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The impact of agrivoltaics on crop production

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List of Abbrevations

ADFom	Acid detergent fibre (after ashing)
aNDFom	neutral detergent fibre (amylase-treated; after ashing)
ADL	Acid detergent lignin
APV	Agri-Photovoltaik
AV	Agrivoltaic
BBCH	Scale for phenological development stages of plants (ger. *Biologische Bundesanstalt für Land- und Forstwirtschaft, Bundessortenamt und Chemische Industrie*)
BMBF	German Ministry for Education and Research (ger. *Bundesministerium für Bildung und Forschung*)
C	Carbon
CAP	Common Agricultural Policy of the European Union
CC	Catch crop
DAP	Days after planting
DAS	Days after sowing
DM	Dry matter
EC	European Commission
EEG	Renewable energies act (ger. *Erneuerbare-Energien-Gesetz*)
FD	Full Density
Fig.	Figure
FiT	Feed-in Tarif
FM	Fresh matter
HD	Half Density
LAI	Leaf area index
MWh	Megawatt hour

N	Nitrogen
PAR	Photosynthetic active radiation
PPFD	Photosynthetic photon flux density
PV	Photovoltaic
REF	Reference
TDR	Time Domain Reflectory
UNECE	United Nations Economic Commission for Europe
VDLUFA	Association of German Agricultural Analytic and Research Institutes (ger. *Verband Deutscher Landwirtschaftlicher Untersuchungs- und Forschungsanstalten*)

Abstract

Facing the consequences of global warming and climate change, the reduction of greenhouse gas emissions is one of the most prior tasks of today's society and policymakers. To achieve this, energy generation is currently transformed towards a reduced utilization of fossil fuels and its replacement through an increased expansion of renewable energy sources. In this context, one challenge will be to spare land resources and diminish potential land use conflicts, in particular between food and energy production. An approach to accomplish this, can be the utilization of production-integrated technologies such as agrivoltaic systems (AV). Agrivoltaic systems are photovoltaic systems specifically adapted for its application in combination with agricultural production. For this, AV systems are installed above or on agricultural fields with certain technical adaptions, enabling agricultural production to be continued. First described in 1981, this approach was taken up in the early 2000s with first AV pilot systems being developed. In first experiments in South-France it has been shown, that through the combined utilization of agricultural land for food and energy production, AV can contribute to an increment of total land productivity. While electrical yields can be increased with an increasing density of the photovoltaic modules mounted above, the proportion of light available for the plants grown underneath and consequently also agricultural yields are reduced.

The aim of the present work was to examine, whether the results from these first experiments on crop production under AV can also be transferred to conditions in more moderate climates and also account for crops other than the so far investigated ones. The following four research objectives were defined: 1.) To what extent is plant-available radiation reduced by the solar panels of the AV system? 2.) How does this effect parameters of aerial and soil climate? 3.) How do the cultivated crops respond to the altered cropping conditions with regard to plant growth and development? 4.) Which consequences does this have regarding the yields and the chemical composition of the investigated crop-species?

In order to examine these research objectives, a field experiment has been established underneath an experimental AV pilot facility in Southwest-Germany, near Lake Constance. Four different types of crops (grass clover, potatoes, celery and winter wheat) have been selected and cultivated underneath the AV system and on an adjacent reference area for comparison within a two-year experiment. Various microclimatic parameters were recorded in a high-resolution monitoring including all investigated crops on both sites. Crop growth and development was monitored in regular intervals during vegetation period. The harvestable yields of both experimental sites, including crop-specific yield components, were recorded and partially supplemented with an analysis of chemical compounds.

The findings revealed, that photosynthetic active radiation below the AV system is reduced by about 30%, with slight fluctuations over the course of the day and year. At the same time, soil and air temperature was reduced in particular during spring and summer months, whereas soil moisture was reduced in particular during winter months. It has been shown, through the roofing with the PV panel, precipitation is unevenly distributed on the surface. Further measurements indicated that spatial variances, depending on the position in relation to the panels, are also conceivable for other microclimatic parameters, but additional investigations have to be awaited. As a consequence of the altered cultivation conditions, an increased vegetative growth was found in all investigated crop species, also leading to an increased vegetative biomass of celeriac and winter wheat at harvest. In the first year of the experiment, harvestable yields (potato tubers, celeriac bulbs and wheat grains) achieved below the AV system were reduced by 18-19% across all crop species, except for grass-clover, for which total cumulated yields of four cuts were only reduced by about 5%. In the second year, harvestable yields of potato tubers and celeriac bulbs increased by about 11-12%, while grain yields of winter wheat increased by about 3% underneath the AV system in comparison to the full-sun control. The cumulated yield of grass-clover was reduced by about 8%. However, it should be noted that not all of these findings were statistically significant. In addition, the calculation of the harvest yields is excluding yield losses resulting from the reduced cultivation area under AV due to the pillars of the supporting structure, which were estimated to be around 8%. The differences between the two trial years, with regard to the changes in harvestable yields, were ascribed to quite different climatic conditions within the two years. It is concluded, that in the hot and dry conditions of the year 2018, changes in microclimatic conditions under the AV system led to a reduction of crops' heat- and drought-related stress responses and thus, may have been beneficial for crop growth. With regard to the chemical composition, the found alterations were more dependent on the year and thus, could not be clearly attributed to the management under AV.

The results show, that crop production under an APV system is affected in several ways. Under the given climatic conditions, losses in harvestable yields as a consequence of a reduction of crop-available radiation are most likely. Exceptional years such as 2018 suggest however, that cultivation under AV can have advantages for crop production, in particular under dry and hot climatic conditions. In order to fully exploit this potential, the application of the APV thus seems to be most suitable for more dry climatic regions, whereby innovations and developments in AV technology as well as an improved water management can facilitate a further optimization. Regardless of this, potential conflicts of interest with regard to land use cannot be ruled out and require the integration of agrivoltaics in the existing legislation.

