greenhouse gas emission scenario, we estimate that potential premium winegrape production area in the conterminous United States could decline by up to 81 % by the late 21st century. While increases in heat accumulation will shift wine production to warmer climate varieties and/or lower-quality wines, and frost constraints will be reduced, increases in the frequency of extreme hot days (> 35 °C) in the growing season are projected to eliminate winegrape production in many areas of the United States" (p. 11217).

The next peak corresponding to the reference publication year 2007 can be assigned to the paper by Webb *et al.* (2007) which appeared in the "Australian Journal of Grape and Wine Research" entitled "Modelled impact of future climate change on the phenology of winegrapes in Australia". The authors modelled impact of future climate change on the phenology of winegrapes and discuss the possible effects on Australian viticulture. They report that "projected impacts from future warming on grapevine phenology have been modelled for two important varieties across six representative wine-growing regions in Australia… Some regions may be adversely affected by the chilling requirement not being met in future warmer climate… An important finding of this analysis is that harvest is projected to occur both earlier in the year and in a warmer climate, *i.e.* a dual warming impact. Harvesting in warmer temperatures can negatively impact grape quality" (p. 165). There are at least two other papers published by L. B. Webb (Webb *et al.* 2008, 2011) with a comparably high reference count but without pronounced peaks in the spectrogram.

The last distinct peak in Fig. 3 appears at reference publication year 2010 and is associated with two papers with a similar reference count. The first paper was published in "Climate Research" by Eric Duchene (Duchene *et al.* 2010), entitled "The challenge of adapting grapevine varieties to climate change". The authors state that the expected "changes will likely have a significant impact on grape and wine quality" (p. 193). The study "highlights the important changes that viticulture will likely face in a future warmer climate and emphasises the need to create very late ripening genotypes or genotypes able to produce high quality wines under elevated temperatures" (p. 193). The second paper corresponding to reference publication year 2010 was published by Markus Keller (Keller 2010) and appeared in a special issue of the "Australian Journal of Grape and Wine Research" with the title "Managing grapevines to optimise fruit development in a challenging environment: a climate change primer for viticulturists". The author "reviews current knowledge on yield formation and fruit composition and attempts to identify challenges, opportunities and priorities for research and practice. The present analysis of published information gives a critical appraisal of recent advances concerning variables, especially as they relate to global climate change" (p. 56).

Finally, we would like to mention a more recent paper (Hannah *et al.* 2013) which had not sufficient time to accumulate a high number of citations. However, the CRExplorer reveals that this paper has been referenced most frequently since the 2008 paper by Webb mentioned above. In their discussion section the authors assert that "Global changes in suitability for wine production caused by climate change may result in substantial economic and conservation consequences. Redistribution in wine production may occur within continents, moving from declining traditional wine-growing regions to areas of novel suitability, as well as from the Southern Hemisphere to large newly suitable areas in the Northern Hemisphere" (Hannah *et al.* 2013, p. 6910).

Beside the top-referenced publications listed in Tab. 4, there are many more cited references within many referenced publication years which also have a substantial impact on research activities of the research field analyzed here. These references can be revealed and analyzed by the interested reader using the CRExplorer interactively.

Discussion

This study is based on a carefully selected publication set of 1039 papers published between 1974 and 2016 dealing with research on climate change and viticulture. A brief

analysis of the publication set reveals (1) the top journals, (2) the top countries of authors, (3) the top research areas, and (4) the most often appearing title words. Many papers in our publication set appeared in "Acta Horticulturae", "Australian Journal of Grape and Wine Research", and "American Journal of Enology and Viticulture" published by researchers from the US, Spain, and Italy. The title word map clearly reveals the importance of climate change research for viticulture as well as the discussion on impacts and adaptation.

Using the RPYS, we identified the 14 most pronounced peaks in the spectrogram and discussed the top-referenced publications. The most frequently cited publications mirror the selection and accentuation of the overall climate change research and viticulture community (*i.e.* the authors of the papers of our publication set). The citation classics can be categorized as providing methodological and theoretical grounds for studies in terms of the effects of temperature (Amerine and Winkler 1944, Winkler *et al.* 1974, Huglin 1978, Spayd *et al.* 2002 and Tonietto and Carbonneau 2004), the estimation of climate change impacts (Jones and Davis 2000, Jones *et al.* 2005, White *et al.* 2006, Webb *et al.* 2007, 2008, 2011), and the exploration of adaptation options (Duchene *et al.* 2010, Keller 2010).

