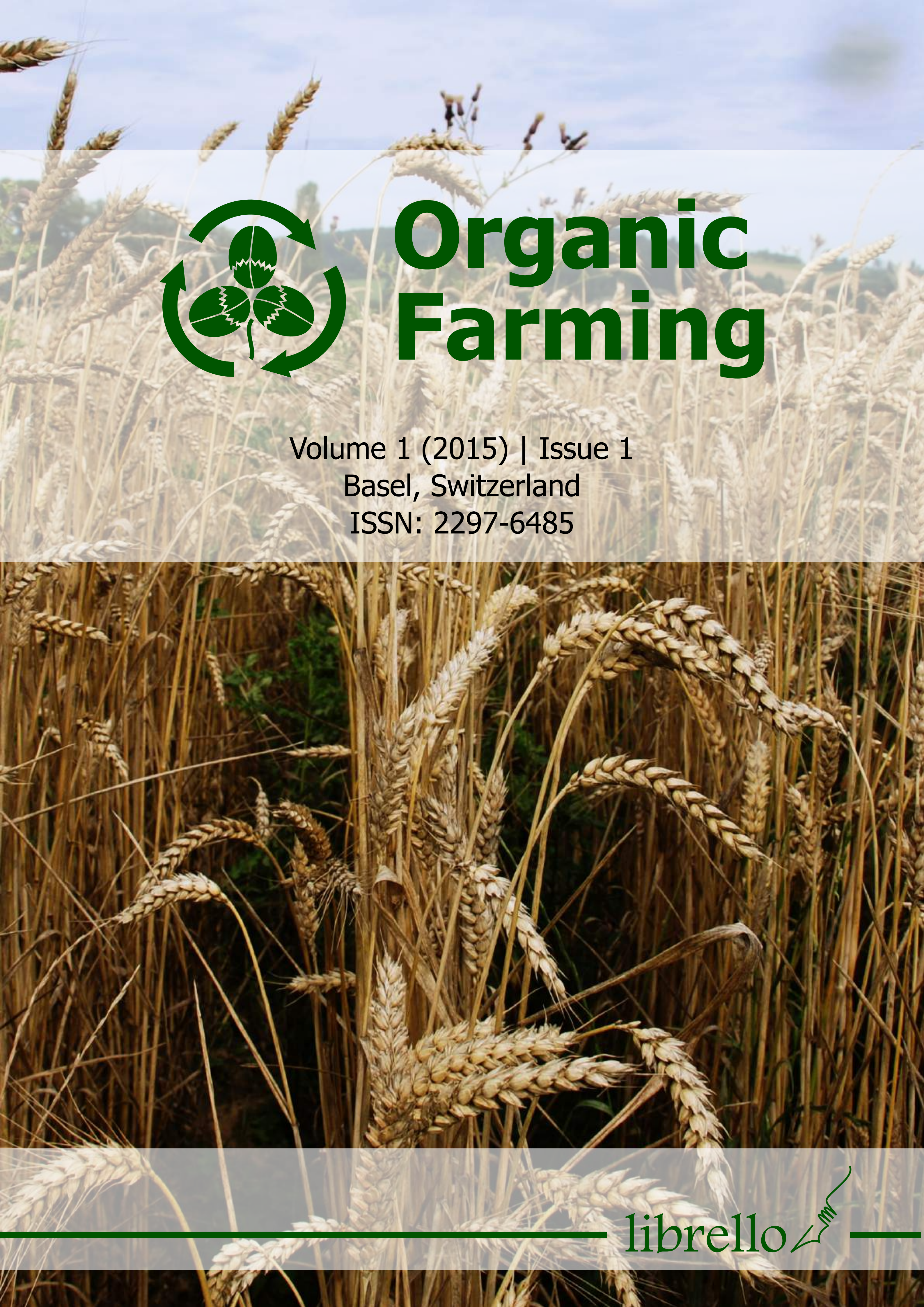

Organic Farming

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Organic Farming is an international, open access, academic, interdisciplinary journal, published by Librello.

Cover image
Organic composite cross population of winter wheat before harvest, Neu-Eichenberg Germany (author: Sarah Brumlop).

About *Organic Farming*

Focus & Scope

Organic Farming (OF; ISSN 2297–6485) is a new open access academic journal that publishes articles on advances and innovations in organic agriculture and food production to provide scholars and other groups with relevant and highly topical research in the field.

Organic Farming is a new open access academic journal that publishes articles on advances and innovations in organic agriculture and food production to provide scholars and other groups with relevant and highly topical research in the field.

Organic Farming welcomes contributions in diverse areas related to organic farming and food production, such as soil and plant management, crop breeding, regulation of pests and diseases, protection of soil, water, biodiversity and other resources, livestock health and management, marketing and acceptance of organic products, food quality and processing, policies and regulations.

The articles of *Organic Farming* will be immediately accessible upon publication and we aim at making this journal a valuable venue for the communication among scientists, but also between researchers, producers, policy makers, traders and consumers of organic products.

Topics covered by this journal include, but are not limited to: agroforestry systems; biodiversity; biological pest and disease control; certification and regulation; compost and manure management; consumer research; crop rotations; ecosystem services; food processing; food quality and safety; green manures; nutrient cycling and run-off; organic energy production; organic farming for food security; plant breeding and genetics; poverty eradication and human development; regulation and policies; resilience and transformations; social acceptance and marketing; soil and water protection; sustainability and ethics of livestock production; sustainable agriculture; tillage and no-till organic farming systems; veterinary aspects of organic livestock production; weed ecology and management; and related topics.

Organic Farming will specially welcome original interdisciplinary and trans-disciplinary contributions.

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Organic Farming

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Editorial

A Fresh Start for Organic Farming Research

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Welcome to *Organic Farming*, a New Open-Access Peer-Reviewed Journal!

Over the past few decades the area of farmland under organic management has significantly and continuously increased [1]. This trend, observed across all continents, has been accompanied by a strong expansion of the market for organically produced goods, and a substantial increase of organic farming research efforts, funded through national and international programmes. At the same time, with the tremendous expansion of organic agriculture and food systems the organic sector has experienced a remarkable diversification and it is therefore essential to conduct research in, and find practical solutions for, an increasing diversity of organic farming systems across the globe.

Research findings from organic food and farming systems have had a significant impact on conventional agriculture, on agricultural policies and of course on the adaptation and optimisation of organic systems in practice [2]. However, organic ideas have not remained unchallenged: from the inception of organic farming research, there has been an intensive and dynamic controversy, both within and outside of academia, over the benefits of organic farming and food systems, and the potential and actual contributions of organic farming to the solution of global challenges such as food security [3-5], biodiversity conservation [6-8], and climate change [9]. It is likely that the years ahead will be no less dynamic, as organic food and farming systems will need to balance mounting economic pressures with organic principles and find their way between inspiring conventional agriculture and simultaneously competing with it.

With these past and expected future developments in mind it is clear that a solid research basis is needed for the progress of the organic sector and related areas. In fact, these thoughts highlight the pressing need to strengthen and expand the forum for research on organic farming. Thus, we are launching Organic Farming as new open-access peer reviewed journal to complement, enrich, and challenge current academic publishing in the area of organic food and farming systems. As the scientific community intensifies its efforts to solve global problems in agriculture and food systems, our journal will strive to facilitate this process, acting as an amplifier and focussing lens to highlight promising innovations and significant insights from organic farming research.

Following the spirit of the organic farming principle of fairness [10], all articles in this journal are free for readers, so as to decrease barriers to sharing knowledge. Publishing costs are met via membership fees paid by authors. This model is based on the idea that the community of contributing researchers jointly bears the costs of publishing; through this membership system [11] we offer a low-cost option to open-access publishing and hope to foster a close identification of contributing authors with the publishing process.

At the same time, establishing this new journal on organic farming offers a unique opportunity to shape the editorial process in a fresh and innovative way and to tackle the well-known problems associated with current academic publishing [12-14]. In particular, Organic

Farming is committed to promoting and highlighting the impact of organic research in practice, alongside the promotion of traditional measures of visibility. We are dedicated to ensuring the highest quality standards through fast and rigorous peer review and editorial policies, and processes are designed to facilitate inter- and transdisciplinary exchange, e.g. by building bridges between research on agricultural production on the one hand and food culture systems research on the other.

The members of the editorial board, with their shared enthusiasm for organic farming research, are committed to scientific quality and service to authors and readers. On behalf of the editorial board I would therefore like to invite you to submit articles to Organic Farming.

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Organic Farming

Research Article

Strategies towards Evaluation beyond Scientific Impact. Pathways not only for Agricultural Research

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Abstract: Various research fields, like organic agricultural research, are dedicated to solving real-world problems and contributing to sustainable development. Therefore, systems research and the application of interdisciplinary and transdisciplinary approaches are increasingly endorsed. However, research performance depends not only on self-conception, but also on framework conditions of the scientific system, which are not always of benefit to such research fields. Recently, science and its framework conditions have been under increasing scrutiny as regards their ability to serve societal benefit. This provides opportunities for (organic) agricultural research to engage in the development of a research system that will serve its needs. This article focuses on possible strategies for facilitating a balanced research evaluation that recognises scientific quality as well as societal relevance and applicability. These strategies are (a) to strengthen the general support for evaluation beyond scientific impact, and (b) to provide accessible data for such evaluations. Synergies of interest are found between open access movements and research communities focusing on global challenges and sustainability. As both are committed to increasing the societal benefit of science, they may support evaluation criteria such as knowledge production and dissemination tailored to societal needs, and the use of open access. Additional synergies exist between all those who scrutinise current research evaluation systems for their ability to serve scientific quality, which is also a precondition for societal benefit. Here, digital communication technologies provide opportunities to increase effectiveness, transparency, fairness and plurality in the dissemination of scientific results, quality assurance and reputation. Furthermore, funders may support transdisciplinary approaches and open access and improve data availability for evaluation beyond scientific impact. If they begin to use current research information systems that include societal impact data while reducing the requirements for narrative reports, documentation burdens on researchers may be relieved, with the funders themselves acting as data providers for researchers, institutions and tailored dissemination beyond academia.

Keywords: interdisciplinary; research evaluation; societal impact; transdisciplinary

1. Introduction

A crucial aim of agricultural research is to address sustainable development. Global challenges like climate change [1] or the degradation of ecosystem services have fundamental negative impacts on human health and well-being [2]. Agriculture is both driving and being affected by those developments ([2] p. 98), [3]. Such challenges require immediate and adequate action on the part of the whole of society, but also the contribution of relevant knowledge through research ([3] p. 3; [4] p. 322). However, whether research is able to make that contribution depends primarily on the conditions and incentives within the scientific system.

In this article, the focus will be on research evaluation, which can be an important driver for developing science in the direction of scientifically robust, societally relevant and applicable knowledge production. Currently, scientific quality assurance is mainly performed through peer review of papers and project proposals, while scientific impact is evaluated based on publication output in peer-reviewed journals and citation-based performance indicators (detailed in Section 2.3). Citations of a publication are a measure of the acknowledgement by the respective researcher's peers. Citations are counted by and in peer-reviewed journals that are indexed for citation counting. Furthermore, a researcher's publication output and citation rates can be subsumed in an index, e.g. the h-index [5]. Citations are also used as a measure of the recognition of journals, where all citations of a journal within other journals are counted, e.g. the Journal Impact Factor (IF) used by Thompson Reuters [6]. Accordingly, scientific impact is associated with high publication output in high-impact journals and high citation rates in other highly ranked journals. These measures assess, at best, the impact of research on science itself. However, they neither assess societal impact nor serve as proxies for it [7]. As a result, research which similarly targets audiences outside academia may not be adequately appreciated in research evaluation. The term societal impact is used here to sum up all the practical, social, environmental, economic and other 'real-world' impacts research may have for its target groups and society as a whole.

To overcome shortcomings in current research evaluation practices, several alternative evaluation concepts which take societal impacts into account have been developed over the past few years (see Section 3.2). However, such an evaluation of societal impact faces some inherent challenges, including time and attribution gaps. The term 'time gap' describes the problem that if impact occurs, it is in most cases with some delay after completion of the research. Secondly, the 'attribution gap' means that impacts are not easily attributed to a particular research activity like a project or publication. For example, the adoption of a particular agricultural innovation may be the result of several research activities combined with policy changes and other influences. Accordingly, the state of the art of societal impact assessment focuses on the contribution of research in complex innovation systems, instead of attributing the impacts linearly in terms of cause and effect [8]. Furthermore, proxies are often employed, instead of direct measures of impact. One example is the concept of 'productive interactions', defined as direct, indirect or financial interactions with stakeholders that support the use of research results and make an impact likely [9].

With bibliometric data it is possible to analyse interdisciplinary publications via references from and citations in different fields [10], as well as interactions between basic and applied research. By contrast, the assessment of societal impact (or corresponding proxies) cannot be built on bibliometric analysis, and in most cases there are no other sources with easy-to-use data available either. Thus the effort involved in data assessment for documentary analysis or interviews, for example, inhibits the frequent use of such evaluation approaches.

Starting from these observations, the aim of this paper is to discuss two possible strategies to facilitate research evaluation that is more balanced, both with regard to scientific quality and impact, and to societal relevance and applicability. The first strategy is to strengthen general support for such evaluation beyond scientific impact; the second is to reduce the effort of societal impact evaluations by improving data availability.

Section 2 below introduces the relevant movements and focuses on shared interests as a base for broader support of evaluation beyond scientific impact. Section 3 then provides concrete measures for such support, including possibilities for improving data availability for evaluation beyond scientific impact. In each section the paper shows how agricultural research that is oriented towards sustainability and real-world impact, with a special focus on organic agricultural research, could be involved in these developments in order to create good conditions for its fields of research. We will conclude with an overview of the actions that may be undertaken jointly by various actors.

2. Multiple Voices Call for Changes in Knowledge Production and Research Evaluation

Various societal groups are demanding changes in knowledge production and research evaluation, for example researchers and funding agencies engaged in sustainability, global challenges and transdisciplinary approaches, the open access movements, and researchers who scrutinise current research evaluation systems for their ability to serve scientific quality.

2.1. Research Engaged in Sustainability, Global Challenges and Transdisciplinary Approaches

2.1.1. Sustainable Development Requires the Support of Interdisciplinary and Transdisciplinary Research Approaches

Several international assessments synthesise scientific and non-scientific knowledge via multiple-stakeholder processes involving science, governments, NGOs, international organisations and the private sector, for example the Millennium Ecosystem Assessment (MA) [2], the International Assessment of Agricultural Knowledge, Science and Technology for Development (IAASTD) [3] and the World Health Summit ([11] pp. 86–87). These assessments, and some scientific groups that give policy advice, such as the WBGU (German Advisory Council on Global Change) [4], point out that there is considerable pressure on society to tackle pressing challenges adequately, which in turn requires knowledge to be produced, accessed and used in ways that assist such adequate action and are conducive to sustainable development.

However, the transfer of existing knowledge and technologies faces several challenges. On the one hand, the balance of power and conflicting interests impede the use of research evidence ([2] p. 92). The reduction in greenhouse gas emissions, for example, is still not sufficient, although the IPCC has been transferring the state of the art regarding climate change to politics for 20 years now. [1]. On the other hand, the need to increase access, clarity and relevance of research evidence for politics has been discussed [12]. Furthermore, concepts for the transfer of knowledge and technology should reflect on possible risks. Instead of merely assuming the superiority of external knowledge and novel technologies, they should be tested beforehand under actual conditions of use ([3] p. 72) or evaluated in sustainability assessments [13].

The challenges in knowledge transfer also lead to a demand for changes in knowledge production in order to increase the applicability and sustainable benefits of knowledge. The reasons for such demands are firstly that technological development is fast and may have deep, in some cases irreversible impacts on our ecological, economic or social environment ([14] pp. 87–93). Secondly, post-modern societies consist of complex subsystems that function according to their own inherent rules and often fail to deal with impacts that occur in more than one of them at the same time ([14] pp. 61–63, 87–93). Thus, knowledge production also needs to cut across specialised areas and societal subsystems ([15] p. 544; [4] p. 322) and should support transformative processes ([4] p. 322), [11]. Thirdly, true participation of stakeholders in research processes is required to support practical applicability, ownership of solutions and sustainable impact of knowledge ([2] p. 98; [3] pp. 72–73; [4] p. 322). Accordingly, recommendations cover enhanced knowledge exchange among disciplines, between basic and applied research ([4] p. 322) and between science and politics [12], ([16] p. 9) and the involvement of stakeholders, including the integration of traditional and local knowledge ([2] p. 98; [3] pp. 72–73; [4] p. 322). Such transdisciplinary processes may also be supported by involving 'knowledge brokers' as intermediaries to facilitate knowledge exchange [12], ([17] p. 17). Additionally, joint agenda setting, including science, politics, the economy and in particular civil society organisations is recommended for research regarding sustainability ([4] p. 322) and agriculture ([17] p. 17) and is, in some cases, already practised [18–20]. This corresponds to the aim of civil society organisations to strengthen their influence in research policy, for example [21].

The recommendations specified in this section are well subsumed in the terms co-design, co-production, co-delivery and co-interpretation used by the project VisionRD4SD [22]. These recommendations show that concepts for inter- and transdisciplinary research (e.g. [23–26]) and approaches of 'systems of innovation', understanding innovation as a set of complex processes involving multiple actors beyond science (e.g. [27]), are now well accepted in policy advice. Likewise, several research funders have started to support sustainability and transdisciplinarity explicitly in research programming ([14] pp. 202–214), [28,29].

2.1.2. Current Incentive Systems Are Criticised

Apart from the promising developments mentioned above, current incentive systems are considered inappropriate for encouraging researchers to focus their research on sustainable development.

Reputation-building processes based on publications in high-ranking scientific journals and third-party funding are often governed by disciplinary perceptions and fail to acknowledge interdisciplinary and systemic approaches ([4] p. 351). Interdisciplinary research usually has to match the standards of different disciplines in peer review processes, which adversely affects publication success [10], ([15] p. 547) and the evaluation of multidisciplinary institutions [30]. Audits based on bibliometric performance indicators [15] and, explicitly, the use of journal rankings [10] have been shown to be biased negatively against inter- and multi-disciplinary research.

Some authors discuss consequences such as poorer career prospects, orientation of research away from complex social questions, reduction in cognitive diversity within a given discipline or the entire science system [10], and an increasing relevance gap between knowledge producers and knowledge users [15]. Similarly, Schneidewind et al. highlight the diversity of the sciences in objectives and theories as a base for societal discussion processes ([14] pp. 30–33) and good scientific policy advice ([14] p. 63).

Thus, researchers, institutions and funding agencies that move towards joint knowledge production for sustainable development may often feel contradicted by the current incentives within scientific reputation systems. Accordingly, the indication is that it is necessary to improve current evaluation practices in general and apply evaluation criteria beyond scientific impact.

2.1.3. Opportunities for (Organic) Agricultural Research

Broader support for changes in knowledge production and research evaluation provides multifarious opportunities for agricultural research. As organic and sustainable farming addresses and works within the complexity of ecological systems, and farmers' knowledge and practices are key to building resilient agricultural production systems, the approaches highlighted in Section 2.1.1 have, since their early days, been advocated in agroecology [31] and organic agricultural research ([19] pp. 15–16), [32,33], Agricultural researchers are often already in contact with actors along the whole value chain of agriculture, and approaches are reflected in diverse concepts for transdisciplinarity e.g. [34–36], and systems of innovation e.g. [37]. Researchers' experiences, and their awareness of the challenges posed by such approaches e.g. ([19] p. 61), [38], promote their adequate advancement via mutual learning with other research communities. Furthermore, the competence of (organic) agricultural research to develop applicable solutions with substantial value in the context of some pressing social and ecological challenges may become more visible.

Research evaluation that goes beyond conventional performance indicators and involves stakeholders is seen as necessary for agricultural research too ([3] pp. 72–73; [17] pp. 81–84; [19] p. 56). Such research evaluation may facilitate the application of transdisciplinary and related research approaches without disadvantages for researchers' reputations. The necessity of such incentive effects is supported by various statements, e.g. "European agricultural research is currently not delivering the full complement of knowledge needed by the agricultural sector and in rural communities" ([19] p. 57). Similarly, the evaluation of an organic agricultural research programme in Sweden resulted in the verdict 'excellent' by scientific peers, while the agricultural advisors indicated too little relevance to pressing problems [39]. The DAFA position paper "Assessment of applied research" considers it necessary to build a consensus about possible indicators, make a commitment to their rigorous application and improve documentation for practice impact [40]. Thus, (organic) agricultural research may use its commonalities with sustainability research in order to jointly advance interdisciplinary and transdisciplinary research approaches and to advocate their adequate support in funding and appreciation in research evaluation.