Zusammenfassung

Um der Erderwärmung und dem damit einhergehenden Klimawandel entgegen zu wirken, ist die Reduktion der Treibhausgasemissionen eines der vordringlichsten Ziele der aktuellen politischen Zielsetzung und zugleich gesamtgesellschaftliche Aufgabe. Als ein Baustein zum Erreichen dieses Ziels wird die Energieerzeugung sukzessive durch eine reduzierte Nutzung fossiler Energieträger und einen zugleich verstärkten Ausbau erneuerbarer Energiequellen umgestellt, um langfristig zu einer Reduktion der Treibhausgasemissionen beizutragen. Eine Herausforderung hierbei ist, die mit diesem Ausbau einhergehenden Flächenverluste auf ein Mindestmaß zu reduzieren und mögliche Flächenkonflikte, insbesondere zwischen Energie- und Nahrungsmittelproduktion, zu vermindern. Eine mögliche Maßnahme, um dies auch auf landwirtschaftlichen Flächen zu erreichen, kann die Nutzung produktionsintegrierter Technologien wie der Agri-Photovoltaik (APV) sein. Die Agri-Photovoltaik beschreibt speziell entwickelte Photovoltaikanlagen, welche über oder auf landwirtschaftlichen Nutzflächen installiert werden und durch spezifische technische Modifikationen eine Weiterführung der landwirtschaftlichen bzw. ackerbaulichen Produktion unter der Anlage ermöglichen. Erstmals im Jahr 1981 beschrieben, wurde dieser Ansatz Anfang der 2000er Jahre aufgegriffen und erste APV-Pilotanlagen entwickelt. In ersten Versuchen in Südfrankreich konnte dabei gezeigt werden, dass durch die kombinierte Nutzung der landwirtschaftlichen Flächen für die Energie- und Nahrungsmittelproduktion, die APV zu einer Steigerung der Flächenproduktivität beitragen kann. Während die Stromerträge mit steigender Dichte der Photovoltaikmodule zunahmen, sanken zugleich der Anteil des für die Pflanzen verfügbaren Lichts und damit auch die landwirtschaftlichen Erträge.

Ziel der vorliegenden Arbeit war zu untersuchen, wie sich diese Ergebnisse aus ersten Anbauversuchen unter APV-Anlagen auch auf die Anbaubedingungen in gemäßigteren Klimaten sowie auf weitere landwirtschaftliche Kulturen übertragen lassen. Die folgenden vier Versuchsfragen wurden definiert: 1.) In welchem Umfang wird die pflanzenverfügbare Sonneneinstrahlung durch die Solarpanele der APV-Anlage reduziert? 2.) Inwiefern werden dabei auch luft- und bodenklimatische Parameter beeinflusst? 3.) Wie reagieren die angebauten Kulturarten auf die veränderten Anbaubedingungen im Hinblick auf das Pflanzenwachstum und die Pflanzenentwicklung? 4.) Welche Folgen hat dies auf die landwirtschaftlichen Erträge sowie die ausgewählten Qualitätsparameter?

Zur Untersuchung dieser Versuchsfragen wurde im Jahr 2016 auf einer Praxisfläche ein landwirtschaftlicher Feldversuch unter einer APV-Pilotanlage im Südwesten Deutschlands, Nahe des Bodensees, angelegt. Um die Auswirkungen auf verschiedene Kulturarten zu untersuchen, wurden für den Versuch vier verschiedene Kulturarten (Kleegras, Kartoffeln, Sellerie und Winterweizen) ausgewählt und in zwei Versuchsjahren unter der Anlage sowie auf

einer nahegelegenen Vergleichsfläche ohne APV-Anlage angebaut. In einem engmaschigen, alle Kulturen auf beiden Flächen umfassenden Monitoring wurden verschiedene mikroklimatische Parameter erfasst. Die Pflanzenentwicklung wurde während der Vegetationsperiode in regelmäßigen Abständen bonitiert. Auf beiden Versuchsflächen wurden die Ernteerträge und kulturspezifische Ertragsparameter erfasst und in Teilen durch eine Analyse der Inhaltsstoffe ergänzt.

Die Ergebnisse der Studien zeigten, dass die photosynthetisch aktive Strahlung unterhalb der APV-Anlage um rund 30% abgeschwächt ist, mit leichten Schwankungen im Tages- und Jahresverlauf. Zugleich waren auch Boden- und Lufttemperatur, insbesondere während der Frühjahres- und Sommermonate, verringert, wohingegen die Bodenfeuchtigkeit vor allem während der Wintermonate unter der Anlage niedriger lag. Die Niederschläge verteilen sich durch die Überdachung mit den PV-Panelen ungleichmäßig auf der darunterliegenden Fläche. Dabei bleibt zu klären, inwiefern auch weitere Faktoren wie die Sonneneinstrahlung oder die Bodenfeuchte eine ungleichmäßige Verteilung unterhalb der Anlage aufweisen. Infolge der veränderten Anbaubedingungen zeigte sich bei allen untersuchten Kulturen ein verstärktes Wachstum der oberirdischen vegetativen Biomasse. Im ersten Versuchsjahr waren die unterhalb der Anlage erzielten Ernteerträge (Knollenertrag bei Sellerie und Kartoffeln, Kornertrag bei Winterweizen und Biomasseertrag bei Kleegras) über alle Kulturen hinweg um 18-19 % erniedrigt. Ausgenommen hiervon ist Kleegras, bei welchem der über vier Schnittzeitpunkte kumulierte Gesamtertrag nur um rund 5% erniedrigt war. Im zweiten Versuchsjahr waren die Ernteerträge von Kartoffel- und Sellerieknollen um rund 11-12 %, der Kornertrag beim Winterweizen rund 3 % höher unter der APV-Anlage. Der Kleegrasertrag lag um rund 8 % niedriger. Zu erwähnen ist, dass nicht alle dieser Veränderungen statistisch signifikant waren. Unberücksichtigt bei der Berechnung der Ernteerträge sind Ertragseinbußen, welche infolge der Flächenverluste für die Aufständerung der APV-Anlage auftreten und im Versuch rund 8% der landwirtschaftlichen Nutzfläche ausmachten. Die Unterschiede zwischen den beiden Versuchsjahren im Hinblick auf die Ertragsveränderungen durch die APV-Anlage wurden auf die unterschiedlichen klimatischen Bedingungen in den beiden Jahren zurückgeführt. Im Jahr 2018 haben die heißen und trockenen Bedingungen mutmaßlich dazu geführt, dass die veränderten mikroklimatischen Bedingungen unter der APV-Anlage zu einer Verminderung hitze- und trockenstress assoziierter Stresserscheinungen geführt haben und damit Vorteile für das Pflanzenwachstum brachten. Im Hinblick auf die chemische Zusammensetzung konnten in Anbetracht der unterschiedlichen Versuchsjahre keine Veränderungen eindeutig auf die Bewirtschaftung unter der APV zurückgeführt werden.

Die Ergebnisse zeigen, dass die APV-Anlage einen deutlichen Einfluss auf die Bewirtschaftung unter der Anlage hat. Unter den gegebenen klimatischen Bedingungen sind dabei Ertragseinbußen infolge der verminderten Sonneneinstrahlung am wahrscheinlichsten.

Ausnahmejahre wie das Jahr 2018 zeigen jedoch, dass der Anbau unter einer Anlage insbesondere unter trockenen und heißen Bedingungen Vorteile für die pflanzenbauliche Nutzung haben kann. Um dieses Potential voll auszuschöpfen bietet sich die Anwendung der APV insbesondere für trockenere Klimaregionen an, wobei eine Weiterentwicklung der APV-Technik sowie ein verbessertes Wassermanagement dazu beitragen können, dieses weiter zu optimieren. Ungeachtet dessen sind etwaige Zielkonflikte im Hinblick auf die Flächennutzung nicht auszuschließen und bedürfen der expliziten Regelungen zur Agri-Photovoltaik in der vorhandenen Gesetzgebung.

