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Identifying sustainable forest management research narratives: a text mining approach

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ABSTRACT

Although it is obvious that research regarding Sustainable Forest Management (SFM) is context specific and developed over time, not many research papers yet intended to investigate these changes. As a matter of fact, the number of scientific publications addressing SFM is relatively high. Hence, such a wide field cannot be sufficiently covered by traditional literature review approaches. With this paper, we aim at identifying the most convergent narratives within the SFM-research landscape by applying a text mining methodology to recent scientific literature. By doing so, we generated results that indicate that there may have been three phases in the evolution of SFM-research: the early phase covers in particular issues regarding land use in tropical and developing countries. Furthermore, papers in this phase tend to focus on general concepts or policy issues. In contrast, the second phase is characterized by a larger share of publications in forestry focused journals. This process is seemingly connected with issues like forest management, certification, forest stand management and the development of sustainability indicators. A third phase can be observed by the relative downturn of publications in forest-focused journals between 2005 and 2010. A new focus in this period is climate change.

KEYWORDS

Sustainable forest management (SFM); SFM meta study; text mining; topic modelling; topics in SFM; evolution of SFM

Introduction

Sustainable forest management is a traditional research field with an outstanding history. Since Von Carlowitz (1713) practically invented the term sustainability in the context of forest management, the general understanding of what sustainable forest management (SFM) is, has undertaken an evolutionary process. Between 1980 and 1990 research communities increasingly started to investigate SFM from multiple perspectives, which initially focused on timber volume. In the early 1980s publications had a strong focus on tropical forests (e.g., Fearnside, 1989; Michon, Mary, & Bompard, 1986; Salati & Vose, 1982; Spears, 1980), for example, reported that sustained management of Amazonian forest is nonexistent on a commercial scale and is in its infancy as a research front. In a similar manner, Schwartz (1989) also referred to the Amazon region addressing social conflicts between rubber tappers, loggers, ranchers, and Indians. In contrast, research on sustainable management of European forests (Corona & Ferrara, 1989) at that time focused on the development of yield models for conifer plantations

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in order to improve the planning of interventions within a low-input silvicultural system. In 1990 a member of the FAO (Murray, 1991) published a paper which discussed the concept of SFM, reviewed the linkages between human populations and forests; pointed out the status of forests in developing countries, and outlined the importance of forests for food security and environmental conservation. A first publication in Science covering SFM was done by Vincent in 1992, addressing tropical timber trade in the context of sustainable development.

In 1992 the United Nations Conference on Environment and Development (UNCED) in Rio de Janeiro achieved for the first time a high level of political commitment to advancing “sustainable forest management” (UN, 1992).

Wiersum (1995) provided an early literature review titled “200 years of sustainability in forestry: Lessons from history”. He postulated that the original principle of sustained yield has gradually broadened to a more inclusive principle of SFM that particularly also encompasses social values. Following the social context strain in the discussion on SFM definitions, Schanz (1996) investigated social norms and values. At about the same time, the issue of timber and management certification schemes entered the scientific arena (e.g., Baharuddin, 1995; Rotherham, 1996). Martin and Darr (1997) investigated market effects and reactions caused by significant reductions in timber harvest due to legal requirements regarding SFM. Later several overviews on SFM and certification have been published (e.g., Van Kooten, Nelson, & Vertinsky, 2005). A meta-analysis comparing SFM standards was finally published by Clark and Kozar (2011).

By the mid-1990s the role of forest soils in the context of SFM received increasing attention. Worrell and Hampson (1997) provided the first review on forest operations impacts on soils. Another paper published in Science introduced the understanding of forests as human-dominated ecosystems (Noble & Dirzo, 1997). This perspective addressed the issue of multi-purpose forestry and proposed objective-specific spatial segregation (e.g., short rotation plantations for wood production and strictly preserved natural forest for biodiversity conservation) (e.g., Binkley, 1997). Since the conservation of biological diversity became one of the important goals of SFM, ecologists and forest resource managers needed measures to judge the success or failure of management regimes designed to sustain biological diversity. Lindenmayer and colleagues (2000) proposed four approaches to enhance biodiversity conservation in forests. Decision support systems were developed to operationalize SFM, considering different dimensions of sustainability in a holistic approach (Mendoza & Prabhu, 2000; Varma, Ferguson, & Wild, 2000).

In his conceptual paper, Wang (2004) classified conventional forest management (CFM) as disciplinary, whereas SFM is trans-disciplinary, less hierarchical, more transient, context is more complex, and this evolving context is shaped by a diverse spectrum of social demands. Hence, he concludes that SFM is more socially accountable and reflexive than CFM, involving a wider set of stakeholders. Schelhas (2003) uses examples from the USA and Costa Rica to evaluate the claim that a new postmodern conservation has emerged in the practice of natural resource management. He postulates shifts from: (1) simple to multiple interests in natural resources; (2) simple ownership to bundles of rights; (3) deterministic science to multiple knowledge systems; and (4) public interest to stakeholder groups.

A general overview on SFM in terms of global forest inventory data was provided by Siry, Cabbage, and Ahmed (2005). Their data provide evidence that many countries in the world are trying to achieve sustainable forest management and certainly are trying to

report data that suggest that they are moving toward sustainable forest management goals. However, they conclude that the empirical evidence that forests are actually well managed and protected is often lacking. Streck and Scholz (2006) review the role of SFM in context of climate change and carbon management. In 2007 a book titled “Sustainable forestry: From monitoring and modelling to knowledge management and policy science” was published (Reynolds, Thomson, Köhl, Shannon, Ray, & Rennolls, 2007). Focusing on climate change and conservation of biodiversity, it highlights four methodologies and shows how they contribute to overcoming the ecological challenges. Considering changing social needs and definitions of sustainability, a literature review by Hahn and Knoke (2010) discusses different sustainability terms, their history, concepts, and relationships, from a European perspective. Finally, flexibility is proposed as a solution to overcome the identified shortcomings at all scales, while focusing on the enterprise level.