2.2. Open Access with Focus on Benefit for Society

Open access movements also aim to increase the benefit of research results for science and society. More than ten years ago, the Berlin declaration called for open access for original research results, raw data, metadata, source materials, digital representations of pictorial and graphical materials and scholarly multimedia [41]. Arguments in favour of open access are for example a) to regard publicly funded knowledge as public property, b) to enhance the transfer, visibility and benefit of knowledge, which is now easily possible via digital technologies and reasonable because of the increased scientific literacy of the public, and c) to support participation in democratic societies [41,42].

Furthermore, the open access movements provide concepts for increased collaboration and interaction in the creation of research results and pluralisation and transparency in the evaluation of publications, and support the full use of technological developments in data processing (see Section 3.1).

However, the inadequate exchange, use, relevance and ownership of scientific knowledge in politics, practice and society indicate that open access alone does not suffice to create benefits of knowledge. Thus co-design, co-production, co-interpretation and co-delivery are necessary on one hand to serve societal benefit, whilst on the other the dissemination of openly accessible research outputs tailored to target groups within and beyond science is also a requirement. Such a comprehensive view of the benefits of research for society increases the credibility of the arguments and supports the view that the corresponding changes in evaluation criteria can be promoted jointly by open access movements and research that is concerned with sustainable development. In our view, (organic) agricultural research is well placed to become a proficient actor in the process of combining the tasks of these two groups. The (organic) agricultural research community is experienced in knowledge transfer and inter- and trans-disciplinary approaches within the diverse agricultural sector and is aware of 'open-access issues', for example interrelations between agriculture and public goods ([3] pp. 24, 30, 73).

2.3. Improve Current Scientific Impact Evaluation Procedures

In general, evaluation procedures that support scientific quality are required for both basic and applied research as foundations for evidence-based decisions. However, as detailed below, current scientific impact evaluation procedures are shown to have potential negative consequences for scientific quality. Knowledge of these consequences and possibilities for improvement is helpful for strengthening scientific quality, increasing awareness of the general effects of evaluation processes, and generating some 'open space' to introduce criteria related to societal impact.

2.3.1. Challenges of Peer Review as a Socially Embedded Process

Several criteria are used by the scientific community to assess scientific quality. The most common are the novelty and originality of the approach, the rigour of the methodology, the reliability, validity and falsifiability of results and the logic of the arguments presented in their interpretation. Peer review processes are broadly perceived as functioning self-control of the scientific community towards scientific quality in publications and third-party funding. Correspondingly, reviewers trust the fairness and legitimacy of their own review decisions [43].

Nevertheless, peer review processes also reflect hierarchy and power within science as a social system. Editors and peers appear as 'gatekeepers', who not only maintain quality but also uphold existing paradigms and decide which of the many high-quality research papers submitted will be allowed to enter the limited space available in the journal concerned [44, 45]. Evaluative processes are found to involve not only expertise, but also interactions and emotions of peers [46] in ([43] p. 210). Instead of erroneously assuming that a "set of objective criteria is applied consistently by various reviewers", it is necessary to focus on what factors promote fair peer review processes ([43] p. 210).

Undesired decision processes such as strategic voting may occur on peer review panels; it has been suggested that fairness is improved if peers rate rather than rank proposals and give advice to funders instead of deciding about funding [43]. Furthermore, in single-blind reviews, knowledge of the author's person, gender and institutional affiliation may influence peer review [43,47–50]. Double-blind and triple-blind reviews, the latter including editor-blindness, partly reduce bias [45], but advantages for native speakers, preferences for the familiar and insufficient reliability of reviewer recommendations do remain ([43] p. 210), [48,50]. For example, the agreement between peers with and without experience in organic agricultural research has been found to be poor with regard to reviewers' assessment of scientific quality in organic farming research proposals [51]. In some cases peer review fails to identify fraud, statistical flaws, plagiarism or repetitive publication [47,50]. Recently, trials on the submission of fake papers have revealed alarmingly high acceptance rates, in high-ranked subscription journals [52] and open access journals [53]. The latter study includes some publishers who were already on Beall's list of 'predatory publishers', which identifies open access publishers of low quality [54], [55].

Accordingly, further possibilities for improving peer review processes are being discussed. They focus on increasing efficacy and transparency in research dissemination and quality assurance via the full use of technological developments in connection with open access (see Section 3.1).

2.3.2. Self-Reinforcing Dynamics of Bibliometric Indicators

Bibliometric indicators (Table 1) are also results of socially embedded processes because, firstly, publication in a certain journal reflects the decisions of reviewers and editors, and secondly, citation-based performance indicators subsume the decisions of many scientists as to whether to cite or not. In general, the publication of research evidence is influenced by researcher bias (the observer expectancy effect), which results in a higher likelihood of false positive findings and publication bias, meaning that "surprising and novel effects are more likely to be published than studies showing no effect" ([56] p. 3). Accordingly, "the strength of evidence for a particular finding often declines over time". This is also known as the decline effect ([56] p. 3). Moreover, non-significant results often remain unpublished. This phenomenon, known as the file-drawer effect, distorts the perception of evidence and reduces research reliability and efficacy [57].

The fact that peer decisions are often influenced by metrics also has to be taken into account: Merton describes the cumulative processes of citation rates as the Matthew effect, which follows the principle that "success breeds success" and results in higher citations being overestimated and lower citations underestimated [58]. Such dynamics are enforced by increasing scarcity of time resources and an augmented need to filter a large amount of accessible information [59]. Evidence of the Matthew effect, also called accumulative advantage, is frequently detected in science [60] and considered by scientists to be the major bias in proposal evaluation ([48] pp. 38–39).

A further interaction occurs between metrics and strategic behaviour: as person-related indicators of productivity (publication output) and impact (citation-based indicators) influence funding or career options [61], dividing results into the 'least publishable unit' [62], increasing the number of authors, or citing 'hot papers' are strategies for boosting scientists' performance indicators [45].

Furthermore, indices may hide information. The popular h-index combines publication output and citation rates in one number. It reduces the disproportionate valuation of highly cited and non-cited publications, with the result that researchers with quite different productivity and citation patterns may obtain the same h-index. This has been criticised, and the recommendation is to use several (complementary) indicators to measure scientific performance, in particular separate ones for productivity and impact [63].

The relevance and use of journal-related metrics are also subjects of intense debate. A review of several empirical studies about the significance of the Journal Impact Factor (IF) concluded that "the literature contains evidence for associations between journal rank and measures of scientific impact (e.g. citations, importance and unread articles), but also contains at least equally strong, consistent effects of journal rank predicting scientific unreliability (e.g. retractions, effect size, sample size, replicability, fraud/ misconduct, and methodology)" ([56] p. 7). For example, a correlation was detected between decline effect and the IF: initial findings with a strong effect are more likely to be published in journals with a high IF, followed by replication studies with a weaker effect, which are more likely to be published in lower-ranked journals [56].

Moreover, the IF and other journal-based metrics are increasingly considered inappropriate for comparing the scientific output of individuals and institutions. This is indicated by the San Francisco Declaration on Research Assessment (DORA), currently signed by nearly 500 notable organisations and 11,000 individuals [64]. DORA substantiates this statement with findings which show that a) citation distributions within journals are highly skewed; b) the properties of the IF are field-specific: it is a composite of multiple, highly diverse article types, including primary research papers and reviews; c) IFs can be manipulated (or 'gamed') by editorial policy; and d) data used to calculate the IF are neither transparent nor openly available to the public [65]. Gaming of the IF is, for example, possible by increasing the proportion of editorials and news-and-views articles, which are cited in other journals although they do not count as citable items in the calculation of the IF [66].

Thus, journal-based metrics are not only found to be unreliable indicators of research quality; the pressure to publish in high-ranked journals may also compromise scientific quality. Furthermore the latter "slows down the dissemination of science (...) by iterations of submissions and rejections cascading down the hierarchy of journal rank" ([56] p. 5) which also enormously increases the burden on reviewers, authors and editors [67].

In agricultural research, some scepticism about journal-related metrics is already evident: the Agricultural Economics Associations of Germany and Austria, for example, perform 'survey-based journal ranking', because this was perceived to be more adequate than using the IF [68].

Apart from current criticism, efforts in indicator development should be acknowledged. In article-based metrics, the weighting of co-authoring and highly cited papers, excluding self-citations, leverage of time frames and inclusion of the citation value (rank of the citing journal) aim to assess scientific impact more precisely. Similarly, the further development of journal-based metrics (see Table 1) involves the exclusion of self-citations and inclusion of citation value, the weighting of field-specific citation patterns, the inclusion of network analyses of citations or weighting the propinquity of the citing journals to one another [69]. Nevertheless, the self-reinforcing dynamics of bibliometric indicators and their interactions with the credibility of science are not taken into account in these indicator variations. For example, the weighting of citation value may even increase accumulative advantage.

To sum up, it seems appropriate to improve peer-review processes, to reject certain indicators, and crucially, to apply a broad set of indicators, because scientific performance is a multi-dimensional concept and indicators always contain the risk that scientists will respond directly to them rather than to the value the indicator is supposed to measure ([10] p. 7). Explicitly, DORA recommends that funding agencies and institutions should "consider a broad range of impact measures including qualitative indicators of research impact, such as influence on policy and practice" [65]. As societal benefit requires scientific quality as a base for evidence, but also goes beyond it, needing a high degree of applicability and positive application impacts, these are in fact supplements, not opponents. Therefore, enriching scientific performance with societal impact indicators can result in decisions and incentives in the scientific system that are more reliable and more beneficial to society.

Table 1. Indicators that are frequently used for scientific impact evaluation.

Citation count	In general, the number of citations received by a paper is counted. They can be summed up for all publications of an institution or person, or calculated relative to the average citation rate of the journal or respective field over a certain period (usually three years) [70,71]. Citation data are counted (except examples provided in Section 3.1) for and in journals indexed in the Journal Citation Report by Thompson Reuters or in the SCImago database by Elsevier [69]. Citations are generally assessed in papers, letters, corrections and retractions, editorials, and other items of a journal.

h-index	The h-index combines publication output and impact in one index: h = N publications with at least N citations, (where the time span for calculation can be selected). For the h-index, there are some derivatives that include the number of years of scientific activity, excluding self-citations, and weighting co-authoring and highly cited papers [5].
IF and journal-based metrics built on Thompson Reuters database	The Journal Impact Factor (IF) is calculated by dividing the number of current-year citations to the source items published in that journal during the previous two years by the number of citable items. It can also be calculated for five years and exclude journal self-citations [6]. Example: $IF = \frac{Number\ of\ citations \in 2014\ for\ articles\ of\ journal\ A\ published \in 2012 \wedge 2013}{Number\ of\ citeable\ items \in journal\ A\ published \in 2012 \wedge 2013}$ Another metric is Article Influence, in which the citation time frame is five years, journal self-citation is excluded and the citation value (impact factor of the citing journal) is weighted [69].
Eigenfactor	Eigenfactor also uses Thompson Reuters citation data to calculate journal importance with several weightings. It includes network analysis of citations, weighting citation value and field-specific citation patterns [72].
Journal-based metrics built on Elsevier's Scopus database	All indicators are calculated within a citation time frame of three years. The Source Impact Normalized per Paper (SNIP) is calculated in a similar way to the IF. The Scimago Journal Ranks (SRJ and SJR2) limit journal self-citation and weight citation value. SJR2 includes a closeness weight of the citing journals, meaning that citation in a related field is calculated as being of higher value, because citing peers are assumed to have a higher capacity to evaluate it [69].

3. Concrete Strategies to Support Evaluation beyond Scientific Impact

While Section 2 introduced relevant movements and pointed to shared interest as a base for further cooperation, this section will describe concrete measures for facilitating evaluation beyond scientific impact. As seen in the previous section, evaluation beyond scientific impact may introduce criteria for various aspects of knowledge production (Figure 1).

3.1. Open Access and Technical Development Provide some Solutions to Improve Current Evaluation Practices

Although the quality of peer reviews and self-reinforcing dynamics affect open and subscribed publication models, several possibilities for increasing efficacy in dissemination and quality assurance via digital communication technologies are discussed in the context of open access. For peer review processes, increased transparency is the core issue [73]. Open review, meaning that reviews are published with the preprint or the final paper, is possible with different degrees of openness and interactivity [42], though some aspects are discussed controversially. Disclosure of authors' identities entails the risk of increasing bias as in single-blind reviews [74], while disclosure of reviewers' identities is shown to preserve a high quality of reviews [75], though suspicions do remain that this may inhibit criticism and make it more difficult to find reviewers [47,76]. However, the publishing of reviews, enabling interactions between reviewers and authors and increasing the basis of feedback and valuation via comment, forum and rating functions for readers, is commonly expected to increase transparency, fairness and scientific progress [44,67,73]. Some applied examples are the Journal BMJ [42], Peerevaluation.org [77] or arXiv.org. At arXiv.org the publication of manuscripts accelerates dissemination and reduces the filedrawer effect; in case of revisions and publication in a journal, the updated versions are added [44,78]. Another possibility is to guarantee publication (except in cases of fraud), but not until there has been a double-blind review of the manuscript focusing solely on scientific quality [67]. Reviews and revised versions may be used for suggested new publication concepts with a modified role for editors [67] or even without journals [56], but also for the current system, where they can serve to assist in publication decisions made on the editorial boards of individual journals.

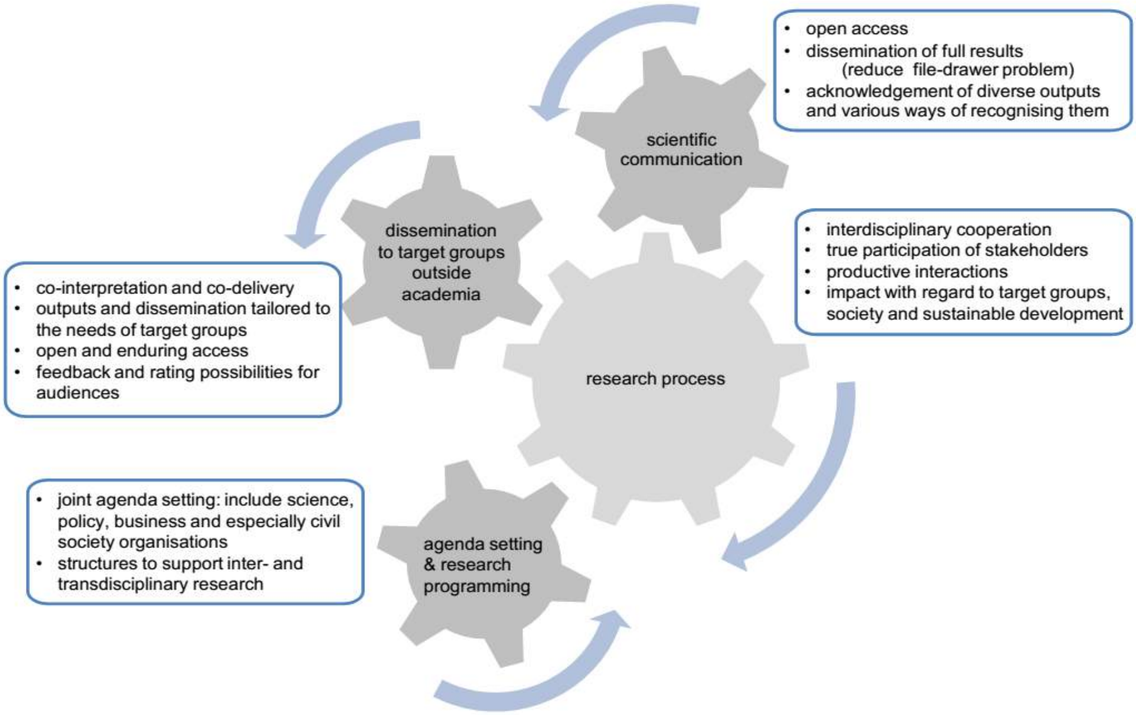

Figure 1. Possible criteria for evaluation beyond scientific impact regarding various aspects of knowledge production.

Additionally, review approaches should allow the engagement of peers in research evaluation to be rewarded [67] and the quality of peer review activities to be assessed [77].

Open access to data is supported by several actors [79]. It enables verification, re-analysis and meta-analysis and reduces publication bias, thus safeguarding scientific quality and societal benefit [80]. Accordingly, it is suggested that the full dissemination of research and re-use of original datasets by external researchers should be implemented as additional performance metrics [80].

Diverse citation and usage data can be accessed via the Internet for all objects with a digital object identifier (DOI) or other standard identifiers [81]. Thus, citation counting beyond Thomson Reuters or Scopus databases is possible, e.g. via Google Scholar, CrossRef, or within Open Access Repositories [42]. Furthermore, responses to papers can be filtered with various Web 2.0 tools (e.g. Altmetrics.com [82]), which are often combined with platforms to share and discuss diverse scholarly outputs (e.g. Impactstory.org). Such data are also tested for the evaluation of the societal use of research [83]. Consequently, the call for open metrics includes open access to citation data in existing citation databases and all upcoming metrics that record citations and utilisation data [42].

In conclusion, there are many opportunities for increasing transparency and interaction in review processes, facilitating and acknowledging cooperative behaviour and including a higher diversity of scientific products and ways of recognising them in research evaluation processes. This may help to improve current evaluation systems. Until now, these approaches have mostly been restricted to scientific outputs, but they may likewise be used to disseminate outputs and implement feedback functions tailored to diverse user communities outside academia. For example, enhanced data assessment and communication tools are also found to support the concept of citizen science [84], where citizens carry out research or collect data as volunteers [85].

3.2. Science Politics towards Changed Incentive Systems

Science politics, funding procedures and applied evaluation criteria are important drivers of research focuses, and therefore determine what knowledge will exist to face future societal challenges. As seen already in Section 2.1.1, research funders are increasingly interested in supporting transdisciplinarity and related research approaches and they also support open access. For example, the most recent European research programme, "Horizon 2020" [86,87] highlights the need for multi-stakeholder approaches and the support of "systems of innovation" via European Innovation Partnerships [88]. It also makes open access to scientific peer-reviewed publications obligatory and tests open data approaches in certain core areas [89].

Adequate measures to support "Research and Development for Sustainable Development" via research programming are provided by VisionRD4SD, a collaboration process between European research funders. It identifies measures for the whole programme cycle, presents them in a prototype resource tool and recommends a European or international platform to support networking, dialogue and learning processes on this subject [90]. Likewise, a guide for policy-relevant sustainability research is directed at funding agencies, researchers and policymakers [91].

Institutions and funders who are interested in applying concepts of research evaluation beyond scientific impact (see criteria in Figure 1) can build on existing approaches. Evaluation concepts are developed for interdisciplinary and transdisciplinary research and for societal impact assessment used by research agencies, research institutions or for policy analysis (reviews may be found in [92–94]). Examples of regularly applied evaluation procedures including societal outputs are the Standard Evaluation Protocol for Universities in the Netherlands ([95] p. 5) (see below) and the Research Excellence Framework in the UK [96].

In the section that follows, we will suggest measures to ensure, that evaluation beyond scientific impact is effectively. First, steps should be taken to ensure that societal impact criteria are applied by reviewers, although these indicators may be felt to be outside of reviewers' realm of disciplinary expertise [97] or of lesser importance to them ([48] pp. 32–35). Interestingly, in one study ([48] pp. 32–35), societal impact indicators such as relevance for global societal challenges or citizens' concerns, public outreach, contribution to science education and usefulness for political decision-makers were ranked higher in agricultural research than in other fields, and they were ranked higher by students than by professors. Such results suggest that not only peers, but also knowledge users ([15] p. 548), [97] should be involved in evaluation. To increase the ability of scientists and others to judge societal impacts, data on the societal impact of research and their proxies (hereinafter subsumed as societal impact data) could provide a transparent and reliable basis for such judgement.

Furthermore, the experiences documented in Section 2.3 suggest avoiding narrow indicator sets and their use for competitive benchmarking or metrics-based resource allocation. Instead, broad indicator sets and fair and interactive processes which support organisational development [30] or learning processes [98] need to be applied. One example is the above-mentioned Standard Evaluation Protocol in the Netherlands, where "the research unit's own strategy and targets are guiding principles when designing the assessment process" ([95] p. 5).