1. General Introduction

Given the impacts of climate change, the United Nations declared in the Paris Agreement in 2015 to limit global warming to below 2°C, preferably 1.5°C, compared to pre-industrial levels [1]. To meet this goal, several countries and continents followed with their own targets since then. In its climate & energy framework, the European Union targets at a reduction of greenhouse gas emissions by at least 40% compared to the levels in 1990, as well as to increase the share of renewable energies on total energy production to at least 32% in 2030 [2]. By 2050, net emission of greenhouse is intended to be zero according to the European Green Deal [3]. In 2018, 35.1% of renewable-based energy in Europe was generated by hydropower, followed by wind power (35%), biomass (17.5%) and solar energy (11.4%) [4]. In Germany in contrast, the most important renewably energy sources on total renewable energy production were wind power (48.9%), biomass (22.6%) and solar energy (20.4%), while only 8% of total renewable energy production was obtained from hydropower [5]. However, the expansion of renewable energies also requires large portions of land and is concerned to affect food security, too, as the ongoing food vs. fuel controversy has shown, which found its peak after the food crisis in 2008 [6,7]. Although direct coherences between energy production and food security are more complex and still being discussed [7], concerns about the land use conflict between food and energy production are reasonable given a present and prospective land scarcity, in particular in developed countries, where arable land has been continually declining during the last decades [8]. It is assumed, that land scarcity will further increase in future, driven by several factors like an increasing demand of a growing world population after food and animal-based products, as well as the loss of agricultural land through soil degradation [9]. It is estimated, that 45,000 km² of arable land each year will be lost until 2050, solely through soil erosion [10]. At the same time, overall food production has to be increased by about 70% until 2050 to meet the global demand [11]. In Germany, today only 22% of overall agricultural area is used for food production, while 60% is occupied for fodder production and 16% by energy and industrial crops (Fig. 1) [12]. Furthermore, agricultural land in Germany decreased by more than 6.500 km² in the last 15 years, in particular through the expansion of traffic and settlement area [13]. In its National Sustainable Development Strategy, the German government targets to restrict the daily increase of traffic and settlement area (which also includes e.g. the construction of ground-mounted PV facilities) to less than 30 ha until 2030, until a “no net land take” is achieved in 2050 according to European and German national policy [14,15]. A target which will become challenging considering the fact, that it is estimated, that, depending on the scenario and the mix of renewable energies, up to 2% of the European land will be required to meet the goal of 100% renewable energy supply in Europe [16]. In general, land consumption for renewable energy production is strongly dependent on the energy source [6]. Power from wind energy is considered to have the lowest impact on land use with less than 1.3m² required per generated megawatt hour (MWh), followed by hydropower and photovoltaics with less than 17m²/MWh [6]. In addition, photovoltaics and on-shore wind energy today are considered to be the most competitive renewable energy sources, even in comparison with fossil energy sources [17]. In Germany, the expansion of on-shore wind power generation has been declining in the last years, whereas power generation from solar energy is increasing [4].

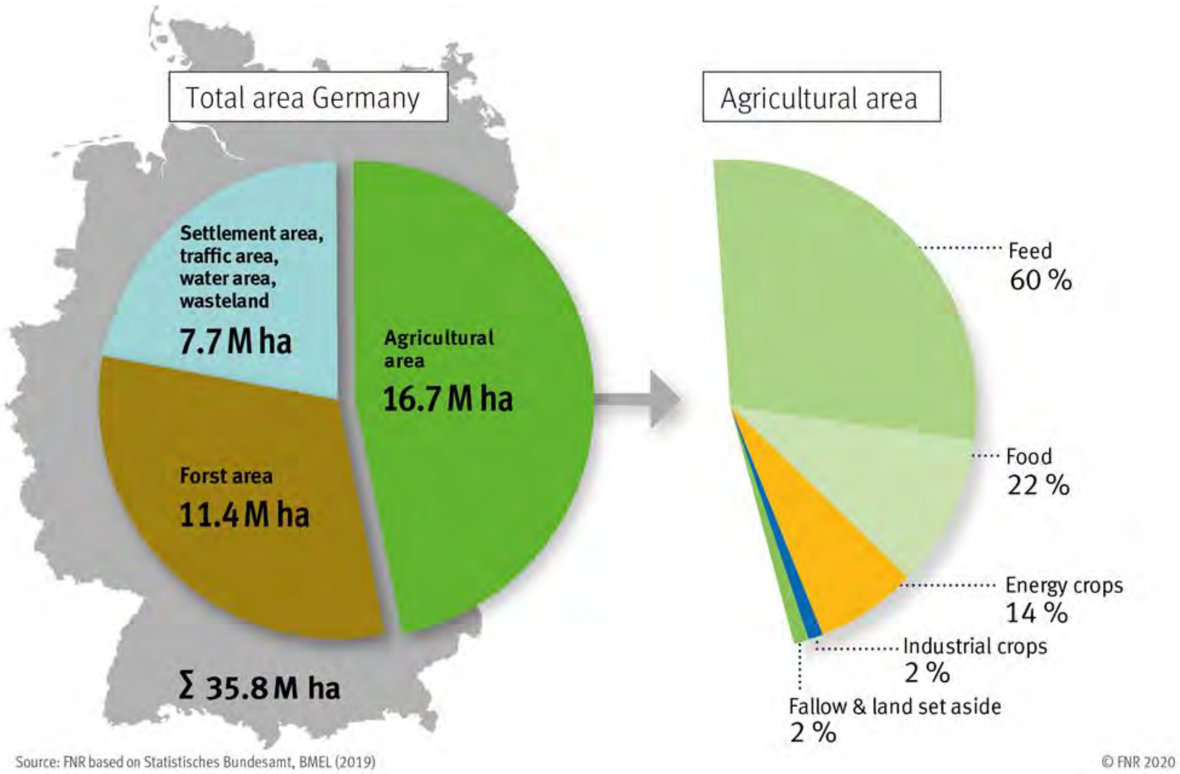

Figure 1: Land use in Germany in 2019 and the share of different crops at overall agricultural area [12]

Although the land-use footprint of photovoltaics is considered to be comparatively low, its expansion has also led to the installation of large ground-mounted photovoltaic (PV) facilities on agricultural land. In Germany, this has led to an adjustment of legal regulations in the past, so that from 2010 to 2014, the expansion of PV was no longer promoted by the renewable energies act (EEG) [18]. Since then, the EEG has been re-imposed, enabling PV facilities to be constructed on arable land again, e.g. if located next to transportation infrastructure, as well as on areas unfavorable for agricultural production in some federal states [18,19]. Correspondingly, a certain trade-off arises between the aims of expanding renewable energy supply, while at the same time preserving land resources and conserving agricultural land. A conflict, which will further aggravate in future, emphasizing the need for concepts to meet these targets.