By the renaissance of forest biomass as a fuel and indicators for sustainable forest fuel production and harvesting also entered the arena of SFM research. A review of standards for sustainable forest management in this context was provided by Stupak, Lattimore, Titus, and Tattersall Smith (2011). Fitzpatrick (2016) investigated environmental sustainability assessment of using forest wood for heat energy and Hansson and Hackl (2016) assessed the potential influence of sustainability criteria on the European Union pellets market.

A review by McDonald and Lane (2004) discussed criteria and indicators (C&I) that define SFM. They conclude that agreement on what SFM is has proven to be a difficult task, both internationally and nationally. At the same time, McCool and Stankey (2004) stated that the search for indicators has led to the development of criteria for good indicators, but it has also been dominated by scientific elites. The consequences of such dominance have led to significant social and policy implications, particularly with regard to how the search for sustainability has become defined primarily as a technical/scientific exploration when it is actually a moral and ethical issue. Lately, an overview on indicators of sustainable forest management in Europe was provided by Corezzola, D’Andrea, and Zapponi (2016).

Although it is obvious that research regarding SFM is context specific and developed over time not many research papers yet intended to investigate these changes. As a matter of fact, the number of scientific publications addressing issues regarding SFM is relatively high. Until 2017 over 9,000 scientific publications are for example listed in the Scopus database considering the terms “sustainable” “forest” and “management” in title, abstract and keywords (the query was conducted on 26th March 2017). Hence, such a wide field cannot be sufficiently covered by the traditional literature review approaches. Sutterlüty and colleagues (in review) applied content analysis on 643 scientific abstracts to investigate the differences in research foci when comparing different continents. In contrast, we apply an automated text mining approach on abstracts originating from 9378 scientific papers to identify the most prominent research narratives regarding SFM.

Method

In recent years, computational methods have increasingly been used for knowledge discovery due to their ability of swiftly parsing vast data sets. Such methods are widely known in science for their usefulness in analyzing numerical data, in particular in the field

of statistics. For example, the principal component analysis allows to find structures and reduce dimensions in multivariate data to identify driving factors behind the data. However, similar to the principal component analysis, there are some specialized, so-called text mining methods for the analysis of textual corpora as well. One of these text mining methods is Latent Dirichlet Allocation (LDA) (Blei, Ng, & Jordan, 2003). This method allows detecting topics (which represent research areas in this study) in separated text corpora with a huge number of entities, such as the entire collection of abstracts of SFM-related publications. Performing an LDA yields clusters of frequently co-occurring nouns of the analyzed textual corpus. These clusters of nouns are typically interpreted as topics, therefore, performing an LDA is also known as Topic Modeling.

Database

We used the Scopus as source and searched for the simultaneous occurrence of the words “sustainable”, “forest” and “management” in article titles, abstracts and keywords of this database to prepare the dataset of SFM-related publications for our endeavor. To ensure a consistent analysis of the temporal development of the subsequently identified research areas, we limited the found data set to the period between 1990 (the first year with a double-digit number of publications) and 2016 (the last complete year). The resulting data set comprised the data of 9378 publications containing author names, title, publication year, abstract and publication source for each paper.

Data preprocessing

Topic Modeling builds on the assumption that topics in texts are represented through nouns (Harris, 1954). Hence, to model the topics of SFM-research, each abstract in our data set had to be reduced to its nouns only. As a first step of this so-called preprocessing procedure, n-grams (nouns that consist of several words, e.g., “land use”) were identified and compounded by the use of hyphens (e.g., “land use” was transformed to “land-use”) to prepare for an appropriate analysis. Labels like “sustainable forest management” were abbreviated (here, e.g., “sfm”). The identification of these n-grams was done manually with computational support. Subsequently, as an essential part of preprocessing, we extracted all nouns from the abstracts. This could be implemented by use of the Stanford POS Tagger (Manning, 2011), which allowed to identify the nouns in each abstract computationally. After this procedure, each abstract was represented through a list of nouns only. Finally, each noun in these lists was stemmed (e.g., “fertilizer”, “fertilizers” and “fertilization” were all stemmed to “fertil”), since the application of stemming is known to improve results in language modeling (Mahajan, Beeferman, & Huang, 1999).

Topic modeling

The lists of stemmed nouns, which represented the abstracts in our data set, were suitable as input for performing Topic Modeling by use of the LDA-method. The LDA allows forming clusters of terms that frequently co-occur in the input data. These clusters have the form of ordered lists of terms which are then interpreted as topics and labeled

appropriately. To perform the Topic Modeling, we used the LDA-function of the python library *gensim* (Rehurek & Sojka, 2010). The model eventually provided ten topics (see [Table 2](#) further below), each representing an area of SFM-research. In the model, these research areas were also assigned to the investigated abstracts, with relative weights. Each weight represents the ratio a topic holds in a publication, where to each publication one or more topics are assigned.