However, when funders or institutions begin to apply evaluation beyond scientific impact, they should focus on increasing the acknowledgement of societal impact within the scientific reputation system in general. This is necessary to ensure that their incentives are effective and do not merely increase researchers' trade-offs between contributing to scientific and societal impact. Adequate measures adopted by funders could be additional funding or distinctions of particularly successful projects as "take-home values" for researchers.

Moreover, research institutions and research funders should become active in improving data availability. Only with reliable and easy-to-use data beyond scientific impact can balanced research evaluation be conducted frequently enough to provide the desired incentives within the scientific system.

Until now, research funding agencies have often demanded detailed reporting on the dissemination and exploitation of results. In German federal research, exploitation plans are required as text documents for proposals and reports [99]. Proposals for Horizon 2020 include plans for dissemination and exploitation ([100] p. 17), but the need to improve digital data assessment for evaluation purposes is also emphasised ([101] p. 47). However, texts with societal impact descriptions cannot be analysed with ease, and the facilities they offer in terms of filtering and cross-referencing are also poor, so they have little value for research evaluation or for the sharing of the information within the scientific system. Likewise, the use of digital systems is only valuable if they allow multiple reuse of data.

4. Improve Data Availability for Evaluation beyond Scientific Impact

To improve the availability of data for societal impact evaluation, we recommend uniting the interests of institutions and funders in such data and giving them more leverage by making use of the current state of interoperability in e-infrastructures, especially research information systems and publication metadata.

Interoperability, in general, enables the exchange, aggregation and use of information for electronic data processing between different systems. Its functionality depends on system structures and exchange formats (entities and attributes), federated identifiers (for persons, institutions, projects, publications and other objects) and shared (or even mapped) vocabularies and semantics [102]. Thus, interoperability includes, besides technical aspects, cooperation to reach agreement.

The interests of institutions and funders in societal impact data may be served by the possibilities of Current Research Information Systems (CRIS). These are used increasingly by research institutions as a tool to manage, provide access to and disseminate research information. Standardisation of CRIS aims to enable automated data input, e.g. via connection to publication databases, and ensure it is only necessary for data to be input manually once but can be used many times (e.g. for automated CVs, bibliographies, project participation lists, institutional web page generation, etc.) [103]. Standardisation is promoted by euroCRIS via the CERIF standard (Common European Research Information Format) [103] and CASRAI (Consortia Advancing Standards in Research Administration Information) via the development of data profiles and semantics [104], and is embedded in diverse collaborations with initiatives related to interoperability and open access [105].

The CERIF standard is explicitly convenient for enabling interoperability between research institutions and funders, because research outputs can be assigned to projects, persons and organisational units. In the UK, interface management between the research councils and higher education institutions is already established, and societal outputs and impacts are part of the data assessment [106,107]. The aim is to develop these systems further by applying the current CERIF standard in order to increase interoperability with institutional CRIS. It has been shown that output and impact types used in the UK can be implemented in the current CERIF standard [108].

Accordingly, research funders should engage in the development and use of CERIF-CRIS that (a) include data related to interactions with, and benefit for, practice and society, and (b) partly replace written documents in the process of application and reporting. They should (c) act as data providers by making data available, e.g. via interface management with research institutions, file transfer for individual scientists and re-use of data for subsequent proposals and reports. Thus, funders can contribute to the provision of comprehensive societal impact data without increasing the documentation effort for scientists. In doing so, they also help to corroborate and ensure the quality of such data.

To facilitate these aims, several measures can be applied. Regarding (a), it is necessary to develop shared vocabularies for societal impact related to outputs and outcomes. Compiling societal impact data (based on existing evaluation concepts and documentation tools) and structuring them in coherence with CRIS standards (e.g. CERIF, CASRAI) is one task in the project 'Practice Impact II' [109]. Furthermore, funders, researchers and their associations that are interested in societal impact could formulate a mandate to CASRAI and euroCRIS to further develop shared vocabularies for types and attributes of output, outcome and impact towards society and stay involved in this process. Such a commitment would also facilitate the integration of societal impact data in their CRIS by different providers, and this would create a base for data transfer between funders and institutions with regard to (c).

Regarding (b), it is necessary to build a closer connection between those data and the documentation requirements in proposals and reports. The above-mentioned research project, "Practice Impact II", is developing this with a focus on German federal research in the realm of organic and sustainable agriculture. The project integrates the user perspectives of scientists, research funding agencies and evaluators in its development and testing [109,110], in order to achieve the required usability and reduction in effort, with regard to (c), above.

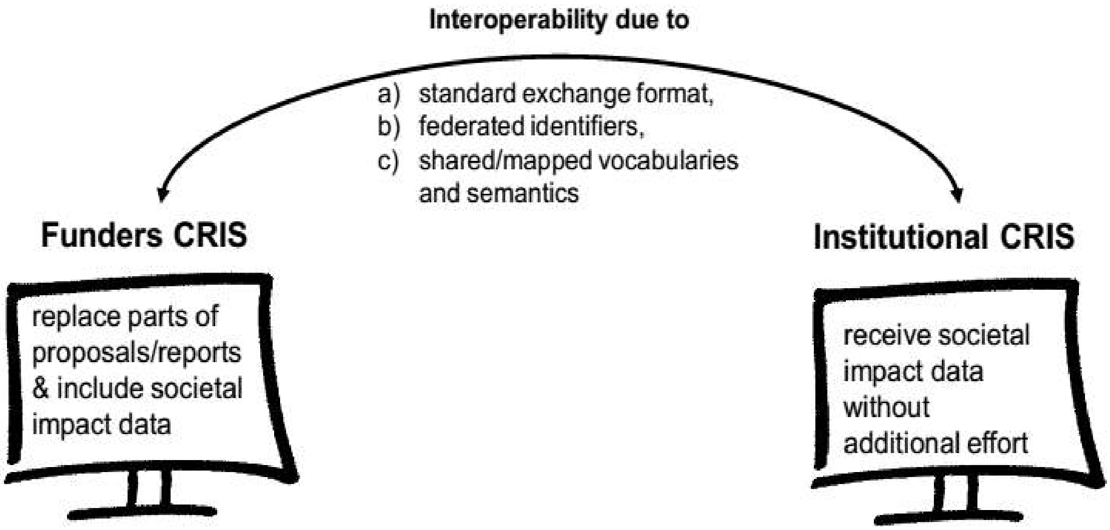

Figure 2. Possibilities for using and developing Current Research Information Systems (CRIS) for interoperable data transfer between funders and institutions to assess and use societal impact data without additional effort.

Regarding (c), there are further possibilities besides the interoperability between funders and institutions. CRIS, with their function as repositories, are also tools for presenting research results to the public. Research funders could use them to support open access dissemination tailored to specific target groups within and beyond academia. Furthermore, closer connections between societal impact data and scientific publications might be established.

For bibliographic metadata of publications, such as authors, title, year, interoperability has already been developed further than it has for other research outputs. Common vocabularies for publication types, advancement of standards and mapping between different standards of metadata are being pushed ahead by libraries [111] and open access repositories [112,113] in order to aggregate machine-readable metadata from multiple systems to create new platforms or services [114]. Furthermore, linked data standards (like the Resource Description Framework, RDF) help to apply the full benefit of web applications for bibliographic metadata. The RDF, for example, allows classical standards-based metadata to be complemented with socially constructed metadata, e.g. user tags, comments, reviews, links, ratings or recommendations [115]. Furthermore, in future, closer links between data and publications will evolve. For example, in 2013, the research data alliance (RDA) started to build social and technical bridges to enable open sharing and interoperability of research data and make them citable, also with an agricultural section [79]. The practice of linking scientific publications with their associated data with the aim of increasing reliability is a recent innovation [80].

Accordingly, the development of systems that link scientific publications via the project to research outputs for audiences outside academia, and to the interactions and impacts of this research as an indication of their societal relevance and applicability is a promising opportunity. Such an increase in the visibility of knowledge tailored towards specific target groups can increase the real-world impact of research and record that impact via feedback functions.

5. Conclusion: Argumentation for Evaluation beyond Scientific Impact

Joint interests of the actors introduced in this paper can be built on the basis that science needs to generate greater societal benefit, and that high scientific quality is a precondition for that. Higher societal benefit is then associated both with open access and with tailored knowledge production and dissemination for audiences beyond academia. Furthermore, evaluation beyond scientific impact can be given some leverage by the full use of digital communication technologies and progress in interoperability. The possible measures suggested in this paper assume close cooperation among various actors (Figure3).

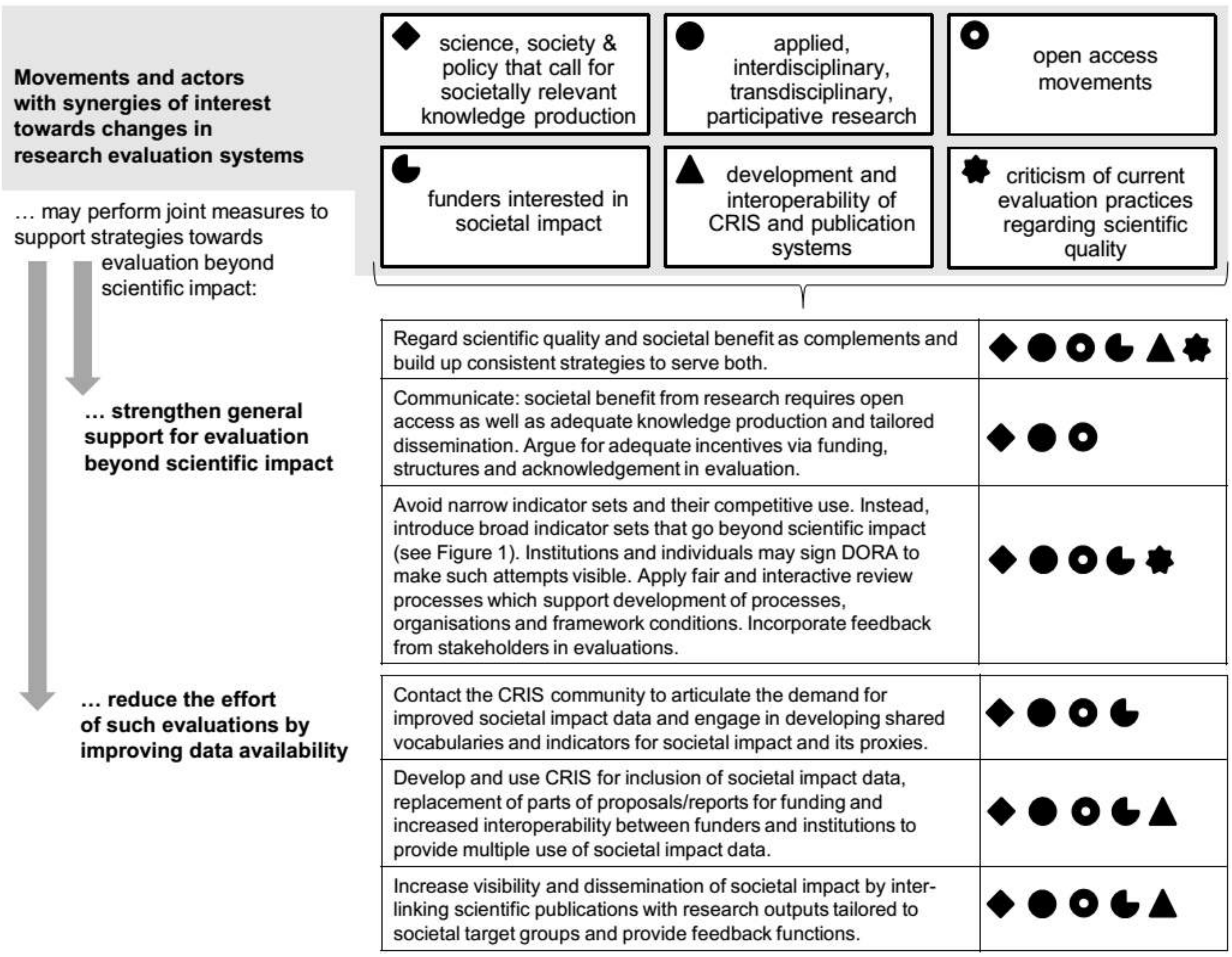

Figure 3. Supporting movements and joint measures to facilitate evaluation beyond scientific impact.

Research funders in particular may support changes in knowledge production because they perform programme design, define funding criteria, and may provide easy-to-use data related to societal impact, for example if research institutions aim to be evaluated with a balance of scientific and societal impact.

As argued in this paper, the measures summarised above are also valid for organic agricultural research and related fields. In the section that follows, some measures and opportunities will be specified.

- Being small, the (organic) agricultural research community may focus on commonalities with other movements. For example, it may benefit from critical voices in scientific impact evaluation, statements of sustainability research and open access movements, which provide the base for introducing criteria beyond scientific impact in research evaluation.
- The (organic) agricultural research community has several synergies with the sustainability (research) community. One is the potential for mutual learning to further develop transdisciplinary research concepts and their proficient application. Another is to organise more powerful support for those research approaches via adequate funding and acknowledgement of societal impact indicators in research evaluation.
- Building up a closer connection between open access and knowledge production tailored to societal needs as two complementary aspects of the societal benefit of science corresponds well with the self-conception of (organic) agricultural research.

If agricultural research funders intend to improve the capabilities for agricultural research to contribute to real-world impact and sustainable development, they should engage in improving access to societal impact data for supporting evaluation beyond scientific impact within the scientific system. Use-cases for CRIS that integrate societal impact data, reveal funders' needs and reduce scientists' efforts towards proposals and reports may be developed successful in agricultural research. This is because funders and the research community in agricultural research are well connected to jointly develop a use-case with effective feedback loops. Furthermore, they may share their experiences in assessment of societal impact data with other research fields and funders. This may lead to further involvement in processes that support the standardisation and interoperability of those societal impact data.

To conclude, the range of interest groups and viable measures is such that there is no need to accept the deficits in current research evaluation systems, it is possible to change them!

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Research Article

Applications of Open Source 3-D Printing on Small Farms

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Abstract: There is growing evidence that low-cost open-source 3-D printers can reduce costs by enabling distributed manufacturing of substitutes for both specialty equipment and conventional mass-manufactured products. The rate of 3-D printable designs under open licenses is growing exponentially and there are already hundreds of designs applicable to small-scale organic farming. It has also been hypothesized that this technology could assist sustainable development in rural communities that rely on small-scale organic agriculture. To gauge the present utility of open-source 3-D printers in this organic farm context both in the developed and developing world, this paper reviews the current open-source designs available and evaluates the ability of low-cost 3-D printers to be effective at reducing the economic costs of farming. This study limits the evaluation of open-source 3-D printers to only the most-developed fused filament fabrication of the bioplastic polylactic acid (PLA). PLA is a strong biodegradable and recyclable thermoplastic appropriate for a range of representative products, which are grouped into five categories of prints: hand tools, food processing, animal management, water management and hydroponics. The advantages and shortcomings of applying 3-D printing to each technology are evaluated. The results show a generalizable technical viability and economic benefit to adopting open-source 3-D printing for any of the technologies, although the individual economic impact is highly dependent on needs and frequency of use on a specific farm. Capital costs of a 3-D printer may be saved from on-farm printing of a single advanced analytical instrument in a day or replacing hundreds of inexpensive products over a year. In order for the full potential of open-source 3-D printing to be realized to assist organic farm economic resiliency and self-sufficiency, future work is outlined in five core areas: designs of 3-D printable objects, 3-D printing materials, 3-D printers, software and 3-D printable repositories.

Keywords: 3-D printing; agricultural tools; distributed manufacturing; farm equipment; intensive agriculture; small farms

1. Introduction

World wide, the area of organic farmland continues to increase significantly [1,2]. Approximately a third of the world's organically managed land (i.e. 11 million hectares) is located in developing countries and nearly half of the world's organic producers are in Africa [2]. In the developing world in particular, these farms are owned by relatively resource-poor landholders. However, such small farms may contribute significantly to agricultural production, food security, rural poverty reduction and biodiversity conservation, despite the historic challenges small farmers face in terms of access to both productive resources and markets [3]. In addition, small farms in the developing world must overcome new challenges including adapting to climate change, market volatility and risks and vulnerabilities associated with integration into high-value chains [3–5]. There is some disagreement in the literature as to whether investments in infrastructure and technical efficiency alone are sufficient to address the negative impacts of climate change for developing-world farmers [6,7]. Although, it is clear that these challenges can at least in part be overcome by increasing the profit of organic farming in the developing world, which in turn is influenced by increasing revenue (e.g. by increasing yields, selling in more lucrative markets, etc.) or by reducing costs. Many organic farmers in both the developed and developing world save money and produce high-quality crops with few or no off-farm inputs, but most producers rely on at least some purchased inputs [8]. In addition, those farmers above the level of poverty subsistence also purchase their own equipment. As one of the costly inputs for organic agriculture is tools and equipment, this study investigates reducing farm-related tool costs for organic farms using open-source 3-D printing. In this way, distributed on-site manufacturing of tools and equipment can aid in organic farm self-sufficiency.

There is a growing body of evidence that low-cost open-source 3-D printers [9,10] can reduce costs not only for high-end products like scientific equipment [11,12], but also for conventional mass-manufactured consumer goods [13–16]. There has been an explosion of open-source scientific equipment [12,17–22] and the number of free consumer designs has been rising exponentially [14]. There is also a body of work proposing that 3-D printers would also be useful for sustainable development [23–25]. While the application of 3-D printing in developing countries is still at an early stage, the technology application promises vast solutions to existing problems [23,24]. For example, most small farmers in the developing world use labor-intensive agricultural hand tools; Ishengoma and Mtaho hypothesize that superior tools can be developed with 3-D printing improving the efficiency of agriculture in the developing world [25]. At the same time it appears likely that the cost-saving nature of distributed manufacturing of 3-D printing could also benefit developed-world small-scale organic farms.

To gauge the current viability of the utility of open-source 3-D printers for organic farms both in the developed and developing world, this paper reviews the current open-source designs available and evaluates the ability of a low-cost 3-D printer capable only of fused filament fabrication (FFF) plastic manufacturing to reduce the cost of small-scale farming. A range of representative products are grouped into five categories of prints for review: 1) hand tools, 2) food processing, 3) animal management, 4) water management and 5) hydroponics. The advantages and shortcomings of each technology are evaluated. Conclusions are drawn on the economic potential of open-source 3-D printing in the organic farming context and future work is outlined to reach this potential.

2. Methods

2.1. Equipment—MOST Delta RepRap

Following lessons developed in free and open source software [26–30], the RepRap project has undergone a rapid technical evolution and offers the lowest cost 3-D printing equipment, which is also capable of printing its own replacement parts [9,10,14,31,32]. The early RepRaps used a Cartesian design, however, several RepRap 3-D printers now use delta robot designs similar to those used for pick and place in the electronics industry [33]. Delta RepRap 3-D printers have a stationary print bed and an extruder that moves in all 3 axes. The 3-D printer works by taking plastic filament into the extruder, melting it and depositing a 2-D pattern on the substrate. The extruder is then moved up a fraction of a mm (normally 0.1–0.35 mm) and the next layer of the 3-D printed object is deposited. The process repeats until the entire object has been fabricated in solid plastic. Delta RepRap 3-D printers use standard AC electricity to run and while printing consume $<$50 W. In order to operate effectively this power should not be interrupted, the results of which will be discussed below.

Although delta 3-D printers are operationally less intuitive, they require less time and are easier to assemble, require fewer parts and have lower capital costs. The MOST (Michigan Tech Open Sustainability Lab) Delta RepRap has three linear actuators arranged vertically around a circle 1. The MOST Delta RepRap costs under $450 in parts and can be built in approximately eight hours once the bill of materials (BOM) has been collected by inexperienced first-time 3-D printers [34,35] (the ability of new users to build working machines has been demonstrated over 100 times in a number of contexts from college classes to seminars and hack-a-thons). This type of 3-D printer was chosen for this study because of the value—it has low capital costs for the quality of the prints and the build volume (250 mm in radius and 270 mm high) provided. In addition, farmers, who are generally handy at fixing equipment, would best be served by a 3-D printer they could maintain themselves. Having access to a machine that they can take apart, fix, upgrade and try their own modifications on provides far more value at a significantly lower cost than a conventional tooling arrangement with warranties that simply may not be available in all parts of the world. In addition, such RepRap technology can contribute to farm self-sufficiency. All of the MOST Delta RepRap design files, schematics, build instructions and bill of materials are available on Appropedia for free [34]. The results of this study are not limited to this particular RepRap, however, all examples can be printed with it—and most other (full size) RepRap variants.