1.1. From concept to application – the development of agrivoltaic systems

The impact of solar systems on land use can be reduced by different strategies like the utilization of degraded land or by its integration or co-location into existing structures [6]. Already in 1982, Goetzberger and Zastrow [20] proposed to integrate solar collectors into agricultural production to increase land benefit (Fig. 2). Based on calculations, they assumed that lifting the modules at a height of 2m with a row distance of 3m in-between, should be sufficient to obtain two thirds of solar radiation available for the crops grown underneath, while at the same time, only one third of arable land is lost for energy production [20]. The authors were undoubtedly ahead of time, taking into consideration, that at the time the study of Goetzberger and Zastrow has been published, PV technology was still at very early stage with first commercial large-scale PV projects just to be taken into operation.

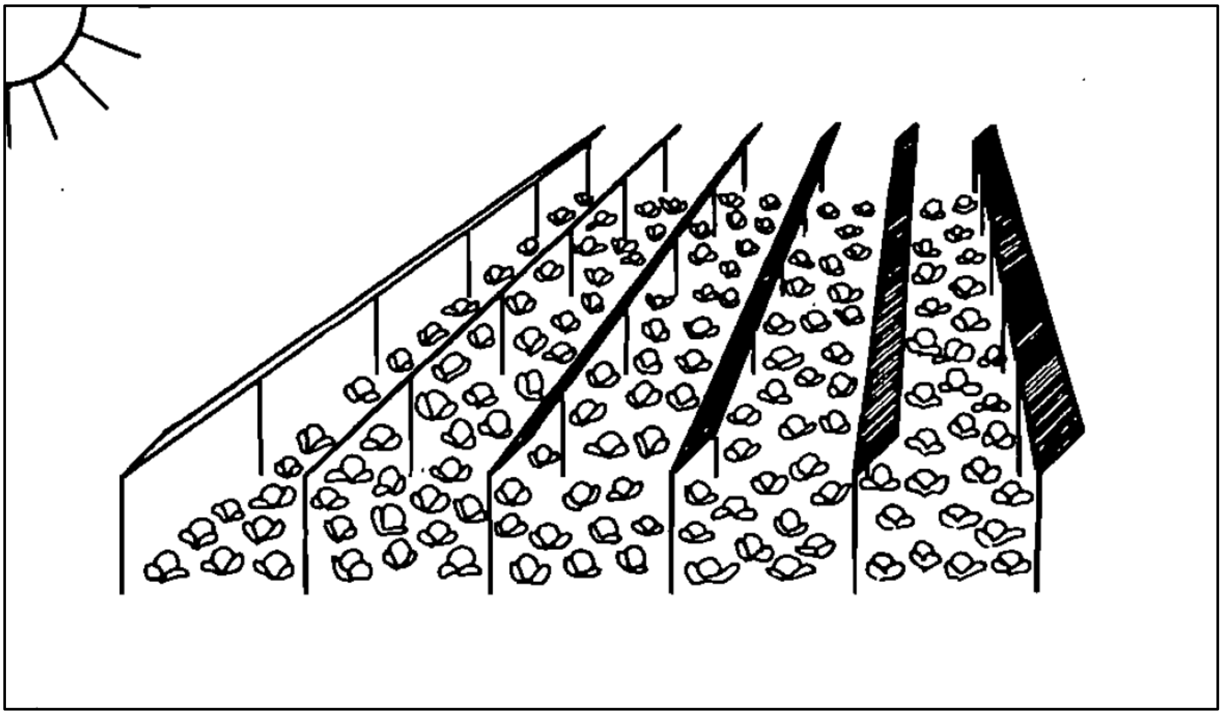

Figure 2: First draft of an AV system from the year 1982. (source: Goetzberger and Zastrow [20])

Consequently, potential land use trade-offs between solar energy and food production were not yet part of a broad social debate, though already being discussed as quoted by Goetzberger and Zastrow [20]. And so, it took more than two decades until this approach was readopted. In 2004, pioneers in Japan began to overbuild farmland with PV modules in first pilot projects (referred to as solar sharing). They concluded, that at a shading rate of 32%, sufficient crop yields can be obtained [21]. In the following, such dual-use systems, combining PV power and agricultural production, will be denoted as agrivoltaic (AV) systems, which is the most established term in anglophone, scientific literature. Depending on the region, further terms like Solar Sharing (Japan), Agrophotovoltaik or more recent Agri-Photovoltaik (Agri-PV or APV) (Germany) as well as Agrivoltaico (Italy) are common.

To study the impacts of AV on crop production scientifically, a first AV research facility was installed in 2010 at the French National Institute of Agricultural Research (INRA) near Montpellier in South France. To examine how microclimate and further also crop growth and development are affected by different shading rates through the modules mounted above, the PV modules of the AV facility were installed in two different densities (full density, FD; half density, HD) [22]. In a first simulation study, the scientists demonstrated that through combined crop and energy production under AV, land productivity can be increased by 35 to 73% in comparison to sole energy and crop production [22]. Furthermore, the simulations predicted that both, crop available radiation and correspondingly crop yield is reduced underneath the AV system. With decreasing module density, predicted reductions of crop available radiation and crop yields were less pronounced, while at the same time less power is generated by the mounted PV system [22]. In a follow-up study, the predicted results were verified in a practical field trial which was conducted in the years 2010 and 2011. Various parameters like microclimate, crop growth dynamics and yields were assessed [23–25]. The measurements confirmed, that crop-available radiation is reduced by 30% and 50% respectively, depending on PV module density. In addition to reduced light incidence, also microclimatic conditions were altered by AV [24]. They assumed that under the dry climate of the Mediterranean region, climatic stress for the crops may be reduced under AV by an improved water use efficiency [23]. Both crop growth and morphology (e.g. leaf size and thickness) were altered by AV, with slight differences between the investigated crop species, which were cucumber, lettuce and wheat [24]. Lettuce yields in the two years ranged from 58-79% (PV modules in full density) to 81-99% (half density) of the unshaded control [25]. Apart from year-effects, the results also differed between the cultivated lettuce varieties, which was linked to different shade-adaptive strategies.

1.2. Aims of the thesis

The experiments in Montpellier gave a first important insight into how crop production is affected by AV. However, before being implemented in practice, further experiments are needed to examine more in-depth, how different crops are affected by the cultivation underneath the solar panels of AV facilities, in particular under temperate climatic conditions. For this purpose, an AV research facility was installed in 2016 on a field of the farm community Heggelbach, which is placed in Herdwangen-Schönach in the region Lake Constance Upper Swabia (ger. *Bodensee-Oberschwaben*) in the north-west of Lake Constance. The study was embedded in the project APV Resola, funded by the German Ministry for Education and Research (BMBF), which had the aim to fully assess the implementation of AV technology including its technical and economic viability, its societal acceptance and its impact on agricultural practice. For this purpose, a multidisciplinary project-consortium of scientists and practitioners with an expertise on these topics was involved. The objective of the present study was to examine, how climatic and microclimatic conditions are altered underneath the AV facility, as well as how the cultivation of different crops is affected. The following research questions were formulated:

1.) To what extent is crop available radiation reduced underneath the solar panels of the AV installation?