Additional data processing

The assignment of research areas to abstracts allowed us to analyze their relative weight and temporal development as well. To investigate also the relationship between continents and research areas, we had to work out the geographical context of each publication. Therefore, we appended the geographical foci to the publications in our data set, in terms of continents. Country and city names mentioned in title or abstract facilitated this procedure. Furthermore, in a similar way, we classified the source names of the publications into the two groups “forest-focused” and “non-forest-focused”. With the assignments of geographical foci and source types, we could analyze the relation between research areas (RA), continents and journal types, respectively.

[Table 1](#) shows data of one publication as the excerpt of our data set to illustrate the outcome of the procedures described in this section. The preprocessing of an abstract provided a list of stemmed nouns. The Topic Modeling procedure took all lists of stemmed nouns and modeled topics based on these lists (the composition of these topics is not part of [Table 1](#)). Furthermore, this procedure also assigned the appropriate modeled topics to each publication. The sample in [Table 1](#) shows, that the example publication was assigned topic 1 with 84% and topic 2 with 14% (due to iterative calculation and rounding errors it doesn't add up exactly to 100%). This means that the example publication mainly focused on topic 1, but nevertheless also covered topic 2 to some extent. The research areas represented by the topics were manually identified afterward.

Our analysis brought forth several results that are built around the co-occurrence of nouns in the investigated text corpus. As both last step of analysis and first step of result interpretation, we interpreted the research areas that were represented through these noun-clusters.

Results

In this section, we first describe which research areas were found by our analysis and how these areas evolved. Furthermore, we illustrate the continent-specific geographical foci of SFM-research and temporal development of these foci as well. Eventually, we present a comparison between the evolution of SFM-research in forest-focused journals and non-forest-focused journals, respectively.

Research areas in sustainable forest management

The subject area we identified as most important and at the core of SFM is an area we named *forests and the development debate*. This area makes up for 43% of covered subjects. *Ecosystem management* as the second largest research area makes up for 23%. Apart from these two dominating areas that together account for two-thirds of the average topical composition of publications, there are eight smaller areas with strong foci. With

Table 1. Example data as an excerpt from our dataset.

Authors	Original Database			Data		Topic Modeling	
	Title	Year	Source Title	Pre-Processing	Research Areas	Journal Type	Continents
Schwarzbauer P., Rametsteiner E.	The impact of SFM- certification on forest product markets in Western Europe...	2001	Forest Policy and Economics	Abstract In the international discussion on labels for sustainably produced wood products...	Stemmed Nouns discuss, label, wood, product, certif, sfm, attent, part...	forest-focused	Europe
						RA1: 0,84 RA2: 0,14 RA3-RA10: 0,00	

8% share of topical composition, *land-use* is the biggest of these areas, followed by *forest stand management* with 6% and *forests – water cycle/watershed management* with 5%. *Forests – carbon cycle/climate change*, *forests - nutrient cycle* and *biodiversity* each make up for 4% of the subjects. The smallest research areas are *modeling* with 2% and *fire* with 1% (Table 2).

The labels of these research areas were determined subjectively based on the composition of the clusters of terms. Table 3 lists fifteen of the most relevant words for each

Table 2. Relative importance of subject areas in SFM-research.

Subject Area	Importance [%]
<i>forests and the development debate</i>	43
<i>ecosystem management</i>	23
<i>land-use</i>	8
<i>forest stand management</i>	6
<i>forests – water cycle/watershed management</i>	5
<i>forests – carbon cycle/climate change</i>	4
<i>forests – nutrient cycle</i>	4
<i>biodiversity</i>	4
<i>modeling</i>	2
<i>fire</i>	1

Table 3. Compositions of clusters of terms (word stems), each cluster represents a subject area.

<i>forests and the development debate</i>		<i>ecosystem management</i>		<i>land-use</i>		<i>forest stand management</i>		<i>forests – water cycle/watershed management</i>	
1	forest	1	forest	1	land	1	tree	1	water
2	manag	2	manag	2	use	2	harvest	2	energi
3	forestri	3	studi	3	degrad	3	growth	3	qualiti
4	develop	4	area	4	product	4	regener	4	wast
5	polici	5	ecosystem	5	cover	5	stand	5	river
6	paper	6	model	6	agricultur	6	timber	6	pollut
7	sustain	7	landscap	7	land-us	7	volum	7	environ
8	product	8	analysi	8	food	8	densiti	8	suppli
9	research	9	conserv	9	chang	9	diamet	9	use
10	resourc	10	inform	10	farm	10	product	10	fish
11	conserv	11	distribut	11	agroforestri	11	popul	11	basin
16	process	12	structur	12	deforest	12	height	12	air
18	knowledg	13	region	13	graze	13	dbh	13	sediment
19	certif	15	method	16	area	14	age	17	flow
20	sfm	20	approach	17	region	15	yield	26	watershed
<i>forests – carbon cycle/climate change</i>		<i>forests – nutrient cycle</i>		<i>biodiversity</i>		<i>modeling</i>		<i>fire</i>	
1	carbon	1	soil	1	divers	1	model	1	fire
2	climat	2	nutrient	2	habitat	2	decis	2	risk
3	biomass	3	site	3	veget	3	system	3	popul
4	chang	4	fertil	4	rich	4	beech	4	occurr
5	energi	5	manag	5	disturb	5	learn	5	wildfir
6	product	6	plantat	6	abund	6	support	6	fuel
7	forest	7	nitrogen	7	plant	7	network	7	frequenc
8	sequestr	8	product	8	composit	8	simul	8	probabl
9	storag	9	matter	9	tourism	9	optim	9	control
10	adapt	10	content	10	canopi	10	uncertainti	10	season
11	co2	13	litter	11	biodivers	11	applic	12	summer
12	mitig	16	ha-1	12	wildlif	12	schedul	13	regim
14	bioenergy	19	chemic	19	bird	13	tool	17	territori
15	redd	22	runoff	22	structur	14	process	18	threshold
16	deforest	23	capac	23	deadwood	15	problem	20	intens