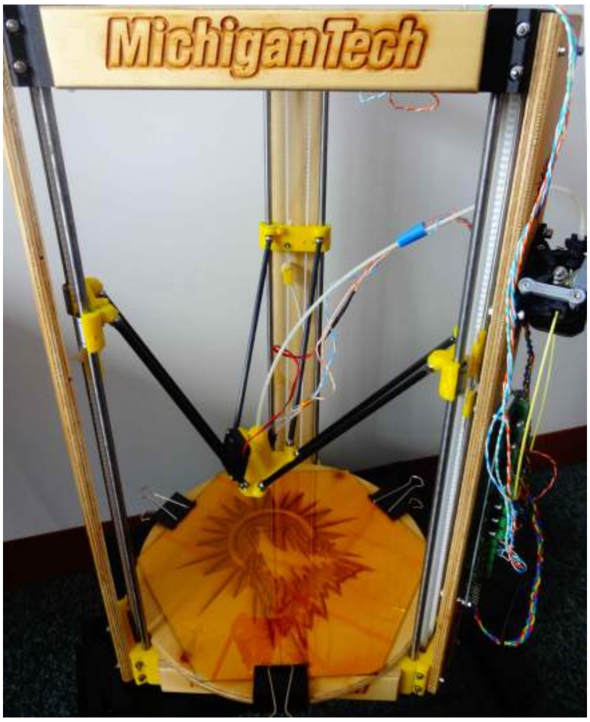

Figure 1. The MOST Delta RepRap 3-D printer. The yellow and black polymer components of the 3-D printer have been printed on the same type of 3-D printer. The glass hexagon at the base is print substrate.

2.2. Free and Open-Source Software Tool Chain

All of the software necessary to design and operate the 3-D printer is free and open source software that can be used for free (at no cost). For farmers wishing to minimize computing costs as well, older low-cost or 'junked' computers can be recycled into useful machines by installing a GNU/Linux [36] based operating system, such as Debian [37]. In addition, open-source computers such as the $35 Raspberry Pi [38] can be attached to recycled peripherals to operate the 3-D printer.

3-D digital designs can be created by farmers themselves or customized from existing designs using OpenSCAD [39], which is a free and open-source script-based solid modeling program. OpenSCAD using parametric variables that automatically manipulate the entire part to enable simple modifications without the need for a deep knowledge in 3-D modeling. Farmers that are comfortable with basic geometry can create complex designs by manipulating primitive shapes (e.g. spheres, cubes, cylinders) in OpenSCAD, which then generates STL (STereoLithography) files of the finished parts, which are in turn sliced with the open-source Cura [40] before being printed (slicing is the software process of dividing a 3-D model into printable 2-D layers and it plots the toolpaths to fill them in). Parts that need structural strength are printed solid with 100% infill, while non-critical components can be printed with lower infill percentages, saving time, energy and plastic costs. Conventional RepRap firmware [41] or the new open-source Franklin printer firmware [42] was used on the printer itself and controlled with Printrun (open-source printer controller) [43].

2.3. Materials—PLA

RepRaps typically print in polylactic acid (PLA) or acrylonitrile butadiene styrene (ABS) for a wide range of colors. In this study, PLA will be evaluated as it is a stronger plastic than ABS; RepRap printed parts have an average tensile strength of 28.5 MPa for ABS and 56.6 MPa for PLA [44]. PLA is a bio-based plastic, made up of a repeating chain of lactic acid. It is recyclable using conventional methods. In addition, PLA can be composted like other organic matter [45]. When composted, the moisture and heat in the compost pile break the PLA polymer chains apart, creating smaller polymer fragments, and finally, lactic acid. However, abiotic hydrolysis has been shown to be a rate limiting step in the biodegradation process of PLA and organisms were not able to accelerate depolymerization significantly by the action of their enzymes [46]. Both the smaller polymer fragments and lactic acid act as nutrients for microorganisms in the compost. As lactic acid is widely found in nature, a large number of organisms metabolize it into carbon dioxide, water and humus, an important component of soil fertility [47–50].

2.4. Categorization of Printable Objects

Utilizing the Appropedia wiki (appropedia.org)—is the largest collaborative site for solutions in sustainability, appropriate technology and poverty reduction—that curates many 3-D printing designs and Yeggi—a printable 3-D model search engine for tens of thousands of designs [51]—a range of 3-D printable objects that may be useful for organic farmers was identified and reviewed. For evaluation in this study, four products or product components were chosen in each of five categories: 1) hand tools, 2) food processing, 3) animal management, 4) water management and 5) hydroponics. The selected prints are summarized with their sources in Table 1. These twenty objects were chosen based upon i) having free and open source designs already available, ii) the ability to be printed on a low-cost MOST Delta RepRap using PLA while preserving their functionality, iii) having been previously demonstrated to be useful in farming and gardening (e.g. not models or toys) and iv) representing a variety of different types of functions for demonstration purposes. As such this is not a complete review of every 3-D printable object that may be useful for organic farmers, nor every object organic farmers may find value in printing, as there are literally thousands of these and the number of free designs is growing exponentially [14]. Rather, this study provides a survey of 3-D printing applications that represent classes of objects already designed and a realistic approach of how small-scale farmers could use available 3-D printers today. Thus, the objects included in Table 1 may also be useful to the broader general agriculture community as well.

Table 1. Selected and categorized 3-D printable objects useful for organic farming.

Hand Tools	Food Processing	Animal Management	Water Management	Hydroponics
Triclaw apple picker [52]	Water tester [53]	Chicken feed holder[54]	Garden hose splitter [55]	3DPonics [56]
Custom shovel handle [57]	Sausage funnels for meat grinders [58]	Ant trap [59]	Gasket [60]	Hydroponic halo ring [61]
Hand shovel [62]	Cassava press [63]	Field dressing tool [64]	Contoured spigot for 5 gallon bucket [65]	Hydroponic plant pot [66]
Pulleys [67]	Corn sheller [68]	Gutting tool [69]	Irrigation stake [70]	Peristaltic pump [71]

3. Results and Discussion

3.1. Hand Tools

Many tools that may be useful for organic farmers are larger than the build volume of the MOST delta RepRap (a cylinder of 250 mm in radius and 270 mm high), yet can be created by it by printing individual components of the tool and then assembling them with non-printed, readily available components. An example of this is the tri-claw apple picker (Figure 2). The tool helps reduce labor in apple picking by eliminating the need to use a stepladder for high apples. The four-bar-linkage claw (Figure 2A) is closed by a sliding collar attached, by another four-bar, to each of the three fingers (Figure 2B). It is operated by pulling the cord visible in the lower right, which is knotted onto a sliding collar further down the pole. The collar is sprung to return the fingers to the open position. The apple picker print is threaded to fit a standard broom handle, which can be used when needed. For a longer pole, farmers can duct tape the broom handle to any pole that is physically manageable. The apple picker has several deficiencies however, that keep it from being as useful for the community as it potentially could be. It is licensed under the Creative Commons Attribution-Non-Commercial license. That means organic farmers can print and use it for their own use, but not sell it. Strictly speaking the CC-BY-NC license is not a true open source license [72]. In addition, only the STL files are shared, meaning farmers can print this version, but not easily make alterations (e.g. adjust fingers for optimal picking of other types of fruit). Finally, even if the source files had been shared, they were from an expensive professional closed-source CAD package (~$4,000 to purchase and over $1,000 per year for upgrades and support) that farmers are unlikely to have the time to develop the skill for, nor justify the budget for purchasing such a CAD software package.

Fortunately, there are several options for quality CAD software with shallow learning curves available as completely free and open-source software, such as OpenSCAD. OpenSCAD allows farmers to customize a design for their exact needs with minimal effort because of the script based parametric nature of OpenSCAD. OpenSCAD will be the primary solid modeling tool of choice for the majority of the designs presented below. For example, a customizable shovel handle (Figure 3) can be used as a replacement part for a broken shovel handle. In addition, it can be used on an existing tool with no handle to apply greater leverage, comfort and wrist relief, which prevents long-term injuries from repetitive motions (e.g. rotator cuff tears from digging). As farming tools have different diameters and farmers want different sized grips, depending on their hand sizes, all of the variables in the design are parametric. For example, at the start of the design, the code tells farmers how to change the diameter of the grip in clear documentation, which is currently set at 30 mm:

$$G\_Dia = 30; //diameter\ of\ Grip$$

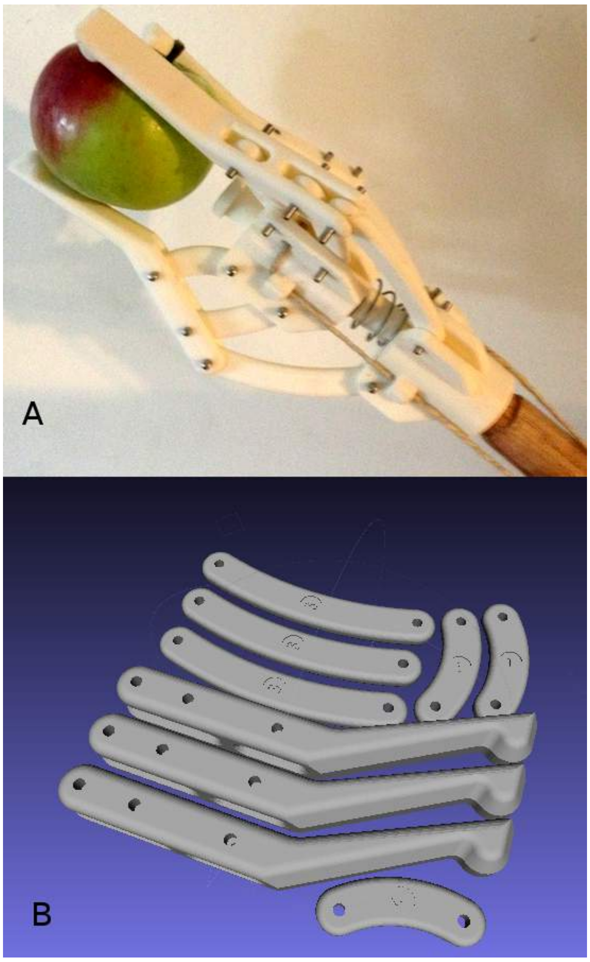

Figure 2. A) 3-D printed tri-claw apple picker grasping apple. B) the components of the claws.

Simply by changing this one number the design can be customized for an individual farmer's grip preference. All of the mathematics to adjust the design have been pre-programmed to occur automatically. In addition, the number and placement of screw holes and also thickness and length of the section that overlap with the shovel can also be easily altered to user preference to obtain the required strength for a given application.

An un-modified RepRap normally only prints in one color at a time. However, it is possible to load in multiple colors of filament to improve aesthetics, enable artistic expression or use a company's logo colors during a print (Figure 3). Finally, the cost of the handle printed with commercial filament is less than a third of commercial plastic D-grip handles [57]. Being able to make custom products for a fraction of the cost of commercial products is a well established benefit of distributed manufacturing with 3-D printing [14]. It should be pointed out that this calculation does not involve any labor cost as, after the file is sent to the printer and even if the print itself takes hours, a well-tuned 3-D printer does not require any human observation (e.g. the farmer can go about other tasks as usual and only go back to the printer to collect his finished product). For farms employing workers, time spent searching for free designs, customizing them, tweaking print settings and maintaining the 3-D printer would need to be included in any economic analysis.

Figure 3. A 3-D printable customizable shovel handle in which the color of the filament had been switched during the print for cosmetic reasons.

Moving beyond only the handle, it is also possible to print an entire shovel (Figure 4). This shovel design enables printing handle components that fit together to extend the reach to the length a farmer requires. The mechanical strength of PLA [44] makes its use possible in tools that can bear a significant load if the parts are printed at 100% or with significant exterior thicknesses. This shovel could be used for light work—such as for adding to a compost pile, however, this shovel would not be appropriate for digging in hard soil. For such applications a metal tool is needed. Fortunately, an open-source 3-D printer capable of printing in steel and aluminum has been developed, which is essentially an upside-down MOST delta RepRap where the extruder is replaced with a gas metal arc welder [73]. Although there has been significant progress in turning the device into a tool for distributed manufacturing [74], it is still at an early stage of development and not ready for mass deployment.

Figure 4. 3-D printable shovel with handle components that fit together to extend the reach to the necessary length.

Finally, another example of a tool that could be functional in plastic, but better suited to metal is the heavy-duty rope pulley (Figure 5). It can be used, for example, to raise water from a well or assist hay bale storage in a barn. As this is licensed under the default Appropedia license: CC-BY-SA (creative commons license that demands attribution and that those that make derivatives share their work under the same license) it is a true open technology. Like the shovel handle, this pulley can be customized to any desired size by changing variables in the OpenSCAD script. It can also be paired with duplicates of itself to further increase mechanical advantage necessary for a given application.

3.2. Food Processing

Some of the 3-D printable equipment developed by the scientific community [11,12] can also be useful on an organic farm, such as the open-source mobile water quality testing platform (Figure 6). This device, which uses printed components and off-the-shelf electronics, can perform colorimetry for biochemical oxygen demand/chemical oxygen demand and nephelometry to measure turbidity using ISO method 7027 [75]. Perhaps more interesting for farms on tight budgets, this approach has resulted in equipment that is as accurate, but costs between 7.5 and 15 times less than current commercially available tools [75]. This platform is currently under further development to add nitrate and phosphate quantification testing by coupling it with low-cost enzymes available from NECi that replace cadmium-based test kits.

Figure 5. 3-D printable heavy-duty rope pulley.

Figure 6. 3-D printable open-source mobile water quality testing platform capable of both colorimetry for biochemical oxygen demand/chemical oxygen demand and nephelometry.

In addition to expensive high-tech equipment, the use of an open-source 3-D printer makes fabricating simple tool additions, like sausage funnels for meat grinders easier (Figure 7). Other such funnels, like those used for canning can also be easily made with a 3-D printer although, depending on the application the type of plastic should be considered carefully. One of the primary reasons PLA is the dominant low-cost 3-D printer plastic is its relatively low melting point (150°-160° C) and glass transition temperature (60°–65° C). Thus, although virgin PLA can be food-grade, PLA softens under some conditions of normal use for applications like canning. There are a variety of other 3-D printer filaments already available commercially including: ABS, nylon (e.g .Taulman 618), high-density polyethylene (HDPE) [76], Laywood [77], Laybrick [78], high impact polystyrene [79], PEEK [80], polyphenylsulfone [80], polyetherimide [80], polyoxymethylene [81], Polykey PLA HS [82], PLA HS NX [82], Polykey PPGF [82], PPMF [82], Polykey PA6GFV0 [82], polycarbonate and polyvinyl alcohol. For some of the high temperature filaments a different hot end on the RepRap is needed, but this does not increase the capital costs of the RepRap by more than a few tens of dollars. These alternative materials extend the range of useful 3-D printable farming applications.

However, PLA itself is quite versatile. Utilizing standard hardware and PLA 3-D prints, entire food presses can be manufactured. Consider a cassava press (Figure 8), which is a tool used in many parts of the developing world for increasing the longevity of food by pressing part, or all of the liquid out of the food. Although many cassava presses are large, this is an example of a household sized one. In addition, with minor design changes the press could be adapted for other uses or expanded to the printer diameter (up to 500 mm).

According to the World Bank there are still over 1.2 billion people (approximately 20% of the world's population) that do not have access to electricity, almost all of whom live in developing countries [83]. Because of this, much of the automated food processing that is taken for granted in developed countries is still carried out by hand in the global south. For example, shelling corn (maize) is a chore done by hand in much of the rural developing world. For some time there have been commercial corn shellers that can save people hours of labor. However, maize comes in different sizes so different shellers are needed in different regions—and the various DIY shellers are a major task to fabricate. Using the OpenSCAD design code, corn shellers (Figure 9) can be customized for an exact location and corn type and 3-D printed in a short time. Various designs are possible, again by changing variables in clearly documented OpenSCAD scripts. All seven of the variables are shown below:

$$h = 55; //height\ of\ corn\ sheller$$
$$rt = 35; //[50:130]//radius\ of\ top\ of\ corn\ sheller$$
$$rb = 0.85 * rt; //radius\ of\ bottom\ of\ corn\ sheller$$
$$d = 6; //number\ of\ digits$$
$$r = 1.5; //digit\ radius$$
$$l = 1; //extra\ length\ of\ digit$$
$$t = 3; //thickness\ of\ sheller$$

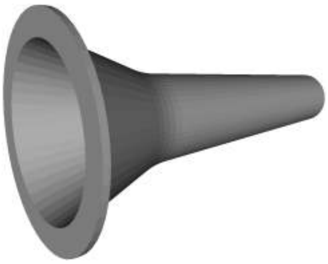

Figure 7. 3-D rendering of a 3-D printable sausage funnel.

Figure 8. A 3-D printable a cassava press, which uses standard threaded rods and nuts.

Figure 9. Corn being shelled with a 3-D printable corn sheller. Insets A and B demonstrate the ability to customize the OpenSCAD code to print corn shellers for different types of maize.

3.3. Animal Management

As the market for organic meat in the developed world has climbed in recent years there has been a significant increase in organic poultry farming in developing countries [84]. In addition to this, in the developing world, poultry farming is a popular project among small-scale organic farmers as the returns can be realized within a short period (approximately 1.5–2 months) [85]. Unfortunately, many of these projects fail due to disease outbreaks. Disease results in large numbers of poultry fatalities and poor production performance in both eggs and meat, which can cause financial losses to already poor farmers, and also increase human infection [86]. The majority of chicken diseases are transmitted through contaminated chicken waste. Appropriate chicken feed holders can help keep feed isolated from contaminated feces, minimizing outbreaks of disease. Thus, after corn is shelled using the print in section 3.2 then ground, it can be fed to chickens using 3-D printable chicken feed holders (Figure 10). This improves the economic viability of raising poultry by raising yield, but also reducing investment in treating sick birds.

Figure 10. 3-D printable chicken feed holder.

3-D printing can also be used to make tools to eliminate unwanted animal pests. For example, a customizable OpenSCAD script can generate an ant trap (Figure 11). The trap can be baited with a mixture of borax and sugar to eliminate ants from an area.

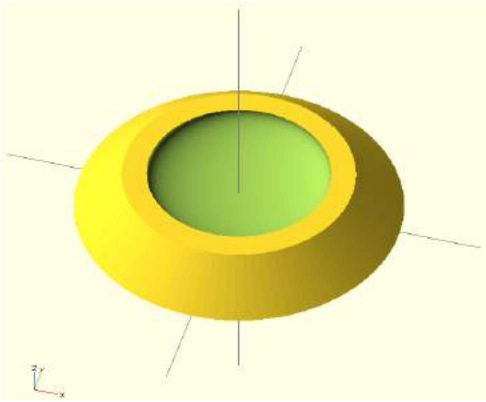

Figure 11. A customizable OpenSCAD rendering for an ant trap.

Finally, 3-D printed objects can be used for processing large animals. Animals raised on an organic farm, or harvested from the field on a small-scale, need to be field dressed and skinned in order to obtain high-quality, unspoiled meat. This process can be interrupted due to dull/blunt or improperly sized cutting blades. A dressing tool can be printed that mounts a replaceable and inexpensive utility blade on a 3-D printed handle with a guard (Figure 12). This tool enables the farmer to cut only what is needed in a safe manner as it allows cutting just beneath the skin without puncturing organs. The replaceable blade ensures ease of use and the lowest possible costs, while ensuring field dressing is faster and safer than with a traditional blade. Another example for this application is a tool used for gutting an animal (Figure 13). The tool is both customizable, so it can be sized appropriately for the animal being processed, and can be printed in its entirety. The tool is inserted into the animal's alimentary canal, twisted and pulled to remove a portion of the intestine, which can then be tied off and removed. This process eliminates the need for cutting around the area with a knife, making the field dressing process quicker, safer, and easier. Printing this tool cost far less than purchasing it commercially.

Figure 12. A dressing tool that mounts a replaceable utility blade on a 3-D printed handle with a guard.