2.) Does the PV canopy also affect aerial and soil microclimatic parameters?

3.) How do different crops cope with the altered conditions and how does this affect crop growth and development?

4.) Which consequences does this have on harvestable crop yields and on selected quality parameters?

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2. Examination of the effects of AV on crop production

The aim of this section is to report how agricultural practice and in particular the production of food and fodder crops is affected by the cultivation underneath agrivoltaic systems. The section consists of three peer-reviewed publications. In the first publication (section 2.1), the current state of art of AV technology and research is reported. To further ponder how crop production, or more precisely, crop growth and consequently crop yields and selected quality characteristics may be affected, the results of different experimental shading studies are consulted, summarized and discussed. In the second and third publication (sections 2.2 and 2.3), the results of a first experimental AV field trial in Germany are reported. The field experiment was located in Herdwangen-Schönach, in the region Lake Constance Upper Swabia in Southwest Germany. The on-farm experiment was conducted under practical conditions on a farm managed according to the principles of organic farming. Overall, four different crops (celeriac, grass-clover, potatoes and winter wheat) have been cultivated within a crop rotation. The second publication (section 2.2) addresses the impacts of AV on growth, yield and quality characteristics of celeriac, while the results on microclimatic alterations through AV as well as on crop performance and yield of the three other crops investigated in the field trial are presented and discussed in the third publication (section 2.3). The three publications integrated in this chapter are:

- Section 2.1:

  Weselek, A., Ehmann, A., Zikeli, S., Lewandowski, I., Schindele, S., Högy, P. Agrophotovoltaic systems: applications, challenges, and opportunities. A review. *Agron. Sustain. Dev.* **39,** 35 (2019). https://doi.org/10.1007/s13593-019-0581-3

- Section 2.2:

  Weselek, A.; Bauerle, A.; Zikeli, S.; Lewandowski, I.; Högy, P. Effects on Crop Development, Yields and Chemical Composition of Celeriac (*Apium graveolens* L. *var. rapaceum*) Cultivated Underneath an Agrivoltaic System. *Agronomy* **2021**, *11*, 733. https://doi.org/10.3390/agronomy11040733

- Section 2.3:

  Weselek, A.; Bauerle, A.; Hartung, J.; Zikeli, S.; Lewandowski, I.; Högy, P. Agrivoltaic system impacts on microclimate and yield of different crops within an organic crop rotation in a temperate climate. *Agron. Sustain. Dev.* **2021**, *41*, 59, https://doi.org/10.1007/s13593-021-00714-y

2.1. Agrophotovoltaic systems: applications, challenges and opportunities. A review.

In this section, the current state of art of AV systems at the time the study was started, is being reported. For this purpose, an overview of worldwide existing AV facilities (including its technical specifications and application fields) as well as the results from experimental and theoretical studies on the topic of AV are presented. To discuss the potential impacts of AV on crop production in spite of very few experimental AV studies, these are complemented with the results from studies with comparable climatic conditions. In accordance with the results from first AV field experiments, a reduction of crop-available radiation is assumed to be most limiting for crop productivity. Thus, particularly studies dealing with the effects of shading on crop production (growth and development, yields and quality) of different crop species have been selected and summarized to identify crops which are potentially suited for the cultivation under AV. Furthermore, also technical innovations and conceivable adaptions in the design of AV facilities to improve the agronomic and electrical performance are presented and discussed. Correspondingly, this section addresses research questions 1 to 4, albeit on a more theoretical level with indications taken from literature, with the aim to present and discuss the current state of art as basis for the experimental studies presented in section 2.2 and 2.3.

This section has been published in *Agronomy for Sustainable Development* (accessible online at https://link.springer.com/article/10.1007/s13593-019-0581-3) as:

Weselek, A., Ehmann, A., Zikeli, S., Lewandowski, I., Schindele, S., Högy, P. Agrophotovoltaic systems: applications, challenges, and opportunities. A review. *Agron. Sustain. Dev.* **39,** 35 (2019). https://doi.org/10.1007/s13593-019-0581-3

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REVIEW ARTICLE

Agrophotovoltaic systems: applications, challenges, and opportunities. A review

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Abstract
The expansion of renewable energies aims at meeting the global energy demand while replacing fossil fuels. However, it requires large areas of land. At the same time, food security is threatened by the impacts of climate change and a growing world population. This has led to increasing competition for limited land resources. In this context, the combination of photovoltaics and plant production — often referred to as agrophotovoltaic (APV) or agrivoltaic systems — has been suggested as an opportunity for the synergistic combination of renewable energy and food production. Although this technology has already been applied in various commercial projects, its practicability and impact on crop production have hardly been investigated. In this review, we give a short summary of the current state of the art and prospective opportunities for the application of APV systems. In addition, we discuss microclimatic alterations and the resulting impacts of APV on crop production. Our main findings are that (1) crop cultivation underneath APV can lead to declining crop yields as solar radiation is expected to be reduced by about one third underneath the panels. However, microclimatic heterogeneities and their impact on crop yields are missing reference and thus, remain uncertain. (2) Through combined energy and crop production, APV can increase land productivity by up to 70%. (3) Given the impacts of climate change and conditions in arid climates, potential benefits are likely for crop production through additional shading and observed improvements of water productivity. (4) In addition, APV enhances the economic value of farming and can contribute to decentralized, off-grid electrification in developing and rural areas, thus further improving agricultural productivity. As such, APV can be a valuable technical approach for more sustainable agriculture, helping to meet current and prospective needs of energy and food production and simultaneously sparing land resources.