cluster, as well as the rank of each of these words. The first cluster in Table 3, for example, has a strong relation to the terms “forest” and “manag”. Moreover, “development”, “polici”, “sustain”, “resourc”, and “conserv” are part of this cluster, therefore we chose the label *forests and the development debate*. Interestingly, “paper” plays a central role as well, however, most probably the stem “paper” is in this cluster referring to the research publications and policy “papers” and not being related to the pulp and paper industry. Like the research area *forests and the development debate*, also *ecosystem management* has a strong relation to “forest” and “manag”. However, other central terms in this second cluster are “area”, “ecosystem”, “landscape”, and “distribution” which are clearly related to the academic discourse about ecosystem management. The third research area represented in this table is *land-use*. Terms related to this subject exhibit a considerable connection to agriculture (“agricultur”, “food” and “graze”) and in connection therewith, indicate socio-environmental conflicts (“degrad”, “deforest”). The fourth cluster contains terms that together definitely refer to *forest stand management*: e. g., “tree”, “harvest”, “growth” and so forth. As a whole, the composition of terms in this cluster has a strong focus on forest management techniques. The label assignment is underscored by the high relevance of the stems “regener” and “harvest” as well as by the fact that the majority of the stems is related to either silviculture or forest inventory (e.g., dbh, height, yield, volum, density, etc.). The subject *forests – water cycle/watershed management* is based on the co-occurrence of terms that are typical for streams, lakes, and wetlands. These terms are “water”, “river”, “fish”, “basin” and “sediment”. Furthermore, some rather unspecific terms are part of this cluster (e.g. “environ”, “suppli”, “use”). Remarkably, “quality”, “waste” and “pollut” are also part of this cluster. These stems imply the subjects water quality, waste management and pollution, which are crucial for watershed management, which is an important topic in SFM and indeed, “watershed” is listed in the cluster as well. *Forests – carbon cycle/climate change* is the sixth research area we identified, it refers to words like “carbon”, “climat”, “chang” and also includes “redd”. These stems in context with “biomass”, “energi”, “product”, “sequestr”, “adaptation”, “deforest” and so forth, reflect the multifaceted discussion on the complex relationship between the problem of climate change and SFM. The cluster we classified as the research area *forests – nutrient cycle* beneath “soil” and “nutrient” also comprises terms like “fertil”, “nitrogen” and “matter”. *Biodiversity* includes terms that could refer to different fields, but fit together in the context of biodiversity. Moreover, this research area explicitly refers to “divers” and “biodivers” as well. The terms “model”, “system”, “simul” and “tool” indicate that the ninth subject is about *modeling*. *Fire*, the last considered research area in our analysis, is defined through terms like “fire”, “risk”, “wildfir”, “fuel”, “intensity” and “regime”.

The relative importance of these ten research areas changed dramatically over the years, as can be seen from Figure 1. In the 90s the core area *forests and the development debate* made up for about half of the topic composition of an average paper in this field, while it only made up for one third in 2016. In contrast to that development, the share of *ecosystem management* grew from 16% to 29% in the same period. *Ecosystem management*, *biodiversity*, *modeling*, and *fire* are topics that became more important over time, while *forests – water cycle/watershed management* was of higher importance in the early 90s that decreased afterward, the same counts for *land-use*. The subject *forests – nutrient cycle* made up for about 2% of the orientation of SFM-research until 1995. Then, within two years the importance of this subject doubled and remained on that higher level the next 20