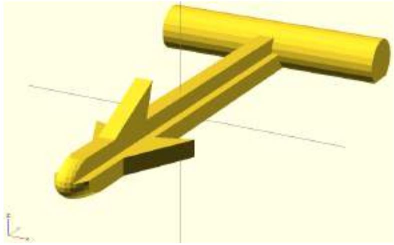

Figure 13. Tool for gutting an animal.

3.4. Water Management

A critical resource on many organic farms is water, and 3-D printing components can help assist water management on a small farm. For example, an adapter (Figure 14) is used to split water streams from a common garden hose nozzle. The splitter can be customized to any desired size, and can be paired with duplicates of itself to enable the construction of complex irrigation systems. The purely PLA 3-D printed version, however, is likely to leak unless heat treated, which may not be acceptable for many farms. As PLA melts at low temperatures a quasi-permanent bond can be created by heating the metal hose end and then screwing it to the bottom of the adapter. This will deform the PLA, which will then form a watertight bond directly to the nozzle. In order to ensure a water tight seal that can be undone, a gasket is needed, either purchased or printed (Figure 15). Customizable gaskets can be directly printed using constrained extruder drivers printing elastomers such as 'ninjaflex' or using caulkstruders. A caulkstruder is an end effector that mounts any type of caulk and pushes it out in a controlled fashion like a syringe. This is a heavy device and cannot be mounted easily on the end effector of a delta 3-D printer. However, a recent innovation with the delta printer design turns the printer upside-down such that the tool (caulkstruder) is fixed in place and the workpiece moves below it [87] (Figure 16). This convertible RepRap is capable of a long list of other functions including PCB milling, cutting, plotting, liquid handling, etc. using a collection of primarily 3-D printable magnet mountable hot-swap tool heads [87]. Thus, hundreds of gaskets can be printed from a single tube of caulk. These are more complex, less-tested machines that may be useful for organic farmers in the future. To enable gasket manufacturing on farm using only standard FFF printing in PLA, it is also possible to print a mold in PLA and fill it with silicone to produce silicone gaskets [88].

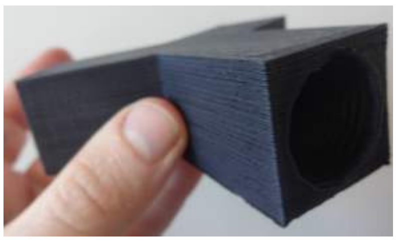

Figure 14. 3-D printable garden hose splitter.

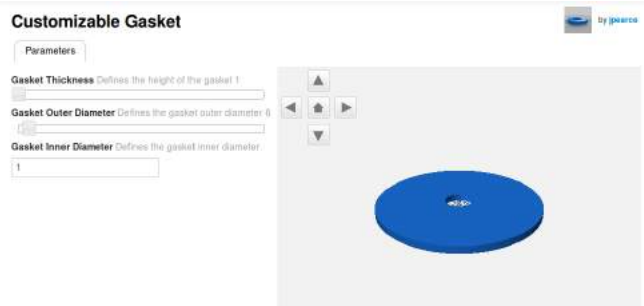

Figure 15. Customizable gasket design for use in 3-D printing.

Figure 16. Upside-down delta 3-D printer with a stationary caulkstruder.

Gaskets made by either process are also useful for larger applications such as the contoured spigot for a five gallon bucket (Figure 17). Spigots manufactured for self-attachment typically rely on large gaskets to maintain a seal, which works with varying success on the curved surface of a bucket or barrel. By modeling a bucket with just its top and bottom diameters and its average thickness, it is easy to design a spigot with contours that fit the targeted water container and, with 3-D printing, a custom spigot attachment can be fabricated. The main attachment is reasonably easy to print and typical modification requires changing only four parameters in OpenSCAD. However, this design is also a good example of the generally unfinished nature of open-source design projects. Although the design of the connection is robust the spigot itself can be improved significantly.

It is relatively well established that organic farms can conserve water using a drip irrigation system, which allows for precise application of water into the root zones of targeted plants while minimizing runoff-related losses or deep percolation. Although savings are possible, many farmers use drip irrigation to improve their water use efficiency—improving the yield for the amount of water used. The use of a drip irrigation system, whether in the developed or developing world, depends primarily on economics [89]. The following must be considered: the capital and labor costs of installing drip irrigation, costs and returns of production, and the price of and access to water. Farmers who use the technology may experience increased yields and higher income per unit of land as, depending on the crop, water applied under drip irrigation is approximately half as much as under flood irrigation. To optimize an irrigation system made up of any of the standard above-ground quarter-inch tubing that connects up to sprayers, drip feeds, and drop hoses, garden stakes (Figure 18) can be used. They are parametric and can be customized for the soil and watering conditions of any organic farm. There are many other water management related open-source 3-D printable designs, such as soil moisture sensors, watering can nozzles and spouts, liquid level sensors and rain water collection devices, including early work on different types of treadle pumps. Perhaps the most interesting progress is water-related 3-D printable designs, however, is in the more high-tech area of hydroponics.

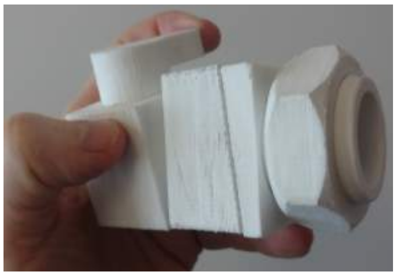

Figure 17. Contoured 3-D printable spigot for a five gallon bucket.

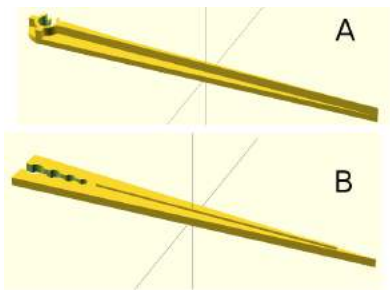

Figure 18. 3-D printable garden stakes used for irrigation systems made up of any of the standard above-ground quarter-inch tubing that connects to sprayers, drip feeds, and drop hoses.

3.5. Hydroponics

Although a small research field in the early stages of development, it is possible to use hydroponic systems and still conform with organic principles [90] and philosophies by using i) nutrient solutions derived from acceptable organic sources, ii) biological pathogen control measures and iii) recirculating hydroponic systems [91–94]. Surprisingly, a study by Atkin and Nichols found organic hydroponics to be a more sustainable system of crop production than classical soil-based organic systems [95]. The environmental benefits of organic farming and food systems are well established [96]: they contribute to climate change mitigation [97] because of improved energy efficiency and biodiversity conservation [98–100]. In order to improve the environmental benefits of organic hydroponics even further, distributed manufacturing with open-source 3-D printers can be used as there is already evidence that it has a lower environmental impact than conventional manufacturing [101,102].

For example, 3Dponics is a 3D-printable vertical hydroponics system (Figure 19) that re-uses 2L bottles as growing platforms. An air pump collects nutrient solution from the bottom reservoir via a 3-D-printed conduit and pushes it through tubing to the top of the system where it drips out of a 3-D printed head into the chain of bottles until in returns to the reservoir to be reused in the next watering cycle (Figure 19A).

More conventional hydroponic system components can also be printed for a few cents and replace components that cost more than $10, like a hydroponic halo ring (Figure 20). The pores in this device ensure that the containers are irrigated with water and nutrient solutions evenly. If used in conventional soil-based applications, three stakes can be added to the ring and it can be used for existing plants by slipping the stalk through the gap. Again the OpenSCAD code can be easily altered to fit any organic farming application or plant type (e.g. changing gap length for more mature plants). There are also several different versions of hydroponic plant pots (Figure 21). Again, a farmer can evolve the open-source design for his specific application and print it for lower costs than purchasing from a conventional supplier. Finally a more complex version of a peristaltic pump (Figure 22), which can be used to pump the water nutrient solution for hydroponics. Peristaltic pumps work off a single motor and have the advantage of fluid never coming into contact with mechanical parts of the machine as it is contained within a flexible tube (Figure 22). As peristaltic pumps have several uses, including as 3-D printer extruders, there are many different designs already freely shared under open-source licenses.

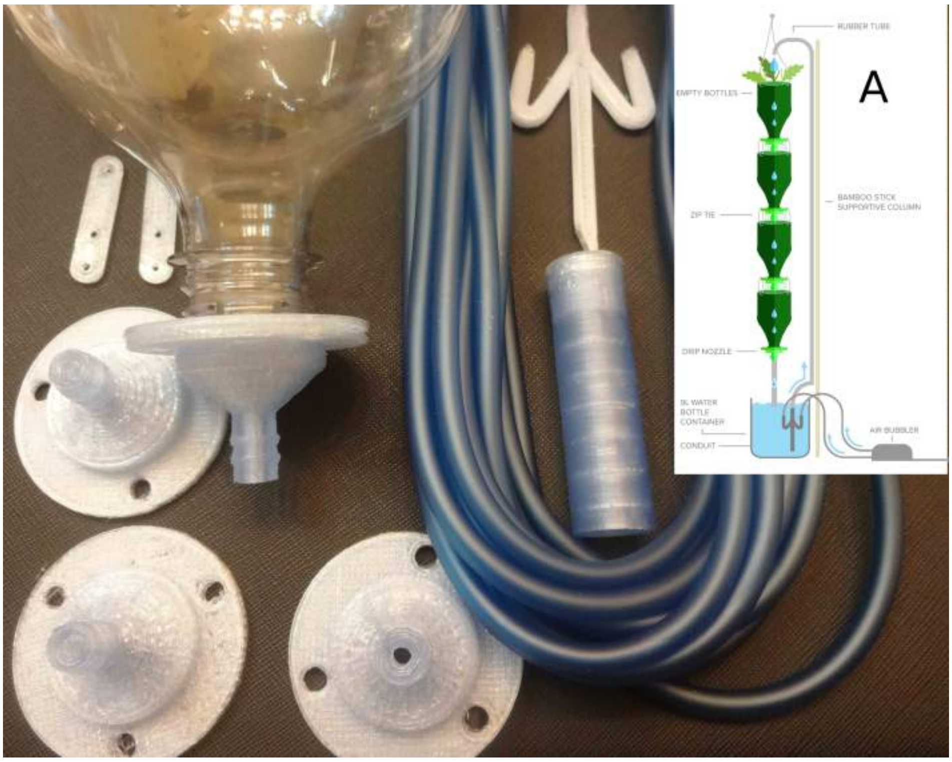

Figure 19. A) Shows a schematic of the 3Dponics system, which is a 3-D printed hydroponics systems that uses discarded 2L bottles as growing platforms. The digital image shows the primary 3-D printed components and rubber tubing used for the system.

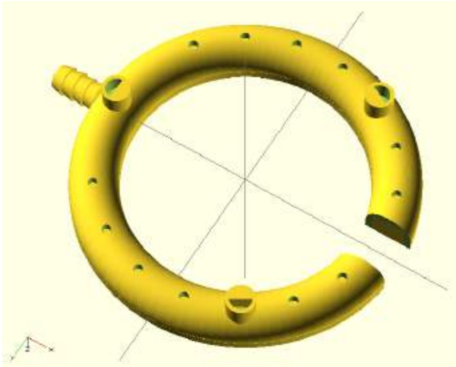

Figure 20. A rendering in OpenSCAD of a customizable 3-D printable hydroponic halo ring.

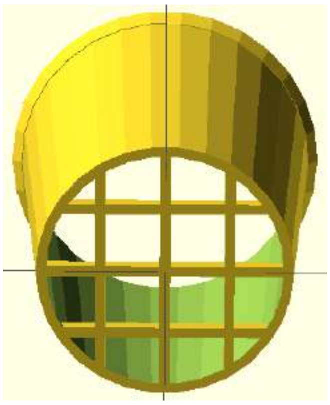

Figure 21. A rendering in OpenSCAD of a customizable 3-D printable hydroponic plant pot.

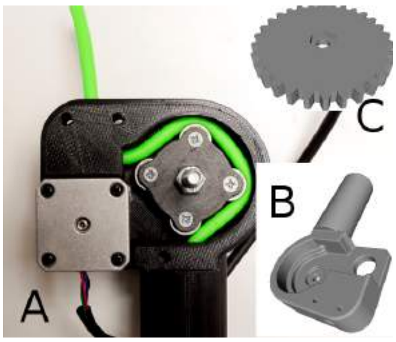

Figure 22. A) a 3-D printable peristaltic pump, B) a rendering of the printable housing and C) a rendering of the printable gear.

3.6. Economics

Most of the preceding examples of PLA 3-D printable designs offer advantages in regards to customization of equipment for organic farmers, and this has a value, although it is difficult to quantify. However, all of them offer direct cost advantages over purchasing commercial equivalents. This economic advantage mirrors past analysis that looked at more generic consumer products [14]. In all of the preceding cases it was assumed that virgin commercial PLA filament was purchased and average U.S. electricity rates were used. In general, these assumptions enable a RepRap to print products for much lower costs than what is available commercially, even if shipping and taxes are ignored.

This already substantial economic advantage of RepRap-based distributed manufacturing increases by a factor of ten when recyclebots [103] (waste plastic extruders) are used to produce the 3-D printer filament. Recyclebots of various designs are now being developed and commercially distributed, allowing filament production from either virgin or recycled material, including the Lyman extruder [104], Filastruder [105], FilaFab [106], Filabot [107], EWE [108], ExtrusionBot [109], and the Strooder [110]. Such recyclebots can produce 3-D printer filament out of PLA from virgin PLA pellets, which decreases the cost of filament from \$20–50 kg^{-1} for commercial filament to \$6 kg^{-1}. If post-consumer PLA is collected and used to make filament, the energy costs are only about US\$0.10 kg^{-1} [103]. Similarly, other plastics can be used with similar material costs. For example, 1 kg of printable HDPE filament can be generated from 20 discarded milk jugs that and uses only US\$0.10 of electricity [103], but more care must be taken with using it for printing. Again, these costs do not include labor. However, use of recyclebots results in such substantial savings, even when labor costs are taken into account, the technology provides a new method of poverty reduction, as waste pickers can gain access to a much greater income from their labor [111]. In addition, there is now substantial evidence from life cycle analysis-based studies that distributed recycling has a significant environmental benefit over traditional centralized recycling [112,113].

If the capital cost of the RepRap 3-D printer is not included, it is clear that distributed manufacturing of equipment for organic farms on site is economically advantageous. It is less clear, even with the widespread selection of existing free designs (of which only a small fraction have been discussed in this article), that a 3-D printer could economically justify the purchase price for organic farm applications alone, as such economics is heavily dependent on the use of the printer [14]. Although a single water testing platform (Figure 6) pays for the entire 3-D printer 4-8 times over, hundreds of irrigation stakes (Figure 18) would need to be printed to cover the capital costs of the 3-D printer. It is obviously also much easier to justify the capital cost of the printer if a recyclebot is available either on farm in or locally. Each organic farmer would need to evaluate his own potential use based on his applications and needs. It is likely that there could be one or several highly utilized products or components that would economically justify purchasing the 3-D printer, and then the other products it manufactured would simply be extra side benefits adding to the profitability of the investment.

As the technological evolution of open-source RepRap 3-D printing continues to reduce costs, improve reliability, resolution and speed and both the number and assumed utility of open-source designs continues growing exponentially [14], open-source 3-D printers could create what is claimed to be a third industrial revolution [114,115]. It appears prudent for organic farmers to realize this opportunity if the savings from self-sufficient farm-manufacturing with 3-D printers meets their minimum acceptable rate of return as the savings are likely to be greater in the future than any return calculated at a given time. This is primarily due to the open source nature of the technologies as future improvements of both the printers and the designs can be accessed for free.

4. Future Work

Although there is considerable evidence that organic food can help provide food security to an increasing global population [116–118], in many contexts the costs of organic food must continue to decline [119–125]. It is clear the open-source 3-D printing can contribute to this goal, but there is substantial future work needed in the area of distributed 3-D printing and agriculture before it can be said to be an open source appropriate technology (OSAT) [126] ready for scaling to drive sustainable development over the entire world [127]. Areas that need further investigation include improvements in: 1) designs of 3-D printable objects, 2) materials, 3) 3-D printers, 4) software and 5) 3-D printable repositories.

Although there are thousands of 3-D printable designs, of which only a few have been reviewed here, they still only represent a small fraction of the number of components and products that could be replaced with farm-fabricated equipment. The number of free designs is growing daily, but there is still more design work needed before organic farmers have access to a free catalog of designs covering all their equipment needs. Many of the existing designs are little more than prototypes, having been designed, printed and tested by a single individual. As the global sharing economy [128–131], P2P (peer to peer) economy [132,133] and the hacker ethic [134] behind it continue to grow, more designs, improved designs (e.g. optimized for printability, conservation of materials and energy, etc.) and mass-tested designs will make their way onto the Internet. There is a large number of opportunities for 3-D printable designs relevant to organic farmers. For example, many other insect traps than the single example shown here, which are discussed by Shimoda and Honda are also 3-D printable [135].

Next, more work is needed in the area of materials development and testing for 3-D printing applications on the farm. PLA is a good printing material, but considerably more work is needed on longevity under farm conditions (e.g. UV radiation tolerance compared to other polymers [136,137], mechanical strength under repeated loading conditions, degradation rates while exposed to water, etc.). PLA must also be tested under repeated recycling cycles using industrial and recyclebot technology to determine the extent of the deterioration of the properties as a function of cycle number and the need to introduce virgin PLA into the mix to maintain adequate material properties. Ideally PLA could be produced from organic agricultural waste on site on a farm, and the small scale OSAT needed to do this has yet to be developed. In addition to PLA, other polymers and other materials, including composites, must become as developed as PLA already has for widespread use. Care should be taken to ensure compatibility with an organic farm so that harmful substances are avoided through the entire life cycle of the material [138].

The technological evolution of the 3-D printers themselves has been rapid, but further improvements in RepRap design will allow for: 1) less complex designs with fewer parts, 2) easier and faster assembly and repair, 3) increased reliability, 4) lower capital costs, 5) faster printing, 6) higher resolution, 7) more consistent properties in printed objects, 8) higher percentages of printable components (until 100% is reached), 9) higher energy efficiency, 10) multi-material and variable material printing and 11) quieter printing. All of these goals are being actively worked on by the international RepRap community, consisting of hundreds of professional scientists, engineers and makers, tinkers, and amateur hobbyists. Each incremental improvement made is shared and dispersed throughout the world, thereby improving the capabilities of organic farmers that adopt the technologies as many 3-D printer upgrades can simply be downloaded, printed and installed on the machine that made them.

One area of RepRap development that is of particular interest to the organic farming community in isolated regions of the developing world is the recent demonstration of several types of solar photovoltaic (PV) powered 3-D printers [138]. These printers can operate literally in the field and thus offer advantages for mobility, as well as use by off-grid organic farmers. When printing using most types of firmware, loss of power represents a catastrophic print failure as the chain of g-code is lost and it is extremely difficult to find the exact location of a failure when the 3-D printer is operating without observation. Normally 3-D printers are operated without continuous user observation for areas with reliable grid power. There is some early development on passive monitoring with web-cams, but at this point, for reliable printing in areas with frequent grid power interruptions some form of electrical power storage is necessary for critical prints, which is designed into to the PV-powered RepRap designs. It should be noted that although Franklin firmware [42] can recover from power failure, which can alleviate this problem somewhat, the pause in the printing process could also effect the mechanical integrity of the part because of the effects of a pause on the solidification process. Additional work is needed to further reduce the cost and reliability of this class of self-powered RepRap systems.

Improvements in the software tool chain will not only improve the ease of use of 3-D printers for farmers and other non-specialists, but also improve performance. Simple 'print' buttons need to be integrated into all popular open-source solid modeling programs (e.g. Blender, OpenSCAD, and FreeCAD) with the necessary code to ensure quality prints on individual machines, just as standard 2-D printing operates today. Improvements in the firmware and integration of the modeler/viewer, slicer and printer controller are all needed. Auto-calibration, self-leveling, error and failed print detection and recovery will all enable a more plug-and-play experience for non-3-D printer experts. Slicers need to be improved to enable fill pattern and density optimization based on finite element analysis of printed components under realistic loads. In addition, printing support must be improved to minimize filament use, time and energy printing and part clean up while ensuring geometric integrity. Further, printer settings including material selection must be optimized in real time for the specific geometries of a given print.