Obviously (and not surprisingly), the highly cited works in climate change and viticulture research mirror the shift in the discussion of climate in the context of viticulture: from the impact of climate on viticulture in general to the possible consequences of global warming and the need for adaptation. The more recent research takes climate change more or less as a matter of fact.

RPYS reveals the papers most relevant for the evolution of the emerging research field climate change and viticulture and the amount of their impact within its community. The decisive advantage of the method is that the seminal papers are detected on the basis of the references cited by the relevant community without any further assumptions. However, the specific role of the cited papers can only be determined by experts. Thus, the results of this study might serve active scientists in the field of climate change and viticulture as complementary information from a quantitative perspective. The combination of a quantitative approach with a more qualitative (expert-based) approach seems to be a good strategy to reconstruct the evolution of the research field.

Viticulture comprises only a small portion of the complete field of agriculture, both in total and with regard to climate change research. In future studies, it would be interesting to study the complete field of agriculture and food science within climate change research in a more comprehensive analysis. Besides grapevine, tea (*Camellia sinensis*) is another luxury food which is affected by climate change in a similar way (Boehm *et al.* 2016). This research topic has just started to emerge; currently, there are only less than 100 papers covered by the WoS databases.

References

Adams, J.; Gurney, K. A.; 2014: Evidence for Excellence: Has the Signal overtaken the Substance? An Analysis of Journal Articles submitted to RAE2008. Digital Science, London, UK.

Allen, R. G.; Pereira, L. S.; Raes, D.; Smith, M.; 1998: Crop Evapotranspiration - Guidelines for Computing Crop Water Requirements. FAO Irrig. Drainage Paper No. 56.

Amerine, M. A.; Winkler, A. J.; 1944: Composition and quality of musts and wines of California grapes. Hilgardia **15**, 493-675.

Boehm, R.; Cash, S. B.; Anderson, B. T.; Ahmed, S.; Griffin, T. S.; Robbat, A.; Stepp, J. R.; Han, W.; Hazel, M.; Orians, C. M.; 2016: Association between empirically estimated Monsoon dynamics and other weather factors and historical tea yields in China: Results from a yield response model. Climate **4** (2), art. 20.

Bornmann, L.; Marx, W.; 2013: The proposal of a broadening of perspective in evaluative bibliometrics by complementing the times cited with a cited reference analysis. J. Informetr. **7**, 84-88.

Bornmann, L.; Mutz, R.; 2015: Growth rates of modern science: A bibliometric analysis based on the number of publications and cited references. J. Assoc. Inform. Sci. Technol. **66**, 2215-2222.

Comins, J. A.; Hussey, T. W.; 2015a: Detecting seminal research contributions to the development and use of the global positioning system by reference publication year spectroscopy. Scientometrics **104**, 575-580.

Comins, J. A.; Hussey, T. W.; 2015b: Compressing multiple scales of impact detection by Reference Publication Year Spectroscopy. J. Informetr. **9**, 449-454.

Digital Science; 2016: Publication patterns in research underpinning impact in REF2014. Digital Science, London, UK.

Duchene, E.; Huard, F.; Dumas, V.; Schneider, C.; Merdinoglu, D.; 2010: The challenge of adapting grapevine varieties to climate change. Climate Res. **41**, 193-204.

Estreicher, S. K.; 2006: Wine from Neolithic Times to the 21st Century. Algora Publishing, New York, USA.

Gladstones, J.; 1992: Viticulture and Environment - A Study of the Effects of Environment on Grapegrowing and wine Qualities, with Emphasis on Present and Future Areas for Growing Winegrapes in Australia. Winetitles, Adelaide, Australia.

Hannah, L.; Roehrdanz, P. R.; Ikegami, M.; Shepard, A. V.; Shaw, R.; Tabor, G.; Zhi, L.; Marquet, P. A.; Hijmans, R. J.; 2013: Climate change, wine, and conservation. Proc. Nat. Acad. Sci. USA (PNAS) **10**, 6907-6912.

Haunschild, R.; Bornmann, L.; Marx, W.; 2016: Climate change research in view of bibliometrics. PLoS ONE **11** (7): e0160393.

Huglin, P.; 1978: Nouveau mode d'évaluation des possibilités héliothermique d'un milieu viticole, 1117-1126. Comptes Rendus de l'Académie d'Agriculture de France.