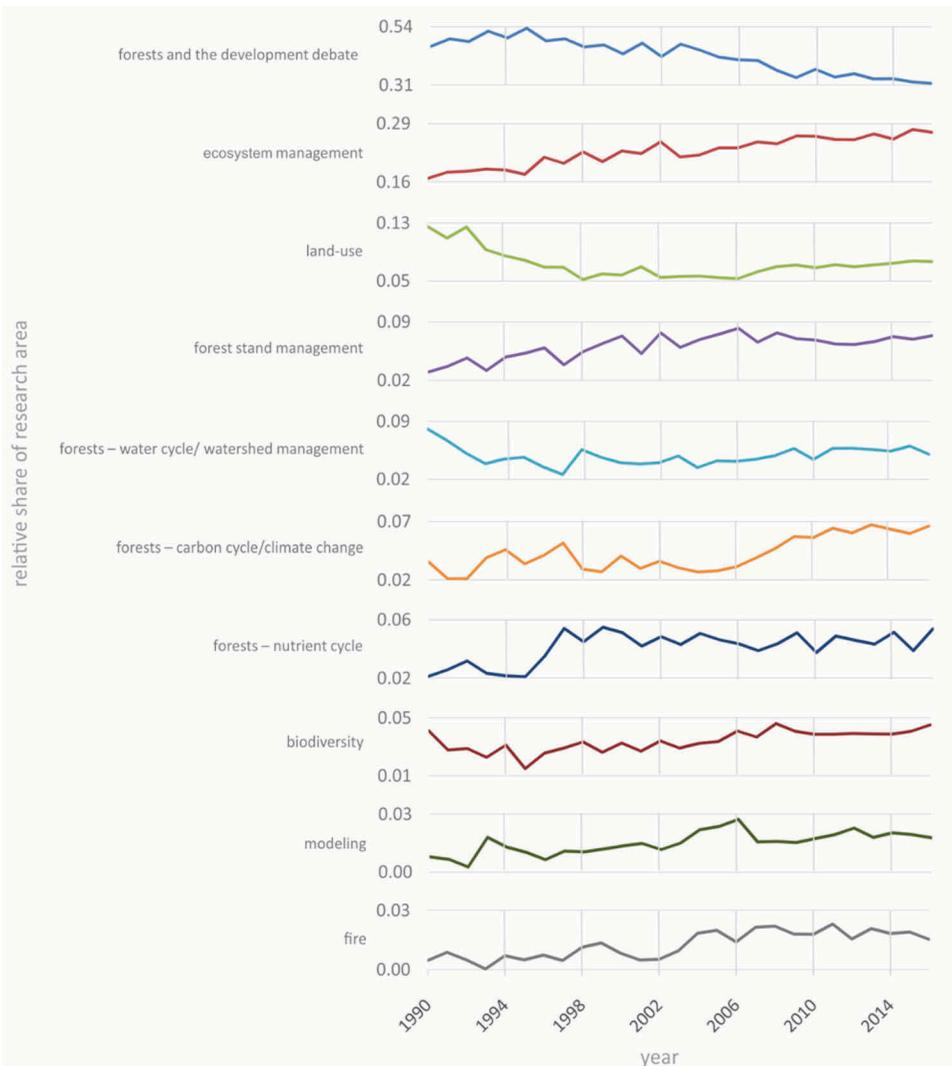


Figure 1. Temporal development of subject areas in SFM-related publications in the period 1990 – 2016.

years. The research area with the most diversified development is *forests – carbon cycle/ climate change*, which was made a more intense subject of discussion already in the 90s but became less important from 2000 to 2006. Since then the importance of this research area grew strongly by a factor of three until 2010 and remained on this high level.

Continent-specific orientation of SFM-research

Like the subject areas also the geographic foci in SFM-research have developed over time (Figure 2). *Asia*, e.g., first was made a strong subject of discussion in 1993 and 1994 and again gained importance from 2003 on. Since 2010, Asia has been having the biggest share of all continents in SFM-research. The relevance of *Europe* showed an almost steady development from 1990 to 2016. In contrast, *Africa* and *South America* only showed a

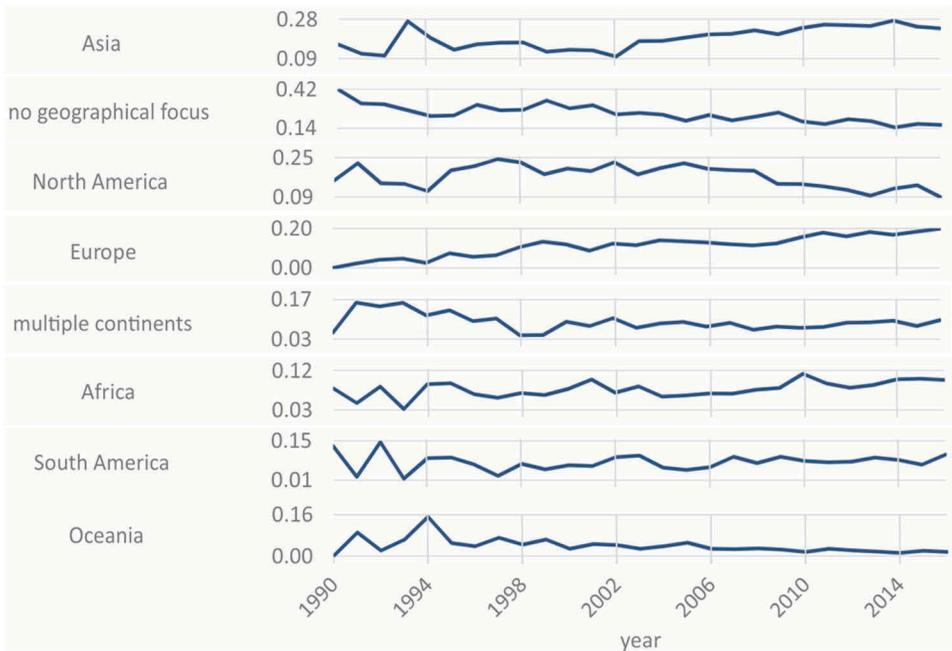


Figure 2. Temporal development of the share of geographical foci in SFM-related publications in the period 1990 – 2016.

slight increase of their relevance in this period. *Oceania*, which had a bigger share in SFM related discussions in the mid-90s played the least important role in recent years. *North America* became less important in recent years as well, after playing a bigger role in the period from 1995 to 2008. Furthermore, the development of North America's importance was very unsteady. Publications referred to North America to nearly one fourth in 1991 but only to one tenth in 1994. Apart from scientific works that focused on one of these six continents, there was also SFM-research that focused on more than one continent. The number of these *multiple continent* publications was higher in the 90s but became less important after 1997. In the early 90s, more than one third of SFM-publications did not focus on any region at all, we subsumed these works under the label *no geographic focus*. In recent years, publications with no geographic focus only made up for one sixth of SFM-research.

In [Table 4](#), the mean value of each curve from [Figure 2](#) is listed. These mean values also stand for the relative overall importance of geographical foci in SFM-research.

Table 4. Geographic orientation of SFM-related studies.