Finally, the free repositories that store 3-D printable files (e.g. Youmagine, Libre3D, etc.) must all be improved. This can be done by improving search, tagging, licensing, easing the uploading of derivatives, and integrating OpenSCAD customizers in addition to STL renderers. The repositories need to go beyond simply storing STLs or even OpenSCAD code and begin to store information about optimal slicing, control and materials. Printed components need to be vetted and tested in a way that enables greater confidence in the printer that the print will perform as intended. This information can all be shared in a way to enable innovation [139] and further sustainable development for everyone. In some cases it will be necessary for independent labs and government agencies to provide this form of testing and approval, but in other cases the solutions can be crowd-sourced [140,140–143]. For example, cabbage white butterflies are known to be antisocial when they are laying their eggs, so if decoy butterflies [144] are printed, it can be hypothesized that they might reduce pest damage in cabbage crops. The number of variations on such an experiment that 3-D printing affords is substantial (e.g. shape, size, type, density etc.) so a crowd sourced experiment could be helpful for developing an inexpensive 3-D printed solution to this crop pest.

5. Conclusions

The results of this review show a generalizable technical viability and economic benefit for adopting open-source 3-D printing for any of the organic farm technologies reviewed, although the individual economic impact is highly dependent on needs and frequency of use on a specific farm. Despite liming the applications of open-source 3-D printing to only the most-developed fused filament fabrication of the bioplastic polylactic acid, five categories of prints : 1) hand tools, 2) food processing, 3) animal management, 4) water management and 5) hydroponics were all found to be technically viable. PLA is a strong biodegradable and recyclable thermoplastic appropriate for use on an organic farm. Capital costs of an open-source 3-D printer can be saved with the on-farm printing of a single advanced analytical instrument in a day or replacing of hundreds of inexpensive products over a year. In order for the full potential of open-source 3-D printing to be realized to assist organic farm economic resiliency and self-sufficiency, future work is outlined in five core areas: designs of 3-D printable objects, 3-D printing materials, 3-D printers, software and 3-D printable repositories.

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Organic Farming

Commentary

A New Evaluation Culture Is Inevitable

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Changes in the production of research (more collaborative, more inter- and transdisciplinary, more oriented towards societal demand) are influencing the ways in which research is evaluated. Traditional methods of evaluation primarily focussing on the production of scientific articles have long since given way to more comprehensive methods in which researchers' other activities are assessed too. Beyond these developments, evaluation also involves research endeavours concerning collaboration with other stakeholders in society, such as industry, NGO's, consumer groups, or governmental organisations.

However, this transformation does not happen without difficulties because there is no broad consensus about how to evaluate research in a more comprehensive way. When reviewing research in the broader perspective of its merits for societal questions, there are at least two kind of questions that arise. The first one is whether we should emulate the kind of indicators used in the evaluation of scientific quality or develop a different kind of methodological approach, for example a more qualitative one. The second type of question is whether we will be able to find data that is robust enough to perform the evaluation in responsible and justifiable ways. Both questions are important for the policy support necessary to develop reliable and acceptable evaluation procedures.

However, perhaps more important is the overarching question of the function of evaluation itself in the newly emerging context. Is it an instrument primarily used for purposes of accountability, or is it an instrument for mutual learning and improving the research effort? Improving in this context does not mean striving for a higher position in one of the international rankings, but being more effective in reaching the scientific and societal goals intended. Further, to make this question even more demanding, societal goals are not undisputed; on the contrary, these goals are often the subject of fierce debates between, for example, policy makers and NGO's, or industry and consumer organisations. Agricultural research is therefore an excellent example, because it shows that it is not a matter of simply finding indicators for applied agricultural research, but that research in this sector is connected to much broader discussions (and controversies) in society about how to produce food in a sustainable way.

It is therefore both timely and necessary that Wolf et al. [1] take a closer look at the strategies necessary to change the mindset of those who are responsible in universities and at other levels of the scientific system for the development of alternative evaluation systems. To focus on the encouragement of connections between parts of the research and innovation system that already have a stake in the transition of science for its own sake to science for society may lead to innovative new networks in which the broader perspective is taken seriously. The debates referred to above will be part of such new networks, and of the development of different evaluation systems. As Wolf et al. show, there are several promising developments in this respect. Unfortunately, as is also made clear, these are still confronted by incentive systems that favour the old style of evaluation and the old method of producing research: mono-disciplinary, with a focus on publication in international journals.

This means that there is a major problem in building a new evaluation culture that is more fitting to the new ar-

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rangements, in which much scientific research currently takes place. A key problem is the continued gap between the advanced understanding of this changing relationship between science and society—as developed by scholars of science and technology—and the policy context. Many policy makers and universities' governing boards still tend to rely heavily on more traditional ranking systems that are relatively easy to work with and work well in the institution's marketing strategy.

Therefore, the possible strategies mentioned by Wolf et al.—valuable as they are—should be extended to include a strategy to change the basic attitude of decision makers. They too should understand that a broader approach is both necessary and useful. This is especially valid for the research efforts addressed in this article, inter- and transdisciplinary research that is the product of collaboration between different fields and expertise coming from science and society. If it is indeed the case that there is joint agenda setting, and co-production, it only makes sense to alter the evaluation process in a direction that does justice to these new arrangements and the kind of questions that are relevant in that context.

To a large extent, this is a question of ownership. In traditional academic research, there was one main funder, the government. Under such circumstances, evaluation becomes primarily an instrument for accountability. The main questions then were whether tax payers' money was spent in a responsible way, and whether the government/researchers were doing the best they could (were they as good as possible?). However, when other funders and stakeholders become part of the equation, the prime goal of evaluation shifts from accountability to communication between partners—regarding goals and research design—and to mutual learning. In this situation, the ownership of the evaluation shifts from one principal funder to a joint responsibility shared among the most relevant stakeholders. Through a joint effort of these stakeholders one might be able to convince policy makers to allow for broader, more comprehensive methods of evaluation. It would help, then, if the availability and accessibility of data was at the best possible level, i.e. as robust and representative as possible for the activities and interactions that take place in the network. Among other things, this would mean that peer review has to be extended to reviews based on broader expertise.

References

[1] Wolf BM, Häring AM, Heß J. Strategies towards Evaluation beyond Scientific Impact. Pathways not only for Agricultural Research. Organic Farming. 2015;1(1):3–18.

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Research Article

100% Organic Poultry Feed: Can Algae Replace Soybean Expeller in Organic Broiler Diets?

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Abstract: Current EU regulations allow 5% of feed for organic poultry to come from non-organic production. This is due to concerns about a 100% organic diet meeting the requirements for specific amino acids such as methionine. This exception is due to end on 31st December 2017. While this may match consumer expectations, protein sourced from global organic production may have a negative impact on perceptions of organic poultry in other ways. Soybean is a commonly used ingredient in poultry feed but soybean production has negative environmental and social impacts. Consumers may also prefer organic poultry to have been fed on locally produced feed and, indeed, this would be in line with organic principles. Preliminary feasibility feed trials were carried out during a summer and a winter season using organic broilers in the UK to test three 100% organic feeds: a control diet with globally sourced ingredients including soybean expeller, a diet based on locally sourced (i.e. within Europe) organic ingredients, and a diet based on locally sourced organic ingredients and algae (a good source of methionine). The results of the summer feed trial showed that there were no significant differences in broiler weight gains. In the winter feed trial differences were found. There was a significant difference (P = 0.034) in weight gain between the local feed (lower weight gain) and the local feed with algae but no significant difference between the control diet with soybean and the two local diets. These preliminary feed trials indicate that there is no significant impact on broiler performance or animal welfare parameters when replacing soybean with European protein sources, possibly including algae, suggesting that, although the research is still at a very early stage, such feeds may be a viable option for 100% organic poultry feed in the future.

Keywords: algae; broiler; feed; organic; poultry; soya

1. Introduction

Current regulations for organic pig and poultry production systems (Council Regulation (EC) No. 834/2007, [1]) have a derogation that permits up to 5% of the feed to be from non-organic sources. This exception is due to end on 31st December 2017.

The 5% non-organic feed ingredients have been allowed primarily due to concerns that a 100% organic diet would be unable to meet the monogastric nutritional requirements for essential amino acids. The essential amino acids for poultry are methionine, cysteine, lysine, threo-

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nine, and tryptophan and these must be fed directly as the birds cannot synthesise them from other food constituents [2]. Fast feathering with good feather cover is important for organic poultry as it helps to protect them from the elements when outdoors, and the main amino acids associated with synthesis of feather keratin are cysteine and methionine [3]. Synthetic amino acids are not permitted in organic poultry feeds and therefore the amino acid requirements must be satisfied by the ingredients within the feed provided.

In a recent review of EU organic regulations [4], interviewed experts expressed concerns as to whether a 100% organic diet would be able to meet these high-protein requirements, especially for high performance breeds. They felt that the non-organic feed was required to meet the methionine and lysine requirements and stated that the majority of pig and poultry producers relied on the derogation.

However, studies of organic consumers [5] have shown that they have indicated a preference for organic husbandry due to its use of natural/healthy feed and they may feel that poultry which are fed up to 5% non-organic ingredients do not match this perception. On the other hand, consumers prefer locally grown organic produce to foreign goods [6] and have been known to choose local, conventional produce over organic produce [7,8]. Thus, if globally produced feed sources are needed to meet the 100% organic poultry feed requirement then this may have a negative effect on consumer perceptions. It would also appear to be contrary to organic principles which suggest that local or regional production should be preferred [4].

The most obvious and commonly used vegetable protein feed source (soybean) is not widely grown in Europe due to climatic conditions. Additionally, there are many environmental, genetic modification and social concerns about using soybean imported from South America [9–11], China and India, and more acceptable alternatives are required. It has been shown that some European protein sources like lupin (*Lupinus albus*, *L. luteus*, *L. angustifolius*) [12] and naked oats (*Avena nuda*) [12–14] (mainly produced in northern Europe) can partly cover the nutrient requirements for laying hens [12], although anti-nutritional factors could have an impact.

Other implications of 100% organic poultry feed are likely to be higher feed costs due to the higher cost of organic protein [4] and the possibility that higher amounts of overall protein will need to be fed to meet the methionine requirements [4] which, as well as impacting on cost, will have an impact on nitrogen excretion, leading to higher greenhouse gas emissions.

There is therefore a need for investigation into European feeds for poultry, perhaps using novel protein sources. There is a need, through performance trials, to evaluate the impact of the feed on growth and productivity.

In this study, the impact of locally (i.e. European) sourced 100% organic feed on broiler performance and welfare was investigated. The definition of "local" used in this study was within the UK wherever possible and otherwise from within Europe. Three 100% organic feeds were compared in preliminary feasibility trials: a control diet with globally sourced ingredients including soybean expeller, a diet based on locally sourced (i.e. within Europe) organic ingredients, and a diet based on locally sourced organic ingredients and algae. The amino acid profile of algae compares favourably with that of most food proteins including soybean [15]. This suggests that algae may make a good substitute for soybean in poultry rations with regards to maintaining a desirable amino acid profile within the feed.

This paper reports on preliminary feed trials carried out in summer 2012 and winter 2013 comparing the performance of broilers fed the three diets described above, in terms of weight gain, feed conversion ratio, breast feather coverage and hock lesion scores. It also discusses in more detail the environmental and social issues concerning soybean production.

2. Material and Methods

2.1. Animals and Housing

Preliminary feed trials to test the feasibility of the diets were carried out at FAI Farms Ltd., Oxford, UK. The first was carried out over the summer period (July–August 2012) and the second over winter (January–February 2013). The houses each contained twelve 3.2 m^2 pens with access to grassland paddocks. Four pens were fed each of the three diets. The bedding used was chopped straw mixed with woodchip. The pens contained Plasson Bell drinkers and standard tube and pan feeders. Prior to the start of the trial, the chicks were fed an organic chick starter feed and were reared in one batch indoors for four weeks. The birds (Hubbard JA 757 broilers) were assigned to pens at random.

For the summer feed trial the birds were housed in two houses positioned side by side. Each pen contained 10 or 11 birds, thus the indoor stocking rates were approximately 0.32 m^2 per bird. In each house, pens 1, 4, 7 and 10 were fed the local feed diet; pens 2, 5, 8 and 11 were fed the control diet; and pens 3, 6, 9 and 12 were fed the local feed with algae diet. Thus, the feed pens were distributed evenly throughout the houses.

For the winter feed trial, due to the colder weather conditions, it was necessary to double the amount of birds in the house to ensure that the birds were able to keep warm. Thus only one house was used in the winter trial. Twenty birds were placed in each pen, giving an indoor stocking density of 0.16 m^2 per bird. Similarly to the summer trial, pens 1, 4, 7, and 10 were fed the local diet with algae; pens 2, 5, 8, and 11 were fed the local diet; and pens 3, 6, 9 and 12 were fed the control diet.

2.2. Diets

The three diets tested were: a standard 100% organic poultry feed currently available in the UK (control) and including soybean expeller in its ingredients, a locally (European)-sourced 100% organic poultry feed and a locally (European) sourced 100% organic poultry feed incorporating algae (*Spirulina spp.*; Table 1).

Only the control feed contained soybean expeller but all three feeds contained soybean oil. In additional the local feeds (but not the control) also contained rape seed expeller and flax expeller. Table 1 shows the ingredients and nutritional information for all three feeds in greater detail. There were slight differences in the ingredients for the three feeds between the summer and winter feed trials due to differing availability of ingredients but the feed manufacturer endeavoured to keep the nutrient contents as similar as possible between the two seasons. The local feeds make use of sweet lupins and beans as a protein source and the local feed with algae also includes algae for protein. The algae used in the feed trials were produced by Merlin Biodevelopments Ltd. (North Wales) using a hydroponic system based on the waste-derived fertiliser from anaerobic digestion. A slurry was produced, freeze-dried and sent to the feed mill for inclusion in a standard pellet form. The diets were provided by Hi Peak Feeds [16] and were fed as 3 mm pellets.

Table 1. Diet ingredients and calculated nutrient contents including amino acid profiles (data provided by Hi Peak feeds [16]).

	Fresh weight percentage (%)					
	Control		Local feed		Local feed with algae	
	Summer	Winter	Summer	Winter	Summer	Winter
Wheat	56.91	53.43	30.00	19.00	30.01	23.00
Soybean Expeller	22.24	18.85				
Sunflower Expeller	9.78	8.49	12.00	19.00	6.61	12.84
Maize	5.00	8.00	21.32	26.75	21.86	28.99
Rape Seed Expeller			14.82		15.00	
Flax Expeller			2.25	5.91	3.53	
Sweet Lupins		5.00	14.35	7.68	10.00	15.00
Beans				15.00	5.00	10.00
Algae					3.00	5.00
Rice Protein	1.15	1.15				
Soybean Oil	2.01	2.16	2.35	2.86	2.49	2.41
Di Cal Phosphate	1.45	1.45	0.46	0.62	0.55	0.88
Vitamins and Minerals	0.75	0.75	0.75	0.75	0.75	0.75
Calcium Carbonate	0.71	0.72	1.20	1.18	1.20	1.13
Px Lucerne Concentrate			0.5	1.25		
Nutritional Information						
Crude Protein	20.15	20.09	19.50	19.27	19.54	19.34
Lysine	0.95	0.95	0.85	0.85	0.88	0.88
Methionine Eq	0.38	0.38	0.37	0.37	0.40	0.39
Methionine	0.33	0.33	0.32	0.32	0.35	0.34
Meth. + Cys.	0.68	0.70	0.70	0.66	0.71	0.69
Tryptophan	0.23	0.23	0.21	0.23	0.20	0.18
Threonine	0.70	0.72	0.74	0.72	0.77	0.74
Av Lysine	0.85	0.82	0.66	0.73	0.64	0.58
Metabolisable Energy (MJ kg^{-1})	12.65	12.65	12.20	12.00	12.30	12.00

2.3. Growth Performance and Feed Conversion Ratio

The weights were recorded on a weekly basis, sampling 50% of the birds from each pen. The weight recording for the summer started when the chicks were 43 days old (week 1) and continued until the birds were at marketable weight (64 days old) (week 4). The trial feeds were used from 36 days old onwards (i.e. once the birds had transitioned from chick starter feed to broiler feed). The weight recording for the winter started at age 47 days (week 1) and continued until the birds were at marketable weight (68 days) (week 4). The trial feeds were used from 43 days old onwards. The birds in both the winter and summer trials were weighed after 11 am to allow for stabilisation of weight after the morning feed. The pens were weighed in the same order each week and at the same time. The mean of the five (summer) or 10 (winter) weights sampled in each pen was taken to give the average bird weight per pen; the pen was then used as the experimental unit. The statistical analysis, discussed below, compared the weight gains on the three diets.

The diets were fed on an *ad libitum* basis. The weight of feed being added to each pen and the weight of feed discarded was recorded to calculate the feed intake. For the winter trial, this information, along with the average bird weights for each diet and number of birds fed that diet were used to calculate the feed conversion ratio (FCR) for each pen; mortality corrections were unnecessary as no birds died. FCR could not be accurately estimated in the summer trial, because of the unknown amount of nutrients consumed in the outdoor area.

2.4. Animal Welfare Parameters: Breast Feather Coverage and Hock Lesion Scores

At each weighing, the birds were also scored on the parameters of breast feather coverage and hock lesion. The breast feather coverage scale, based on the LayWel scale [17,18], gave a score of 1 for fully feathered, 2 for some feather loss, 3 for some feather coverage and 4 for no feathers. The hock lesion scale, based on the Gleadthorpe scale [19], ranged from 1 for no lesion to 2 for small and superficial lesions to 3 for mild lesions, 4 for moderately severe lesions and the highest score of 5 for very severe lesions.

2.5. Statistical Analysis

The statistical analysis was carried out using R version 2.15.2 [20]. The pen is the statistical unit. After using a Shapiro-Wilk test to confirm that the data has a Gaussian distribution, weight gains across the diets were compared using ANOVA (analysis of variance). The weight gains were calculated for each weekly period (week 1 to week 2, week 2 to week 3, week 3 to week 4) and for the entire period of the experiment (week 1 to week 4). For the summer trial, the data was examined using diet as a factor and including the house in the random term of the model. For the winter trial, the birds were housed in a single house and a one-factor ANOVA test was used to investigate differences due to diet. The buildings were blocked with four blocks per house, each containing three pens, one for each diet.

The statistical model for the summer and winter trials is $y_{ij} = \mu + \alpha_i + \varepsilon$, where μ is the mean, α_i is the effect of the i^{th} diet, and ε the error term. In the summer trial the error term included the house. P values less than 0.05 were considered to be significant.

Post-hoc testing was carried out where necessary using Tukey's HSD. Effect sizes were calculated using η^2.

The breast feather coverage and hock lesion score data was analysed using the Kruskal-Wallis test. This is the non-parametric equivalent of ANOVA and therefore is the appropriate test for use with score data.

3. Results

3.1. Growth Performance

The weight data is summarised in Table 2.

As shown in Table 3, there was no significant difference in total weight gain from 43 (week 1) to 64 days of age (week 4) for the summer period ($P_{2,14}$ = 0.7279). In fact, running the ANOVA for each week (Table 3) gave no statistically significant differences in weekly weight gains across the three diets (P was greater than 0.05).

For the winter trial, there was a statistically significant difference in weight gain between the diets with a large effect size for the period from ages 47 days to 68 days (i.e. week 1 to week 4; $P_{2,6}$ = 0.03431, η^2_{diet} = 0.4283). There was no statistically significant difference in weekly weight gain period (P was greater than 0.05). *Post-hoc* testing indicated that the significant difference in weight gain over the whole period of the feed trial (47 to 68 days) was between the local feed (with a lower weight gain) and the local feed with algae, with no significant differences between the two local diets and the control.

3.2. Feed Conversion Ratio

The feed conversion ratio calculation for the winter trial is summarised in Table 4 below. The FCRs were calculated for each pen for the experimental period (the averages for each diet are shown in Table 4) and the statistics were drawn up on a per pen basis similarly to the weight data discussed above.

Table 2. Broiler body weights (mean weight in kg and standard error for each diet) for the summer and winter feed trials.