Keywords Agrophotovoltaic · Agrivoltaic · Photovoltaics · Crop production · Microclimate · Agricultural yields

Contents

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1 Introduction

The development of renewable energy sources as a means of meeting the global energy demand and simultaneously replacing fossil fuels as one of the key drivers of climate change has become one of the major societal challenges of our time. In this context, photovoltaic (PV) systems offer great potential and are considered even more efficient in capturing sunlight energy than photosynthesis (Blankenship et al. 2011). This, and the fact that the installation of these systems on open areas is the lowest cost option (Fraunhofer ISE 2015), has also led to PV systems being established on agricultural land. However, this can result in a land-use conflict between energy and food production, and can be of major concern especially in regions with limited land area or a dense population. The extensive installation of large-scale ground-mounted PV facilities has led to dwindling societal acceptance in some regions and increasing concerns about the loss of arable land for more profitable PV energy production (Nonhebel 2005). In view of this conflict, the development of agrophotovoltaic (APV) systems can be seen as a way of combining PV and food production on the same land area (Fig. 1). The concept of APV was introduced by Goetzberger and Zastrow (1982) more than three decades ago. Recently, several commercial APV plants and small-scale research facilities have been established around the world (Obergfell et al. 2017). As demonstrated by several studies, APV can increase land productivity (Dupraz et al. 2011a; Elamri et al. 2018; Valle et al. 2017). It thus offers great potential as a resource-efficient, co-productive renewable energy system in regions with dense populations or limited land area, such as mountainous regions and islands (Dinesh and Pearce 2016). However, its highest potential is anticipated in semi-arid and arid regions, where various synergistic side effects can be expected (Marrou et al. 2013a; Ravi et al. 2016). Here, crop cultivation often suffers from the adverse effects of high solar radiation and concomitant water losses. Water use efficiency has been shown to increase underneath the panels in PV installations (Hassanpour Adeh et al. 2018), and similar results have been observed in APV systems (Elamri et al. 2018; Marrou et al. 2013a). These findings are becoming even more relevant, as water demand for irrigation is expected to increase in prospective future climatic conditions (Elamri et al. 2018; Hannah et al. 2013). In addition to improved water productivity, crops cultivated in arid climates may also directly benefit from the reduction in solar radiation through the PV panels (Harinarayana and Vasavi 2014). Besides its impacts on crop production, the implementation of APV enhances the profitability of farming by generating additional income through energy production (Dinesh and Pearce 2016; Malu et al. 2017) and further may improve rural, off-grid electrification as part of decentralized energy systems (Burney et al. 2010; Harinarayana and Vasavi 2014; Malu et al. 2017; Silva Herran and Nakata 2012). Therefore, APV can be an important component of future renewable energy production systems, while simultaneously ensuring food production and the economic viability of agriculture (Dinesh and Pearce 2016). However, regarding the land-use conflict, the actual value of APV as combined food and energy production system requires a clear demarcation from primarily energy producing PV systems by maintaining a sufficient crop productivity. First field experiments addressing the utilization of this technology and its impact on crop cultivation have shown that the land use efficiency of combined PV and food-crop systems can be improved compared to separate production (Dupraz et al. 2011a; Marrou et al. 2013c). Electrical yield and economic profit can be enhanced by increasing the PV module density, which simultaneously reduces crop-available radiation (Dupraz et al. 2011a). This emphasizes the importance of finding an appropriate relation between food and energy production. The impact of APV on crop

Fig. 1 Potatoes growing underneath an APV facility. The facility was set up within the project APV RESOLA and is located at Heggelbach, administrative district of Sigmaringen, Germany. Its implementation in agricultural production is currently investigated (source: University of Hohenheim)

development and performance is inevitable, but has so far only been scientifically investigated for a small number of crop species, such as lettuce, cucumber and durum wheat (see e.g. Marrou et al. 2013c). This shows the necessity for further research. This review paper summarizes existing literature on APV systems and gives a general overview of the APV technology with present-day application examples, recent developments and prospective application areas. First reports on experiences with crop production in APV systems are analysed with the aim of assessing current knowledge on APV and the effects of shading on crop production. In addition, we discuss various technical and agronomic aspects of APV systems, focusing in particular on their impact on microclimate and crop production to evaluate their applicability in agricultural food production.

2 Agrophotovoltaic systems: application and current status

2.1 The concept of APV

The concept of agrophotovoltaics (APV) was initially proposed in the year 1982 by Goetzberger and Zastrow as a means of modifying solar power plants to enable additional crop production on the same area. Their idea was to raise the solar collectors to 2 m above the ground and increase the spacing between them to avoid excessive shading of the crops. They assumed that these systems would only require one third of the incoming radiation and that further technical improvements could increase their suitability for application in crop production. It took about three decades until this concept, referred to as agrophotovoltaic, agroPV, agrivoltaic or solar sharing, was implemented in various projects and pilot plants worldwide. Calculations have shown that the application of this technical approach can increase farms' incomes by over 30%, if yield losses through shading effects are minimized by the selection of suitable crops (Dinesh and Pearce 2016). Dupraz et al. (2011a) applied the Land Equivalent Ratio (LER), a method of evaluating the productivity of an intercropping system in comparison to a single-crop cultivation system (Mead and Willey 1980), to determine the advantages of a dual-use APV system over a single-crop and PV production. Their simulations revealed that overall land productivity can be increased by up to 70% in APV systems. In a recent modelling study addressing biogas maize production, Amaducci et al. (2018) showed that renewable-energy land productivity can be even doubled by APV compared to the separate production of maize and energy with ground-mounted PV modules. In 2010, Dupraz et al. (2011a) set up an APV test facility to validate their assumptions. In order to find a well-balanced combination of food and energy production, they tested two different densities of PV modules. While PV yield increased with panel density (Dupraz et al. 2011a), the optimum conditions for simultaneous crop production were found under less dense PV modules (Marrou et al. 2013c). The solar panels were raised to 4-m clearance height to allow common agricultural machinery to pass underneath. A number of studies on crop cultivation between ground-mounted PV rows designate such systems as agrivoltaic (Hassanpour Adeh et al. 2018; Santra et al. 2017). However, in this review, we make a clear distinction between ground-mounted PV systems and our definition of APV, where the PV facility is lifted off the ground and further adapted to meet the requirements of sufficient crop production underneath.

The technical features of APV systems are steadily being refined and vary between regions and companies. Some APV projects already use mobile PV modules that enable solar tracking. These maximize photovoltaic yield and at the same time improve light availability allowing sufficient crop growth (Valle et al. 2017). This approach has recently been investigated by Valle et al. (2017) with 1-axis orientable PV systems and different tracking settings. They showed that the performance of both energy and crop production can indeed be further increased by the application of dynamic PV modules. In the regular solar-tracking mode, the modules automatically adjusted to the solar altitude, optimizing electricity generation and also increasing solar radiation at plant level compared to fixed PV modules (Valle et al. 2017). To increase the radiation transmitted to the crop and thus further improve its productivity, Valle et al. (2017) also tested a controlled tracking mode incorporating diurnal changes in solar radiation. In the morning and late afternoon hours, the position of the photovoltaic panels was altered to reduce crop shading, whereas at solar noon, shading was increased to reduce evapotranspiration and adverse effects of high temperature and excessive radiation on plant growth. As a result, crop biomass increased under controlled tracking, but electricity production declined compared to the regular solar-tracking mode (Valle et al. 2017). Solar tracking technology has already been implemented in various commercial APV facilities (Table 1; see also in Section 2.2) and recently also been investigated in PV greenhouses (Li et al. 2018). However, the extent of radiation available underneath the APV array is affected more by panel density than by panel mobility (Amaducci et al. 2018). In addition to improving light-use efficiency for both PV and crop production, mobile PV panels can also be used to improve rainfall distribution underneath APV systems (Elamri et al. 2017; see also in Section 2.3.1). The incorporation of the APV concept has recently also been considered in cropping systems such as viticulture and in intensive fruit production, where the utilization of supporting structures is already common practice and synergistic effects may exist (Sun'Agri 2018). A study modelling the APV potential of Indian grape farms revealed that the annual income of these farms could be multiplied compared to conventional farms without APV, while still maintaining