Geographic Focus	Importance [%]
<i>Asia</i>	21
<i>no geographic focus/unclassified</i>	21
<i>North America</i>	18
<i>Europe</i>	14
<i>multiple continents</i>	9
<i>Africa</i>	8
<i>South America</i>	8
<i>Oceania</i>	3

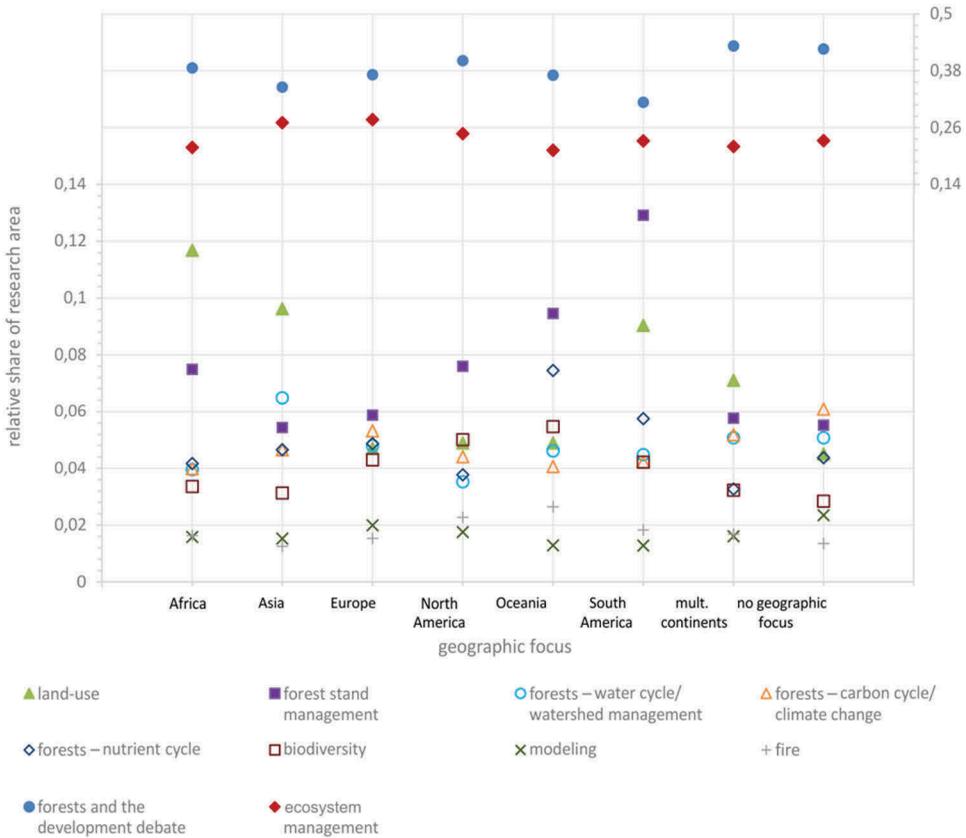


Figure 3. Relative share of subject areas with respect to the geographic focus.

In addition to the temporal development of the geographic foci in SFM-research, we also analyzed the average topical composition of publications for each geographical focus. The results of this analysis are plotted in Figure 3. Please note that the y-axis in this figure is subdivided into two sections of different scaling: the lower part ranges from 0% to 14%, the upper part ranges from 14% to 50%. The upper part of this figure illustrates that for each geographic focus the subject areas *forests and the development debate* and *ecosystem management* were the most and second most important, whereas the lower part of the figure paints a picture of regional diversity. For SFM-research with a focus on *Africa*, the subject area *land-use* (~12%) made a significant contribution and *forest stand management* (~8%) was of importance as well. The other subject areas were rather insignificant for Africa. Like for Africa, also for *Asia* the subject area *land-use* (~10%) was of higher importance. Furthermore, *forests – water cycle/watershed management* and *forest stand management* were relevant too. In contrast, *Europe* had a completely different composition of subject areas: *forest stand management*, *carbon cycle/climate change*, *forests – nutrient cycle*, *forests – water cycle/watershed management*, *land-use*, and *biodiversity* all had a share of four to six percent. The average topical composition of SFM-publications with a focus on *North America* was comparable with the European case, but with higher importance of *forest stand management* (~8%) and lower importance of the other subject areas in turn. *Forest stand management* in *Oceania* (~10%) had a big share as well. However, more

exceptional the subjects *forests – nutrient cycle*, *biodiversity*, and *fire* all had their biggest share in publications with a focus on this continent, compared with all other geographic foci. For *South America*, *forest stand management* (13%) was by far the most important subject area, followed by *land-use* (9%) and *forests – nutrient cycle* (6%). The average composition of publications that refer to *multiple continents* or *no geographic focus* shows a similar picture. In both cases, the importance of the subject area *forests and the development debate* was particularly high compared to the continent cases. In turn, none of the subject areas in the lower part of [Figure 3](#) was of higher significance. Publications that took into account regions on several continents made in particular *land-use* (7%) and *forest stand management* (6%) a subject of discussion. The subject areas *carbon cycle/climate change* and *modeling* both had their biggest share in SFM-research with no geographic focus; moreover, *carbon cycle/climate change* is the third important research area as well.

Journal-type-specific orientation of SFM-research

Our final analysis tackled the question if there has been a difference in the evolution of SFM-research in forest-focused journals and non-forest focused journals, respectively. To answer this question, we analyzed the share in terms of numbers of publications of either of these types of journals for each year. The result of this analysis is illustrated in [Figure 4](#).