Feed Trial	Diet	Week 1	Week 2	Week 3	Week 4
Summer	Control	1.54 ± 0.027	2.02 ± 0.028	2.49 ± 0.039	2.85 ± 0.048
	Local	1.60 ± 0.036	2.05 ± 0.052	2.50 ± 0.066	2.83 ± 0.068
	Local with algae	1.58 ± 0.032	2.04 ± 0.042	2.58 ± 0.053	2.86 ± 0.066
Winter	Control	1.83 ± 0.041	2.31 ± 0.059	2.78 ± 0.063	3.16 ± 0.074
	Local	1.78 ± 0.036	2.24 ± 0.052	2.67 ± 0.056	2.99 ± 0.070
	Local with algae	1.73 ± 0.039	2.22 ± 0.045	2.67 ± 0.064	3.13 ± 0.059

Table 3. Weight gain statistics. * indicates P value below 0.05, ** indicates P value below 0.01, *** indicates P value below 0.001, N.S. indicates no statistically significant difference between the diets.

Field Trial		Week 1 - Week 2	Week 2 - Week 3	Week 3 - Week 4	Week 1 - Week 4
Summer	$P_{2,14}$ value	0.7371	0.3072	0.7304	0.7279
	Significance	N.S.	N.S.	N.S.	N.S.
Winter	$P_{2,6}$ value	0.8733	0.9187	0.3069	0.03431
	Significance	N.S.	N.S.	N.S.	*

Table 4. The feed conversion calculation (FCR) for the winter feed trial for the experimental period showing the cumulative feed intake, weight gain and FCR.

Diet	Cumulative feed intake (kg)	Total number of birds	Total bird weight gain (kg)	Mortality weight (kg)	**FCR**
Local	444.70	84	101.15	0	**4.40**
Control	440.90	85	113.64	0	**3.88**
Local with algae	448.40	85	118.80	0	**3.77**

For the winter feed trial, there was a significant difference between the FCRs of the three diets with a large effect size ($P_{2,6}$ = 0.02001, η^2_{diet} = 0.44396). *Post-hoc* testing indicated that the difference was between the FCR of the local diet and the local diet with algae. It can be seen from Table 4 that the local diet had a higher feed conversion ratio.

3.3. Breast Feather Coverage and Hock Lesion Scores

Table 5 summarises the breast feather coverage data. Given the small number of hock lesions recorded (see below) this data is not summarised in a table. As the data is score data (rather than continuous variables) the average given is the median rather than the mean, and the range is shown by quoting the first and third quartiles (sometimes known as the 25th and 75th percentiles).

For the summer feed trial, the results of the Kruskal-Wallis test showed that there was no statistically significant difference in the breast cover scores between diets at any of the weighing dates (at 50 days, P = 0.2681; at 57 days, P = 0.1271; at 64 days, P = 0.7263). The hock lesion data was not analysed statistically as only 10 instances of "red" hocks were recorded over all of the weighing periods and these were noted to not be serious enough to score a 2.

Similarly, for the winter feed trial there was no statistically significant difference in the breast cover scores between diets at any of the weighing dates (at 54 days, P = 0.1274; at 61 days, P = 0.8019; at 68 days, P = 0.7628). The hock lesion data was not analysed statistically as only 4 instances of scores greater than 1 were recorded over all of the weighing periods.

4. Discussion

As discussed in the introduction, from 31st December 2017, 100% organic diets for poultry and pigs will become compulsory in the EU, thus there is an urgent need to develop feeding strategies based on organic feed which will supply poultry with the required level of nutrients in different phases of production.

The move to 100% organic feed for poultry would ap-

Table 5. Breast feather coverage data for the summer and winter feed trials. The scale is as follows: 1 for fully feathered, 2 for some feather loss, 3 for some feather coverage and 4 for no feathers.

Feed trial	Diet	Statistic	Week 1	Week 2	Week 3	Week 4
Summer	Control	Median	1	2	2	2
		Quartile 1	1	1	2	2
		Quartile 3	1	2	2	2
	Local	Median	1	2	2	2
		Quartile 1	1	1	2	2
		Quartile 3	1	2.25	3	3
	Local with algae	Median	1	2	2	2
		Quartile 1	1	1	2	1
		Quartile 3	1	2	3	3
Winter	Control	Median	1	1	1	1
		Quartile 1	1	1	1	1
		Quartile 3	1	2	1	2
	Local	Median	1	1	1	1
		Quartile 1	1	1	1	1
		Quartile 3	1	2	1	2
	Local with algae	Median	1	1	1	1
		Quartile 1	1	1	1	1
		Quartile 3	1	1	1	2

pear to be in accordance with consumer perceptions of organic food [5] and with organic principles. However, it may not be possible to supply protein with the required amino acid profile using sources from the farm/region alone and so there is a conflict between the requirement for 100% organic feed on the one hand and the desire to have localized production on the other.

Soybean meal, the most obvious and commonly used vegetable protein feed source with a good methionine content, is not widely grown in Europe due to climatic conditions. Global demand for soybean for animal feed and oil has increased in recent decades [11]. Increased demand has led to expansion of soybean production in Latin America, especially in Brazil [9,10] where production has increased by 357% between 1990 and 2011 [11]. Soybean production is a threat to biodiversity as land is needed not just for growing the crop but for the transportation infrastructure to take it to its markets [9]. This puts habitats, especially in the Amazon region, at risk. The IUCN Red List indicates that in Brazil, crop farming is currently threatening 34 critically endangered species and a further 65 endangered species ([11] and references therein). The requirement for land for soybean production also has a social impact as smaller farmers are displaced to make way for larger farms [9,10]. A World Bank report highlights that during the major expansion of farming in the Cerrado region, many small farmers lost their land due to poor land records and limited protection of land rights [11].

This paper reports on preliminary feed trials carried out in summer 2012 and winter 2013 comparing the performance in terms of weight gain, feed conversion ratio, and animal welfare parameters (breast feather coverage and hock lesion scores) of broilers fed three different organic diets. The diets were: a standard 100% organic poultry feed currently available in the UK and including soybean expeller (control), a locally (European)-sourced 100% organic poultry feed and a locally (European) sourced 100% organic poultry feed incorporating algae (*Spirulina spp.*). The results of the summer trial showed that there was no statistically significant difference in bird weight gains between the three diets. In the winter trial, there was a statistically significant difference in weight gain over the entire trial period between the local diet (lower weight gain) and the local diet with algae. There was a statistically significant difference in FCR between the local diet and the local diet with algae, with the local diet having a higher FCR. The significant results in the winter compared with the summer may be partly because of the possible contribution of the outdoor area in the summer trial to the nutrient supply of the broilers. In addition, there were differences in diet composition (e.g. energy, protein, lysine) between the three diets, there were also slight differences in feed ingredients between the summer and winter feed trials due to differing availability of ingredients, but the feed manufacturer endeavoured to keep the nutrient contents as similar as possible for each of the three diets between the two seasons. However, it should be noted that across both periods (summer and winter) there was no significant difference between the performance of the control feed containing soybean expeller and the local feed with algae or the local feed. Algae have a favourable amino acid profile compared with other sources of protein including soybean [15] and may be a good alternative to replace soybean meal in broiler diets [21]. Becker [15] provides a table comparing the amino acid profiles of various algae with that of products such as soybean and egg. The table shows that *Chlorella vulgaris* (2.2 g per 100 g protein), *Dunaliella bardawil* (2.3 g per 100 g protein), *Scenedesmus obliquus* (1.5 g per 100 g protein), *Arthrospira maxima* (1.4 g per 100 g protein) and *Spirulina platensis* (2.5 g per 100 g protein) contain more methionine per 100 g protein than soybean (1.3 g per 100 g protein). This suggests that algae may make a good substitute for soybean in poultry rations with regards to maintaining a desirable amino acid profile within the feed. The algae used in the preliminary feed trials reported in this paper were produced using a zero-waste hydroponic system based on the waste-derived fertiliser from anaerobic digestion. While not currently certified as organic, the ability to produce a protein source tailored to specific amino acid profiles as a by-product of anaerobic digestion presents an opportunity for further exploration as a sustainable alternative to imported soybean.

There were no statistically significant differences in the animal welfare parameters (i.e. breast feather coverage and hock lesion score) in either feed trial period (summer or winter). This suggests that replacing soybean with locally produced protein sources has no impact on bird welfare in terms of feather coverage and hock lesions.

Further investigation of the environmental impacts of the three diets would be interesting. A lifecycle assessment of broiler production in the USA found that feed provision was the major contributor to the cradle to farm gate impacts of production [22]. They found that, if offsets due to litter management (avoiding fertilizer production) are excluded, then provision of feed accounts for 80% of energy use, 82% of greenhouse gas emissions, 98% of ozone depletion emissions, 96% of acidifying emissions and 97% of eutrophying emissions. Corn (which was assumed to constitute 70% of the feed by weight) was responsible for 41% of the impact, while soybean (20% by weight) was responsible for 12% of the impact. A lifecycle assessment of soybean production [23] found that significant greenhouse gas emissions can result from land-use change due to the expansion and cultivation of soybean. Pelletier [22] found that fishmeal production for poultry feed had a higher impact than crop production due to the fuel inputs for fishing and the energy and emissions involved in processing to obtain fishmeal and oil. Pelletier [22] suggests that the use of organic ingredients "which are typically less energy and emissions intensive due to the disallowance of synthetic fertilisers in their production" may reduce the life-cycle impacts of broiler production. An investigation of the environmental impacts of the feeds used in the trials reported here would need to consider the impact of the algae production and also freeze-drying of the algae as well as the production impacts of the other ingredients.

5. Conclusions

In both the summer and winter feed trials, neither local feed (with or without algae) performed significantly differently from the control. However, the local feed with algae outperformed the local feed without algae. This suggests that a diet based on local protein sources, in this case wheat, sunflower expeller, maize, rape seed expeller, sweet lupins, beans, flax expeller and soybean oil and algae could replace a diet reliant on soybean expeller in a 100% organic broiler feed. The algae used in this feed trial were produced using a small scale set-up and so were relatively expensive. However, it is conceivable that the drive towards 100% organic feed for monogastric livestock could result in greater demand for such products leading to economies of scale and subsequent reductions in cost. The fact that they were produced using a system that utilised waste-derived fertiliser from anaerobic digestion may have positive implications for the environmental impact of future algae-based diets, although this would require further investigation due to the energy costs of freeze-drying the algae.

The results of these preliminary feed trials suggest that using locally sourced feed does not have an impact on broiler productivity and adding algae to the feed can improve its performance compared with a locally sourced feed without algae. It is necessary to perform digestibility studies with novel protein sources to provide good nutritional data for these novel proteins before progressing to larger scale performance studies. As well as larger scale, more commercial feed trials, further trials to test possible seasonal effects could be carried out. It might be useful to consider carrying out taste tests to ascertain that none of the diets change the consistency or taste of the broiler meat (although no research was found to suggest that this might be the case using any of the ingredients used in these trials). Further feed trials using laying hens could also be considered to ascertain whether the ingredients trialled in this study may also be appropriate for use in laying hen rations.

Further research could also include further more detailed investigation into the costs of such feeds and the possibilities for economies of scale (as was briefly mentioned above). The environmental impact of each of the three diets discussed in this article should be investigated in greater detail to identify which of the diets are the most sustainable in the long term.

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Organic Farming

Book Review

A Review of 'Crop Protection in Medieval Agriculture. Studies in Pre-Modern Organic Agriculture'

Published: 7 October 2015

Keywords: agrobiodiversity; ancient varieties; crop protection; e-book; landraces; medieval history; precautionary principle; risk assessment; scholarship; seed exchange networks

Crop Protection in Medieval Agriculture. Studies in Pre-Modern Organic Agriculture
Zadoks JC
Sidestone Press: Leiden, the Netherlands. 2013
333 p.; ISBN: 978-90-8890-187-4

"*Tutto quello che fan gli uomini adesso è cronaca, diluita in migliaia di articoli, domani sarà storia, e di un migliaio di nomi, 999 saran perduti*" [1] (transl.: All that human beings now do is news, diluted in thousands of articles; tomorrow it will be history, and, of thousand names, 999 will be lost).

This brilliant and original book by Jan Zadoks, a renowned, prolific and polyglot Dutch plant epidemiologist [2], provides a systematic, learned and well-structured overview of our understanding of medieval crop protection in Europe. This is not the first book in which Zadoks looks at crop protection from a wider perspective (e.g. [3]); the long-term experience of the author in research, teaching and scholarship transpires throughout. The book is peppered with well-chosen verbatim quotes from the examined original sources and is seasoned with pictures (both original drawings and author's photos with examples of crop pests mentioned in the book). The pictures are not just there for embellishment, we can learn a lot from examining them, e.g. when Zadoks comments that (p. 51) "*frequently, the cereal crop is about as tall as harvesters are, say 1.60 m. Medieval people were, on average, shorter than people today and, at the same time, wheat and rye were taller than today*".

There are excellent short summaries at the beginning of each chapter. Also, the book is closed by a helpful, brief recapitulation of the contents of each chapter, together with well-prepared and comprehensive indexes. At a time when:

i) scientific publications are growing at such a pace that the overflow in scientific information might be leading to a decline in overall scientific quality and public trust in science [4–7];
ii) there is often, unfortunately, little interest of scientists in the history of their own discipline [8];
iii) nonetheless, historical research is flourishing (e.g. [9–11]), including many historical studies of agriculturally (and environmentally) related topics (e.g. [12–18];
iv) there are however few incentives for scientists to write books rather than papers (or emails) [19]; and
v) most scientific books are so expensive that few students and citizens can actually afford to buy them [20,21];

Zadoks reminds us that crafting an affordable e-book, looking at historical times, can be enlightening in many ways.

First of all, by studying history we can learn not only about the past, but also about ourselves, e.g. in the comparison between medieval agriculture and modern organic agriculture. Second, it can be illuminating to stop, for a while, our more and more specialized endeavours for reflecting on a broad canvas of the centuries that led to the present times. Third, writing a book provides the room to investigate an issue with a broader perspective than what a literature review paper allows.

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Personal Recollections

Indeed, personal recollections, often shunned in peer-reviewed papers, add value to the distillation of the literature and sources. For example, Zadoks reports how, (p. 54) "*in Amazonian Peru, 1974, [he] stumbled upon a local rice variety, tall and leafy, that produced a fair yield notwithstanding a moderate attack by foliar blast due to the blast fungus, whereas nearby modern high-yielding varieties had been killed by the fungus*".

Often, Zadoks' recollections corroborate an inference from the studied treatises or provide evidence that medieval practices carried on until relatively recent days, e.g. when reporting that (p. 135) "*wheat sown among the olive trees was of common occurrence from antiquity until recently. In the 1950s (Zadoks) saw many such fields in South Spain. There, mulberry trees (to feed the silk worms) were planted in rows bordering the wheat fields*".

In another example about mixed cropping of cereals, Zadoks relates (p. 137) that, already in 1766, Tozetti noticed reduced rust infestations of wheat in wheat-rye and wheat-vetch mixtures during a rust outbreak in Tuscany.

Medieval Agriculture vs. Modern Organic Agriculture

These extracts lead us to a core question of the book: whether (p. 217) "*a comparison of medieval agriculture and crop protection with their modern organic counterparts [is] sensible*". Zadoks finds various reasons to believe so. For example, in both cases (p. 14) "*the emphasis [is] on prevention, . . . and preventive methods [are] embedded in general crop husbandry*".

Zadoks argues that (p. 43) "*pre-modern agriculture was 'organic agriculture', in today's legal sense*" but also that (p. 224) "*the natural products and botanicals recommended in pre-modern times, being broad-spectrum pesticides, supposedly had the same deleterious effects on beneficials as their modern synthetic counterparts [allowed in organic agriculture]*". However, the author also finds arguments for a discontinuity, (p. 223) inasmuch as "*modern organic farms [have] yields incomparably higher than those of medieval farms*".

Today, (organic) food can be easily moved over long-distances to satisfy consumers [22], so that we struggle to imagine what it meant when this was not the case, particularly when far away from the sea (p. 223): "*Medieval farming lacked many stabilising inputs, and this posed serious problems. Buying food when yields were deficient was nearly as difficult as selling produce when it was abundant because the market system did not function well, mainly due to the awkward overland transportation facilities*". This meant that famine was always looming, but also implied reduced chances of long-distance movement of new plant pests and pathogens, which is now an increasing problem worldwide due to the massive inter- and intra-continental trade of plant commodities [23]. European Medieval farmers did not have the luxury of all the crops that have later been moved from America to the Old World, but they also did not have to cope with their associated diseases (unless they were already present in Europe on other crops).

A Holistic Approach Aware of Its Limitations

Studying medieval crop protection and agriculture teaches us that the holistic perspective of organic farming has a long tradition [24]: (p. 16) "*Singling 'crop protection' out, separating it from its agronomical context, is an anachronism, a sequel of the analytical approach by the natural sciences in the 20th century*". The approach of the book is also holistic, ranging from storage, weeds and crop mixtures to allelopathy, habitat fragmentation and soil fatigue.

The author is aware of the (i) the risks involved in comparisons of ancient and modern times, (ii) the problems inherent in generalizations for different regions and (iii) the often inconclusive nature of the examined evidence. Zadoks emphasises that, in medieval times, (p. 206) "*the interventive side of crop protection abounded with superstition, magic, and false concepts*". He also recognizes that, although "*from a present-day viewpoint the scientific status of pre-modern crop protection is modest at best, . . . this judgment does not imply that pre-modern crop protection was without a logic of its own*". Indeed, modern farmers might still sometimes be rather medieval in their thinking: (p. 233) "*In recent times I have seen cases where, for the treating farmer, the psychological effect of a treatment was more important than the crop protection effect*". On the whole, (p. 199) "*we might call the medieval approach to pest control a prophylactic or precautionary control. The grower took his precautions and then he had to sit, wait, and pray*".

This precautionary approach (which is still in use nowadays in risk assessment) was e.g. backed by the wide variety of cultivated crop landraces: (p. 54) "*In the old days farmers went for yield stability rather than for top yields. Old varieties had a certain 'rusticity', which implied that they did not produce top yields but produced an acceptable yield under a wide range of environmental stresses of abiotic and biotic nature*". The importance of old varieties for sustainable agriculture is still recognized, despite some modern misconceptions [25]. We can only try to imagine the slow but widespread and unrelenting networks of seed exchange among medieval farmers, which led to an unmatched diversity of local cultivars. Many of these are now unfortunately lost, despite the value they would have had for adaptation to the expected rapidly changing environmental conditions [26–29]. A similar process took place for the knowledge associated with ancient varieties: (p. 205) "*Old agricultural knowledge was rather like a network originating from many sources with countless deletions and additions*".

What can we bring home from studying medieval agriculture? Many things, and I recommend making time to read this book in order to discover them, without spoiling further your reading. But may I close with one further quote, to whet the appetite with some wise words by Zadoks on the classical pest tetrahedron (p. 218):

"*The original tetrahedron was published in 1979 [by [30]]. The design is characteristic for the optimism of the last quarter of the 20th century, an outcrop of the positivist tradition of the 19th century: man on top of everything. It represents man as the great maker, able to solve any problem. In retrospect the figure is emblematic for the 'makeable society', the idea of 'engineering the society', an idea which, in a way, led to the disaster denounced in Rachel Carson's 'Silent Spring'. A medieval thinker would never have placed man on top in this way, considering it totally unacceptable hubris*".

Disclaimer

The positions and opinions presented in this article are those of the authors alone and are not intended to represent the views or scientific works of EFSA.

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Research Article

Exploring the Feasibility of Using Silage-Based Feed with Alternative Sources of Protein in Organic Pig Rations

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Abstract: Current regulations for organic pig and poultry production systems permit feed ingredients of non-organic origin at an inclusion rate of up to 5 per cent. This is primarily due to concerns that there is an insufficient supply of organic protein on the European Union market, in terms of quality and quantity, to meet the nutritional requirements of pigs and poultry raised on organic farms. However, 100 per cent organic diets for monogastric livestock will become compulsory in the EU from 1 January 2018, and there is therefore a need to develop sustainable feeding strategies based on organic feeds. This feed trial conducted in the UK explores the feasibility of using a silage-based feeding system for Gloucester Old Spot pigs, and compares the inclusion of soya, beans and peas as protein sources in terms of pig growth performance. No significant difference in the pen mean daily live weight gain was observed during the grower phase (pen mean age of 11–14 weeks) between the diet groups. However, during the finisher phase (pen mean age of 15–22 weeks), pigs on the soya and pea rations had significantly faster growth rates than pigs fed the bean ration. It is speculated that the slight shortfall in growth rate observed in the pigs fed the bean ration may be offset by the lower cost of production of beans in the UK. This feasibility trial demonstrates that a 100 per cent organic diet for pigs using alternative, locally-grown sources of protein as part of a forage-based ration can provide a viable alternative to a soya-based diet.