Table 1 Overview of existing APV facilities with technical specifications and crops cultivated underneath. The numbers in the first column correspond to those in Fig. 2

No.	Location	Country	Electricity yield [kWh a^{-1}]	Capacity [kWp]	Solar tracking	Cultivated crops	Source
Commercial facilities							
1	Monticelli D'Ongina	Italy	4,842,000	3230	Yes	Winter wheat, maize	Praderio and Perego (2017); Rem Tec (2017a)
2	Castelvetro	Italy	1,890,000	1294	Yes	Winter wheat, maize	Praderio and Perego (2017); Rem Tec (2017a)
3	Virgilio	Italy	3,325,000	2150	Yes	Winter wheat, maize	Praderio and Perego (2017); Rem Tec (2017a)
4	Abruzzo	Italy	Unknown	800	Yes	Pasture, tomato, watermelon, wheat	Corditec (2017)
5	Anhui province	China	887,000	544	Yes	Unknown	Rem Tec (2017a) (Rem Tec 2017b)
6	Zhejiang province	China	40,000,000	30,000	Yes	Rice	Tonking New Energy (2018)
Research facilities							
7	Arizona	USA	Unknown	Unknown	No	Cabbage, chard, kale, tomato, onion	Tricoles (2017)
8	Montpellier	France	Unknown	Unknown	Partly	Cucumber, durum wheat, French bean, lettuce	Marrou et al. (2013b); Valle et al. (2017)
9	Heggelbach	Germany	244,401	194	No	Winter wheat, clover grass, celeriac, potato	Authors' project
10	Santiago de Chile	Chile	21.437	Unknown	No	Various cabbage varieties (broccoli, cauliflower, kale), potato, pumpkin	Fraunhofer Chile Research (2017b); Fraunhofer Chile Research (2017c)
11	Chiba Prefecture	Japan	35,000	Unknown	No	Cabbage, cucumber, eggplant, peanut, tomato, taro, yam	Movellan (2013)

grape yields (Malu et al. 2017). Extrapolating to nationwide scale (i.e. taking the entire Indian grape cultivation area of about 34,000 ha into consideration), Malu et al. (2017) calculated an APV output of 16,000 GWh, enough to meet the energy demand of more than 15 million people.

The most promising potential of APV systems can be expected in arid regions where various synergistic effects may occur. Crop production may benefit from increased water savings by reduction in evapotranspiration and adverse effects of excessive radiation, while economic viability is increased and rural electrification is made possible (Majumdar and Pasqualetti 2018; Ravi et al. 2016). As Amaducci et al. (2018) have shown, reduced soil evaporation under APV may also diminish yield losses in dry years and improve yield stability.

2.2 Existing projects and technologies

Several commercial and research APV facilities have been realized in the last few years (Fig. 2; Table 1). From 2004 onwards, a number of small-scale APV plants have been built in Japan (Movellan 2013). These systems, referred to as 'solar sharing', consist of PV panels mounted on poles with a 3-m ground clearance. They combine solar energy production with the cultivation of various local food crops such as peanuts, yams, eggplants, cucumbers, tomatoes, taros and cabbages. A few APV projects have also been implemented in Europe in recent years. In addition to several research facilities in France and Germany, three commercial APV projects, patented as 'Agrovoltaico', have been realized in North Italy. The installed systems have capacities of up to 1500 kWp using mounted solar modules (4–5 m height) with solar-tracking technology (Casarin 2012; Rem Tec 2017a). Another APV field in Abruzzo uses 67 stand-alone solar trackers with various crops such as tomatoes, watermelons and wheat grown underneath and generates a total output of 800 kWp (Corditec 2017).

The first pilot APV research facility in the South of France was divided into two subsystems with different PV panel densities to investigate the effect on solar distribution and energy yield (Dupraz et al. 2011a). In a follow-up study, Marrou et al. (2013a) performed a field trial with four lettuce varieties to confirm simulated results. They investigated the impact of APV systems on growth, morphology, yield and microclimatic conditions. To test its applicability in crop rotations, further species including cucumber, French bean and durum wheat were cultivated. In their experiments, the authors used an APV system with fixed mounted solar panels. Marrou et al. (2013a) suggested that further improvements in crop and PV performance might be achieved using