In accordance with [Figure 4](#), it can be proposed to distinguish at least three phases of SFM-research within the period from 1990 to 2016, the early phase until about 1995, the central phase from 1995 to 2008 and the current phase since then. In the early phase (1. Phase) the relative share of forest-focused journals in SFM-research grew from about 30% to about 45%. In the central phase (2. Phase) the share of both forest and non-forest journals remained more

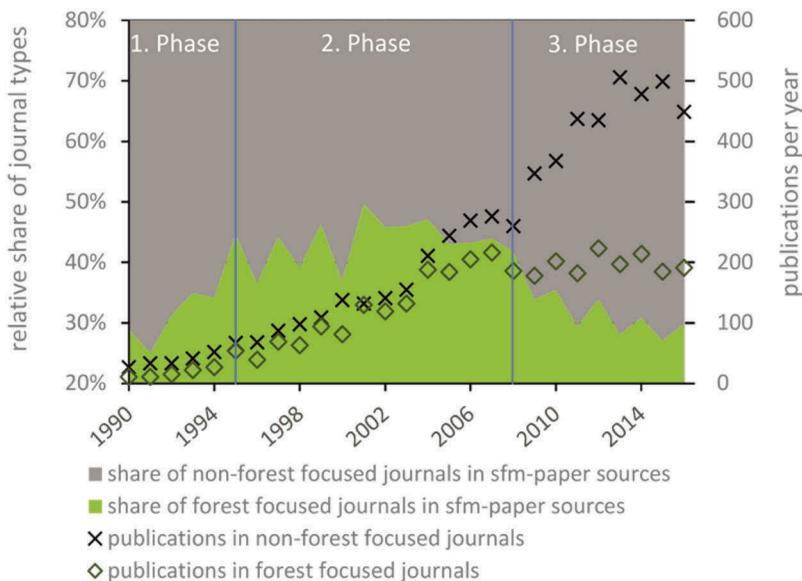


Figure 4. Temporal development of the share of journal types in SFM-related publications in the period 1990 – 2016.

or less constant for almost 15 years. In the current phase (3. Phase) the absolute number of SFM-related publications in forest-focused journals mounted around 200 for each year, while the number in non-forest focused journals increased to nearly 500 annual publications.

Discussion

The results of our analysis emphasize various contrasts that can be observed within the SFM-research, like the study of Sutterlüty and colleagues (in review) did. However, while Sutterlüty and colleagues identified research foci in SFM in an iterative process of interpretation of preselected abstracts from SFM-research for the period 2008–2015, we applied a recent statistical text mining method on the corpus of abstracts that were published between 1990 and 2016 to provide an overview of the evolution of SFM-research.

By doing so, we established ten research areas of different importance and breadths, of which two are in the core of SFM-research. In accordance with our findings, the development debate with a focus on forest policy is essential. Our observation is supported by Giessen and colleagues (2016) who conclude that “*The last two decades of forest policy discussions have been dominated by calls for sustainable management of forest resources*”. In addition, our findings show that forest certification belongs to this very subject area. These findings are in accordance with the conclusions from Rametsteiner and Simula (2003), who identify forest certification as a crucial instrument for the promotion of SFM. However, Rametsteiner and Simula (2003) also stress that certification is a complementary mechanism to policy instruments (e.g. national criteria and indicators for SFM) and is focused on operationalization of SFM on a forest management unit level (FMU). On the contrary, our results show that scientific discussion on SFM has predominantly discussed certification as an instrument for the promotion of the concept of SFM, while its actual impacts on the stand characteristics and forest management techniques have received comparatively less attention. From a global perspective, in this field particularly Europe seems to be a “late adopter” at first, but steadily increased its interest in SFM over time, according to our results. There are two plausible explanations for our results. Firstly, the increase in the number of publications is in compliance with the continuously growing importance of forest management in the national policy (bioeconomy, EU renewable energy strategy, EU forest strategy, etc.). Furthermore, it also corresponds to the establishment of *The Ministerial Conference on the Protection of Forests in Europe* (the Helsinki-process) and development of the European guidelines, criteria, and indicators for SFM (MCPFE, 1993). Therefore, it can be assumed that the scientific narrative is closely following the policy developments in Europe. Apart from that, European forest scholars formerly possibly published in domestic journals and native language and only have become more integrated into international scientific publishing over time. Moreover, prior to the early 90s, “close to nature”-silviculture was a broadly used concept in European forestry and thus the existence of such a competing concept to SFM could cause a low number of observation at the beginning of the analyzed time frame. Conversely, our results for North America depict a continuously decreasing trend in the number of SFM related scientific publications. We did not find any possible explanatory variable in our analysis. Thus, this question represents an interesting line of scientific inquiry in the future. However, the

importance of these scientific debates (*forests and the development debate*), which are addressing issues of more conceptual and theoretical nature, decreased over time. We see this as the logical consequence of the formation process of SFM-research. Moreover, the decrease of these theoretical debates is reflected also in a relative decline of publications that have no geographic focus, their share in research decreased by a factor of three in the examined period. In turn, the more applied field of ecosystem management has been gaining importance. In Europe and Asia, this research field is very present, while it is less present in Africa and Oceania. As regards content, we found that the term “ecosystem” alone is very important in this field. Indeed, wider social trends have emphasized protection of ecosystem services (MEA, 2005) and forestry scholars have awarded increased amount of attention to ecosystem services in their research (Pretzsch, Grote, Reineking, Rötzer, & Seifert, 2008). Our observations, therefore, suggest that “ecosystem management” (Kimmins, 2002) emerged as a dominant paradigm in the scientific community and is the most widely used framework for operationalization of theoretical principles of SFM concept.