Keywords: beans; forage; monogastrics; organic; peas; pigs; roughage; silage; soya; soybean

1. Introduction

According to European regulation ((EC) No 889/2008 and (EU) No 836/2014), organic producers will be required to provide 100 per cent organic feed to pigs (*Sus scrofa domesticus*) from 1 January 2018. The current derogation allows the inclusion of up to 5 per cent non-organic feed ingredients. The transition to 100 per cent organic pig rations requires the development of viable and sustainable feeding strategies based on locally-grown organic feed, which fulfils the nutritional requirements for pig health and welfare.

The transition to 100 per cent organic pig rations presents a number of technical and sustainability challenges to the pig industry. One hundred per cent organic rations have been associated with dietary deficiencies in amino acids due to the difficulties in formulating rations of high nutritional density and balanced amino acid profile under organic management; the supplementation with synthetic amino acids or those manufactured in a fermentation process is prohibited in organic systems; there is a ban on feeding certain animal by-products; and there is substantial variation in the feeding value of home-grown forage and protein crops [1]. Soybean meal provides a highly digestible and amino acid-rich source of protein in monogastric rations [2]; however, it is not widely grown in Europe and imported soya is associated with negative environmental and social impacts. For example, the expansion of soybean production in countries such as Brazil, which has seen an increase in production by 357 per cent between 1990 and 2011 [3], has resulted in the loss of natural ecosystems and threats to biodiversity [4]. The requirement for land has also displaced smallholder farmers to make way for larger farms [4,5]. European-grown alternative protein sources such as lupin (*Lupinus albus, L. luteus, L. angustifolius*) and naked oats (*Avena nuda*) are available, but only partially fulfil the requirement for the essential amino acid methionine of growing pigs [6]. In addition, the provision of sufficient methionine and lysine in alternative protein sources is often accompanied by the over-supply of total protein, with the associated negative environmental effects of nitrogen excretion and emission of greenhouse gases, and the adverse impacts of high dietary contents of protein and anti-nutritional factors on piglet health [1,7].

In light of these numerous challenges and with feed accounting for up to 65 per cent of conventional pig production costs in England [8], a sustainable solution to organic pig nutrition is required, with equal consideration of the economic, environmental and ethical impacts (the '3Es') [9].

It is widely understood that herbage has the potential to make an important contribution to pig nutrition [10,11], and could play a greater role in organic pig production. Pigs are naturally opportunistic foragers and omnivores. The intestinal microbiome of the porcine hindgut can digest cellulosic, fibrous feed and accounts for 48 per cent of the pig's fermentative capacity [12], enabling them to digest a variety of other foodstuffs including plant materials such as grass. Notwithstanding the limitations of including forages as dietary components, in terms of reducing digestibility and energy availability from the overall ration [13], herbage can make a valuable contribution to nutrition at all stages of pig development. It offers a source of minerals and vitamins, enhances feed intake, and supports gut health by reducing the risk of gastric ulceration associated with grain-based feeds [14–16]. The provision of forage can support positive gut colonisation, which inhibits pathogenic microbes [16], and Danielsen et al. [17] found a tendency towards improved feed utilisation when clover grass was included in concentrate-based rations for finishing pigs.

Herbage-based diets facilitate foraging behaviours that engage pigs in the natural activities of searching for food, rooting and chewing for two thirds of their time [18]. This also fulfils EU legislation to provide pigs with access to manipulable materials. According to Studnitz et al. [19], "exploratory behaviour in pigs is best stimulated by materials that are complex, changeable, destructible, manipulable, and contain sparsely distributed edible parts". FAI Farms has utilised a home-grown silage-based ration in its strawyard pig production system for over 10 years, and high levels of natural foraging behaviours and minimal aggression such as tail-biting behaviours have been observed (Anna Wharton, University of Oxford, Oxford, UK. Conversation with Laura Higham, 27 January 2015.). This natural foraging behaviour and reduced aggression has removed the need for tail docking in this herd.

The present feasibility study compared the growth performance of grower-finisher pigs, fed on a novel silage-based diet with soya as the protein source, to that of grower-finisher pigs fed on two different silage-based diets that contained either field beans (*Vicia faba*) or peas (*Pisum sativum*) as replacement of the soya protein source. The protein sources were compared in a practical farm setting on an 'as-fed' fresh weight basis. The stomach mucosae of a sample of pigs at slaughter were also assessed to explore the effect of silage-based rations on gastric health. The current study was conducted in the UK as part of project 'The Improved Contribution of local feed to support 100 per cent Organic feed supply to Pigs and Poultry' (ICOPP) [20,21].

2. Materials and Methods

A two-part controlled feeding trial was conducted at FAI Farms in Oxford, UK, from August to November 2012 ('summer trial') and from February to May 2014 ('winter trial').

2.1. Animals and Experimental Design

Forty-six and fifty-six home-reared Gloucester Old Spot weaner gilts and entire boars entered the summer and winter trials, respectively. Gloucester Old Spot pigs are a traditional English breed [22], and are relevant to organic pig production in the UK. This breed of pig has been utilised in FAI's home-reared, closed herd for ten years, thus offering pigs of a known high health status to this study. Pigs were sex segregated and randomly assigned to one of three groups using a blocked randomisation list [23] (refer to Table 1). The control treatment groups, consisting of one male and one female pen in each of the summer and winter trials, received a daily ad-lib total mixed ration (TMR) comprising home-grown lucerne silage chopped to a length of 5–8 cm using a Kennan mixer wagon (Richard Kennan UK Ltd, Warwickshire, UK), home-grown rolled barley, minerals and soybean meal. The two treatment groups, each consisting of one male and one female pen in each of the summer and winter trials, received a daily ad-lib TMR composed of home-grown lucerne silage chopped to a length of 5–8 cm using a Kennan mixer wagon, home-grown rolled barley, minerals and milled field beans (*Vicia faba*; group 1) or milled peas (*Pisum sativum*; group

Table 1. Arrangement of pens as part of the feed trial to compare silage-based rations including different protein sources (diet).

Trial	Pen number	Diet	Sex	Number of pigs
Summer	1	Soya	Male	7
	2		Female	8
	3	Beans	Male	8
	4		Female	8
	5	Peas	Male	7
	6		Female	8
Winter	1	Soya	Male	8
	2		Female	9
	3	Beans	Male	8
	4		Female	11
	5	Peas	Male	9
	6		Female	11

2). The proportions by fresh weight of the lucerne silage, barley, minerals and the protein source comprising the diets were equal across all three treatment groups and remained constant throughout the trial period, as shown in Table 2. Diets were formulated as such to meet the nutritional requirements of pigs according to Whittemore et al. [24] (Table 3) as closely as possible in all three diets.

The pigs were housed in groups of between seven and eleven, in indoor straw yards of dimensions 8.3 m $\times$ 4.3 m (35.7 m^2 in area), with woodchip-straw bedding in the rear third of the pens and concrete floors to facilitate floor feeding. Water was continuously available from three drinking valves in the front of the pen. Temperature was not controlled, although the pens were sheltered from rain and wind. All piglets recruited into the trial were home-reared with access to the same forage-based diet in family pens from two weeks of age. Mean pen age at recruitment into the trial ranged from eight to ten weeks.

Table 2. Percentages of feed ingredients comprising the total mixed ration (TMR) by weight, as fed, used for three groups of pigs as part of the feed trial.

Treatment group	Protein source	Percentage of feed ingredients in TMR by weight (%)				
		Lucerne silage	Rolled barley	Minerals	Protein source	Total
Control group	Soybean meal	55	30	1	14	100
Group 1	Beans	55	30	1	14	100
Group 2	Peas	55	30	1	14	100

Table 3. Nutritional requirements and expected feed intakes of pigs [24].

Requirement, Expected feed intake	Pig body weight (kg)			
	15 kg +	25 kg +	40 kg +	60 kg +
Metabolisable energy (ME; MJ day^{-1})	10.1	12.8	22.17	26.87
Crude Protein (CP; g day^{-1})	185	219	270	310
Lysine (g day^{-1})	9.5	10.9	13.8	25
Voluntary feed intake (kg DM day^{-1})	1.25	1.75	2.5	3.5

2.2. Measurements and Sampling

Pigs were fed each morning on an ad-lib basis. The weight of feed provided per pig was increased incrementally over the trial, and leftover feed was removed and weighed each day to ensure that pigs were offered an amount in excess of consumption, and to ensure the provision of fresh feed each day.

Nutritional analyses of the ration components (home-grown forage was analysed by Independent Soil Services, Norfolk, UK) were used to calculate the nutritional values of the three mixed rations per kilogram fresh weight (Table 4), allowing any feed deficiencies to be identified based on the nutrient requirements of pigs defined by Whittemore et al. [24]. All three diets were balanced in their supply of crude protein and energy, fulfilling the requirement of the pigs at each stage, but lysine deficiencies were noted in all rations, which is a common constraint in organic production. All pigs were weighed individually using calibrated weighing scales (Pharmweigh, Bury St. Edmunds, UK) on a weekly basis, and the pen mean daily live weight gain was calculated. Daily live weight gains 'd' of individual pigs were derived on a weekly basis using the following formula, and a pen mean was calculated.

$$d = \frac{w_x - w_{x-1}}{7} \tag{1}$$

where d = daily live weight gain, and w = live weight of pig in week x.

The trial was terminated when a pig in the study approached the farm's criteria for slaughter, yielding thirteen weeks of data in both the summer and winter trials.

To explore the effect of a forage-based diet on gastric health in pigs, the stomachs of two pigs from each pen in the winter trial (n = 12) were assessed at the abattoir for gastric ulceration, rating them on the 0–3 scale described by Mackin et al. [25]. For comparison, six organic pigs reared on a different farm and fed an organic pelleted ration were also assessed for gastric ulceration, using the same scale.

Table 4. Nutritional value of foraged-based total mixed rations for pigs, with different protein sources.

Feed value (on fresh weight basis)	Composition of forage-based rations, per kilogram of feed (fresh weight)		
	Control group ration with soya	Group 1: ration with beans	Group 2: ration with peas
Metabolisable energy (ME; MJ kg^{-1})	7.30	7.11	7.12
Crude protein (CP; g kg^{-1})	116.23	93.35	89.74
Lysine (g kg^{-1})	4.15	3.76	3.74
Dry matter (g kg^{-1})	580.00	580.00	580.00

2.3. Statistical Analysis

Pen was considered the experimental unit. The trial was conducted over two thirteen week periods, from recruitment into the trial at a pen mean of eight to ten weeks of age. Using the mean age of the pigs in each pen rounded to the nearest week, mean daily gain for 'growers' was calculated between 11 and 14 weeks of age, and mean daily gain for 'finishers' was calculated from 15 weeks of age to the end of the experimental periods (day 91, 22 weeks of age).

Pen mean daily live weight gains for each growth phase, grower and finisher, for each diet were compared by use of General Linear Modelling, assessing trial and sex as factors, and pen mean starting weight, number of piglets per pen and pen mean age as covariates. Planned contrasts were performed to compare differences between diets. All data analyses were performed using the statistical package SPSS version 19 (SPSS, Chicago).

3. Results

For the grower period (between 11 and 14 weeks of age): sex, number of piglets in the pen, pen mean starting weight and pen mean age of the piglets did not explain a significant proportion of the variation within mean daily live weight gain and thus were not included in the model. An insignificant effect of diet on mean daily gain was observed (ANOVA: F(2,8) = 2.377, MSE = 0.004, p = 0.155; Figure 1, Table 5), however there was a significant effect of trial (ANOVA: F(1,8) = 9.704, MSE = 0.004, p = 0.014).

For the finisher period (15 weeks of age to the end of the experimental periods (day 91)): trial, sex, pen mean starting weight and number of piglets in the pen explained an insignificant proportion of the variation within mean daily live weight gain. The pen mean age of the piglets, when included as a covariate, was significantly related to mean daily live weight gain (ANCOVA: F(1,8) = 23.52, p = 0.001, partial η^2 = 0.31). There was a significant effect of diet, after controlling for the effect mean age of piglets (ANCOVA: F(2,8) = 18.943, p = 0.001, partial η^2 = 0.73). Planned contrasts revealed that there was a significant reduction in mean daily gain for the beans diet compared to the soya diet (t(8) = -5.67, p $<$ 0.001), but there was no significant difference in mean daily live weight gain between the peas and soya diets (t(8) = -1.229, p = 0.254; Refer to Figure 1 and Table 5).

Table 5. Pen mean (± standard error) daily live weight gains (DLWGs) of pigs during grower and finisher phases when fed silage-based diets supplemented with either soya (control), beans or peas.

Diet	Trial	Average age at start of trial (days)	Grower phase Average daily gain (kg)	Finisher phase Average daily gain (kg)
Beans (Group 1)	Summer (1)	66.38	0.30 ± 0.02	0.59 ± 0.02
	Winter (2)	65.41	0.34 ± 0.03	0.58 ± 0.01
	Combined trials 1&2	65.89	0.32 ± 0.02	0.59 ± 0.01
Peas (Group 2)	Summer (1)	65.37	0.28 ± 0.01	0.66 ± 0.00
	Winter (2)	70.22	0.41 ± 0.03	0.60 ± 0.02
	Combined trials 1&2	67.80	0.35 ± 0.04	0.63 ± 0.02
Soya (Group 3)	Summer (1)	63.07	0.33 ± 0.08	0.69 ± 0.05
	Winter (2)	64.65	0.50 ± 0.05	0.69 ± 0.02
	Combined trials 1&2	63.86	0.42 ± 0.06	0.69 ± 0.02

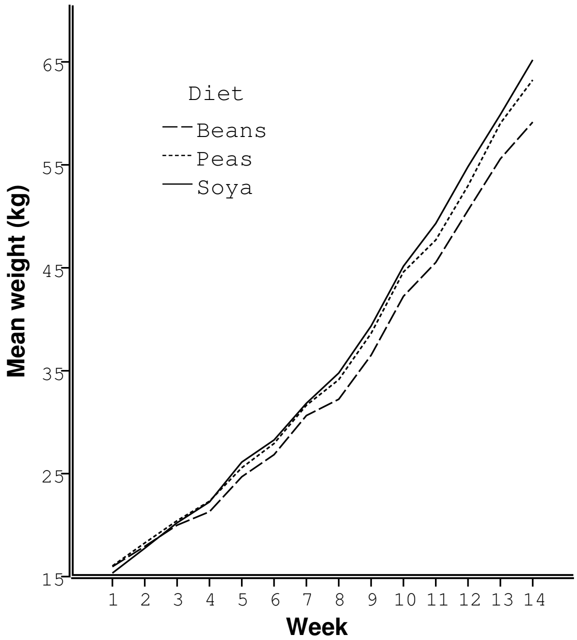

Figure 1. Growth curves depicting the mean pen weights of pigs, consisting of the pen means of both the summer and winter trials, on the control and treatment diets during the 13 week trial periods.

The results of the gastric health assessment in the abattoir showed that seven of the twelve pigs from the current study had no visible lesions, two pigs had evidence of parakeratosis indicative of early inflammation and three pigs had focal, shallow erosions. Six pig carcasses in the abattoir that were not included in the feeding trial and that had received a commercial organic pelleted feed were also examined for gastric lesions. Three of these carcasses had focal shallow erosions and three had diffuse or deep ulcerations. It should be noted that these cannot be treated as a direct control for the trial pigs as they had not been reared under the same management conditions, but they do provide a preliminary comparison for pigs on a commercial diet.

4. Discussion

During the pigs' grower phase (11–14 weeks of age), there were no significant differences between the daily live weight gains of pigs on rations containing soya, beans and peas. However, during the finisher phase (15–22 weeks of age), the pen mean daily live weight gain of the pigs on beans was significantly lower than that of the pigs on soya. During the finisher phase, no significant difference was observed between the growth performance of the pigs on the pea ration and those on the soya ration. However, in a practical context it is speculated that the slight shortfall in growth rate observed in the pigs fed the bean ration may be offset by the lower cost of production of beans in the UK. Overall, these results suggest that providing 100 per cent organic feed for pigs combining locally grown protein sources, particularly peas, as part of a lucerne silage-based ration is feasible, although further research to explore the use of these feeds with commercial pig breeds is required. Beans and peas may represent economically viable alternatives to soya, as they can be cheaper to grow than soya is to buy in the UK. However, a comprehensive assessment of the economic implications of replacing soya with peas and beans as part of a forage based ration for pigs is required.

The gastric health assessments in the abattoir suggest that TMR forage-based diets for pigs may be beneficial for gastric health. These preliminary findings are consistent with those of Kortelainen et al. [15] who conducted digestibility trials and suggested that grass silage could provide some available protein and other nutrients for growing pigs, and could prevent the development of gastric ulcerations. A trial is warranted to investigate these effects further by comparing forage-fed pigs to pigs fed a commercial grain-based ration under the same management conditions, in terms of gastric health.

Comparisons between the amounts of energy and nutrients provided by the TMRs per pig each day during this trial, and the daily nutritional requirements of the grower-finisher pigs, revealed a dietary deficiency in lysine throughout the trial in all diets. This is one of the main challenges in organic ration formulation, which may restrict the growth rate and feed conversion efficiency of pigs [26]. It is proposed that if this feeding system was utilised for conventional pigs, synthetic amino acids could be added to the TMR formulation to mitigate deficiencies.

During this trial, it was noted that as the pigs were occupied with foraging for the majority of their time, very low levels of aggressive and adverse behaviours were observed (Anna Wharton, University of Oxford, Oxford, UK. Conversation with Laura Higham, 27 January 2015.). These observations were made for the purposes of a separate study in three ten-minute blocks weekly, for the duration of the trial, using behavioural indices adapted from Andersen et al. [27] (Anna Wharton, University of Oxford, Oxford, UK. Conversation with Laura Higham, 27 January 2015.). Aggression in established groups can be caused by competition for food [28] and misdirected foraging behaviour towards pen mates [19]. These aggressive motives may be abated in this system by providing forage-based feed over a large floor area allowing synchronous feeding behaviour for most of the day, as well as manipulable bedding materials. In conjunction with the outcomes of the gastric health assessments, the behaviours observed in this study suggest that there may be positive welfare effects of providing forage-based rations for pigs.

The use of home- grown silage-based rations incorporating locally grown protein sources may be economically more efficient than purchasing commercial organic feeds for growing and finishing pigs. Work is required to evaluate the total cost of production of pigs on forage-based rations, taking in to account the necessary labour and equipment for preparing the rations. The observations in this study have been made despite differences in the crude protein intakes of pigs in the different groups. Future work including the effects of protein source and intake on carcass grades, back fat measurements and other carcass traits would be valuable.

In this paper, we discuss a number of potential welfare, environmental and economic ('3Es') benefits of a novel forage-based feeding system for organic pigs [9]. The use of Gloucester Old Spot pigs in a straw yard system demonstrates the feasibility of this feeding system for a traditional breed, which may be applicable to diversifying mixed or arable farms with a mixer wagon and suitable housing facilities. However, it is acknowledged that further work is required to explore the feasibility of this feeding system in commercial pig production facilities. This study could inform future research in the growth performance of pigs of commercial breeds fed forage-based rations, and to compare '3Es' outcomes of forage-based feeds and commercial, conventional rations. Future research may seek to compare the effect of the protein sources on weight gain by balancing the crude protein intakes, thereby providing isonitrogenous diets to the pigs in each group. In addition, work is required to further investigate the effects of forage-based rations on gastric health in pigs as part of a controlled trial.

5. Conclusions

In light of the environmental impacts of soybean production, increasing price and concerns for the future availability of soya, UK-grown grain legumes including peas and beans were hypothesized to offer sustainable alternatives as part of a TMR for pigs. A two-part trial in 2012 and 2014 was implemented in Oxford, UK, to test this hypothesis. Notwithstanding the limitations of the current feasibility study that utilises a traditional pig breed in a straw-based unit, results suggest that the inclusion of locally grown sources of protein, particularly peas, may be used to replace soya as part of a forage-based diet feeding strategy for organic pig production from 1 January 2018. This novel feeding strategy may be particularly of interest to farmers seeking options for diversification within mixed or arable farms with suitable facilities.

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