IPCC Synthesis Report – Climate Change 2014: http://www.ipcc.ch/report/ar5/syr/

IPCC Synthesis Report – Climate Change 2014. Summary for policymakers: https://www.ipcc.ch/pdf/assessment-report/ar5/syr/AR5_SYR_FINAL_SPM.pdf

Jones, G. V.; Davis, R. E.; 2000: Climate influences on grapevine phenology, grape composition, and wine production and quality for Bordeaux, France. Am. J. Enol. Vitic. **51**, 249-261.

Jones, G. V.; White, M. A.; Cooper, O. R.; Storchmann, K.; 2005: Climate change and global wine quality. Climatic Change **73**, 319-343.

Keller, M.; 2010: Managing grapevines to optimise fruit development in a challenging environment: a climate change primer for viticulturists. Aust. J. Grape Wine Res. **16**, 56-69.

Leydesdorff, L.; Bornmann, L.; Marx, W.; Milojević, S.; 2014: Referenced Publication Years Spectroscopy applied to iMetrics. Scientometrics, Journal of Informetrics, and a relevant subset of JASIST. J. Informetr. **8**, 162-174.

Marx, W.; 2011: Special features of historical papers from the viewpoint of bibliometrics. J. Am. Soc. Inform. Sci. Technol. **62**, 433-439.

Marx, W.; Bornmann, L.; 2014: Tracing the origin of a scientific legend by reference publication year spectroscopy (RPYS): the legend of the Darwin finches. Scientometrics **99**, 839-844.

Marx, W.; Bornmann, L.; Cardona, M.; 2010: Reference standards and reference multipliers for the comparison of the citation impact of papers published in different time periods. J. Am. Soc. Inform. Sci. Technol. **61**, 2061-2069.

Marx, W.; Bornmann, L.; Barth, A.; Leydesdorff, L.; 2014: Detecting the historical roots of research fields by reference publication year spectroscopy (RPYS). J. Assoc. Inform. Sci. Technol. **65**, 751-764.

Marx, W.; Haunschild, R.; Thor, A.; Bornmann, L.; 2016: Which early works are cited most frequently in climate change research literature? A bibliometric approach based on reference publication year spectroscopy. Scientometrics, publ. online.

Spayd, S. E.; Tarara, J. M.; Mee, D. L.; Ferguson, J. C.; 2002: Separation of sunlight and temperature effects on the composition of *Vitis vinifera* cv. Merlot berries. Am. J. Enol. Vitic. **53**, 171-182.

Thor, A.; Marx, W.; Leydesdorff, L.; Bornmann, L.; 2016: Introducing CitedReferencesExplorer (CRExplorer): A program for reference publication year spectroscopy with cited references standardization. J. Informetr. **10**, 503-515.

Thor, A.; Marx, W.; Leydesdorff, L.; Bornmann, L.; 2016: New features of CitedReferencesExplorer (CRExplorer). Scientometrics **109**, 2049-2051.

Tonietto, J.; Carbonneau, A.; 2004: A multicriteria climatic classification system for grape-growing regions worldwide. Agric. For. Meteorol. **124**, 81-97.

Van Eck, N. J.; Waltman, L.; 2010: Software survey: VOSviewer, a computer program for bibliometric mapping. Scientometrics **84**, 523-538.

Webb, L. B.; Whetton, P. H.; Barlow, E. W. R.; 2007: Modelled impact of future climate change on the phenology of winegrapes in Australia. Aust. J. Grape Wine Res. **13**, 165-175.

Webb, L. B.; Whetton, P. H.; Barlow, E. W. R.; 2008: Climate change and winegrape quality in Australia. Clim. Res. **36**, 99-111.

Webb, L. B.; Whetton, P. H.; Barlow, E. W. R.; 2011: Observed trends in winegrape maturity in Australia. Glob. Chang. Biol. **17**, 2707-2719.

White, M. A.; Diffenbaugh, N. S.; Jones, G. V.; Pal, J. S.; Giorgi, F.; 2006: Extreme heat reduces and shifts United States premium wine production in the 21st century. Proc. Nat. Acad. Sci. USA **103**, 11217-11222.

Winkler, A. J.; Cook, J. A.; Kliewer, W. M.; Lider, L. A.; 1974: General Viticulture. University of California Press, USA.

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