The research area land use reveals a significant conjunction between agriculture and socio-environmental conflicts in SFM-research. Therewith, our observations reflect the results of the latest “Global forest resource assessment” (<http://www.fao.org/forest-resources-assessment/en/>, accessed on 2nd August 2017), which show that agriculture is the main driver for deforestation through land use change (LUC). However, although land use still is a major problem in developing countries, research on land use almost continually lost importance in SFM-research since 1990, while studies conducted in Africa and Asia significantly increased in general. The decrease in the share of land use research could be explained by the fact that the global annual deforestation rate also decreased from 1.8% of total forest area in 1990 to 0.8% in 2015 (FAO, 2015). While land use is most relevant on each continent that belongs to the “global south” (South America, Africa, and Asia), forest stand management dominates in South America and Oceania as well. In the early years of SFM-research this field was barely noticeable, however, it plays a steady role since the year 2000.

In accordance to our analysis, with the water-, the carbon- and the nutrient cycle also the major cycles of substances are focal points in SFM-research, each of which of comparable importance (4–5% share of research areas). The water cycle/watershed management, for example, is frequently addressed in research conducted in Asia, which reveals a disproportionately high focus on this subject. This focus may partially be explained by the hugely popular approach of watershed management on that continent. Both India and China have massive watershed management programs, on which plenty of research has been published. Moreover, these are also the two most populous countries and experience severe water shortages that have to be managed with appropriate forestry (see, e.g. Luo, Zheng, Wang, and Du (2017)). In contrast, the carbon cycle that appears in association with climate change is a matter of discussion particularly in publications with multiple geographic foci or no geographic focus at all and in studies conducted in Europe as well. Moreover, it seems like the climate change narrative is independent of other topics. It is lately primarily driven by the increased use of wood as a renewable energy source, e.g., the rise of the second generation of biofuels. In total, this research area reflects the long-lasting debate on the controversial character of the impact of energy use of forest biomass on climate change (Berndes et al., 2016).

Our findings suggest that an ecological and silvicultural approach to the issue of climate change is also highly relevant and, in addition, underscores the important role of wood products in carbon sequestration. Nevertheless, interestingly the carbon cycle was of higher importance for a period in the 1990s and then again after 2005. Furthermore, currently, this subject area is heterogeneous and comprises multiple approaches to sequestration of carbon in forests and forest products (e.g., bioenergy, storage in wood products and conservation), which implies that none of the strategies has established itself as a dominant approach to mitigation of climate change. However, after the inclusion of forest restoration and conservation into Paris agreement it remains to be seen if such a development will be reflected in the research of the scientific community investigating SFM. The nutrient cycle primarily plays a role in Oceania and South America and is in connection to research on plantation issues. Interestingly, plantations do not seem to be of comparable importance for research focused on the water cycle/watershed management or on biodiversity, although the excessive water use (Vanclay, 2009) or the negative impact on biodiversity (Stephens & Wagner, 2007) are often stressed as the main research foci in context of timber plantations. Biodiversity, in turn to land use, is primarily made a subject of discussion in continents usually associated with the expression “global north” (Europe, North America and Oceania), e.g. in context with sustainability indication (Barbati, Marchetti, Chirici, & Corona, 2014). Nevertheless, the effects of SFM on biodiversity are also considered in association with, e.g. Asian tropical forests (Shearman, Bryan, & Laurance, 2012). Modeling is the only research area in our results that amongst its most important terms, comprises one that is referring to a tree species (“beech”). As a whole, our analysis of this research area suggests that the application of models represents the dominant approach for development and research of decision support systems applied in SFM. Furthermore, our results demonstrate the importance of models when dealing with the issue of uncertainty in SFM. The final research field in this discussion is the forest fire, which plays a remarkable role in North American and Oceanian SFM-studies. These studies are addressing, in particular, the implications of fire on the practical implementation of SFM as did, for example, Bergeron, Gauthier, Kafka, Lefort, and Lesieur (2001). An important topic in the literature addressing forest fires is fuel reduction (Puettmann, 2014), which is indicated by our findings as well.

Additionally, our analysis of the differences between forest- and non-forest-focused journals referring to SFM yielded interesting insights. We conclude that there may have been three phases in the evolution of SFM-research. First the early phase, which reaches until mid 1990ties, covers in particular issues regarding land use in tropical and developing countries such as Asia and Africa. Furthermore, papers in this phase tend to focus more on general concepts or policy issues. In contrast, the second phase is characterized by a larger share of publications in forestry focused journals. This process is seemingly connected with issues like forest management certification, forest stand management and the development of sustainability indicators. A third phase can be observed by the relative downturn of publications in forest-focused journals between 2005 and 2010. As shown in [Figure 4](#) this relative change is due to a strong increase in total publications. A new focus in this period is, for example, climate change in the context of SFM. This interpretation corresponds well with Wang (2004) who described the development process of the SFM concept in 3 stages. In particular, the last stage is characterized by the integration of other disciplines, apart from forestry, into the concept of SFM. Wang (2004) stressed the rising role of forests as carbon sinks in this stage, which suits our data very well.

In conclusion, with the comprehensive survey of SFM-research, our study provides an example of the opportunities of modern text analysis techniques. These techniques could be used as well to shed light on more detailed subjects like the discussed topics of biodiversity in SFM, but also could be applied on bigger text corpora that partly include SFM-research to work out how this field is entangled in other fields.

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