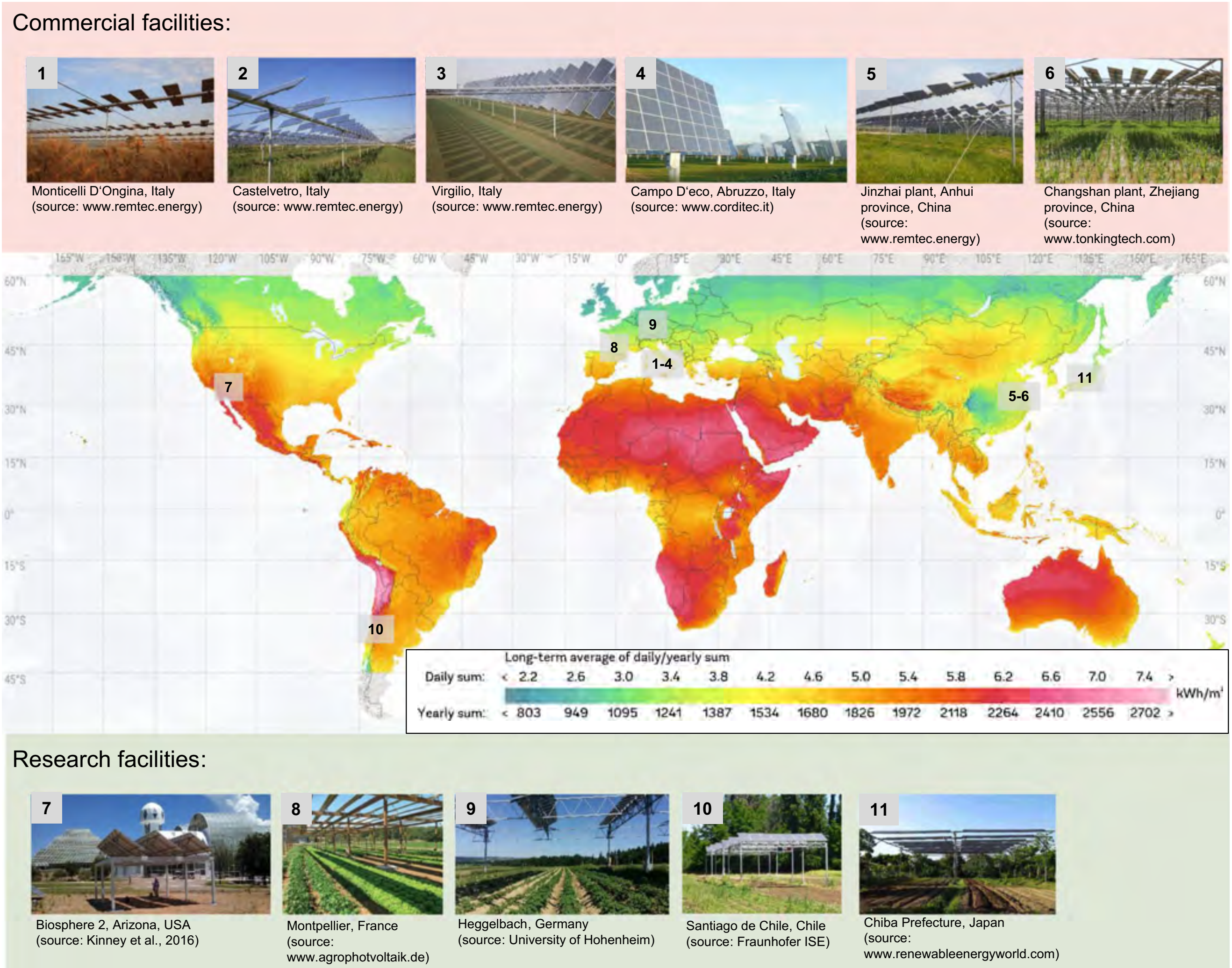

Fig. 2 Overview of APV projects and facilities with location. The colour gradient indicates the long-term average of daily/yearly sum of global horizontal radiation [kwh/m^2]. The numbers indicate the location of the described facilities (Global horizontal irradiation map © 2018 The World Bank, Solar resource data: solargis.com, used under CC BY 3.0 IGO, modified from original)

solar-tracking technology. As described above, this approach has been adopted in another study that addresses the use of solar trackers and the potential benefits for energy and crop production compared to systems with stationary PV panels (Valle et al. 2017). All commercial plants listed in Table 1 are equipped with solar-tracking systems, but only one research facility has a partly tracking system. In Germany, the Fraunhofer Institute for Solar Energy Systems (Fraunhofer ISE) is at the forefront of APV research. In 2016, the Fraunhofer ISE constructed an APV research plant in South Germany, which is described in more detail in the next section. In cooperation with their Chilean subsidiary Fraunhofer Center for Solar Energy Technologies (Fraunhofer CSET), three further pilot plants have been realized near Santiago de Chile to investigate the implementation of APV and its impact on field crops in different climate zones (Fraunhofer Chile Research 2017a; Fraunhofer 2017). In the USA, a small-scale APV research plant has recently been installed in Arizona as part of the Biosphere 2 research facility (The University of Arizona 2018; Table 1) and it is planned to set up further testing sites in rural Arizona and northern Mexico (Kinney et al. 2016; Pallone 2017). In addition to the potential benefits of APV for crop cultivation through alterations in microclimate, the researchers are focusing on how the crop canopy might provide a cooling effect on PV modules in arid regions. While in Europe and America mainly small-scale research and a few medium-scale commercial APV facilities have so far been established, China is already implementing this technology on a large scale (Huawei FusionSolar 2017; Rem Tec 2017a; Tonking New Energy 2018). APV plants with capacities up to 700 MWp and various technical add-ons, such as irrigation systems and dual-axis tracking, have recently been set up in several regions (Huawei FusionSolar 2017; Tonking New Energy 2018). Various agricultural crops including rice and forage grasses are cultivated. According to the executing company, this technology enables the temperature to be lowered and an appropriate microclimate for crop cultivation to be created underneath the panels by reducing irradiation by about 30% (Tonking New Energy 2018). This could be advantageous in hot regions like Southern China. The currently most powerful APV facility with a capacity of 700 MWp has recently been put into operation in Ningixia (Huawei FusionSolar 2017).

Although the APV technology is increasingly being applied all over the world, there is very little accompanying scientific research to examine its impacts on agronomic parameters, such as crop performance and crop yields. In addition to regions with land limitation, arid areas with a high solar radiation are considered the most promising locations for the application of the APV technology in terms of electricity output and synergistic effects on crop cultivation. However, so far, only the Biosphere 2 research facility and the Fraunhofer pilot plants in Chile are located in such regions (Fraunhofer Chile Research 2017b; The University of Arizona 2018). APV plants in Southern Europe and South China give first indications for the potential of APV systems in dry climates. To determine their full potential, however, further investigations are necessary, with results being made accessible through publications.

The project APV-RESOLA (AGROPHOTOVOLTAICS Resource-Efficient Land Use) was launched in 2015 under the German Federal Ministry for Education and Research (BMBF) funding schemes. Preliminary simulations were performed by the Fraunhofer ISE during patent development for the technical optimization of APV systems (patent EP 2811819 B1). An APV research plant was then installed on-farm in 2016 near Lake Constance in south Germany. This region was chosen because of its low share (6%) of renewable-based electricity generation in gross electricity consumption (Energieagentur Ravensburg gGmbH 2012) in comparison to the national average of 17% in 2010 (BMWi 2016). In addition, the promotion of renewable energies in touristic regions like the Lake Constance area is facing a lack of acceptance as wind turbines and PV plants are considered detrimental to landscape scenery. This APV research plant is used to examine the impacts of the technology with regard to various aspects including renewable energy production, economic feasibility, crop production, social acceptance and technological design. It has a total size of 0.3 ha and a capacity of 194 kWp. The solar panels are mounted on stilts with a vertical clearance of 5 m. The facility has a number of specific features to enable uniform light distribution for the simultaneous optimization of PV and photosynthetic yield, (Beck et al. 2012; Fraunhofer ISE patent EP 2811819 B1). The fixed PV panels are oriented in a south-west direction with a tilt angle of 20° and a row spacing of 6.3 m. The plant-available photosynthetically active radiation (PAR) below is predicted to reach values of about 60% of total PAR above the array with variations between winter and summer (Obergfell et al. 2017). Bifacial PV modules are used to further enhance PV energy yield. These are able to utilize light from both sides and thus also intercept reflected radiation. The system was set up on an arable field of a commercial farm managed according to biodynamic principles in order to investigate its practical suitability for farm machinery and impact on crop rotation. The main motive for the farmers to join the project was to become energy self-sufficient or even produce excess energy for the neighbouring village. Four crops (celeriac, potato, winter wheat and clover grass) were chosen to represent a typical organic crop rotation. These were cultivated both underneath the APV facility and on an adjacent reference site without PV modules. The impacts of APV on the environment and agriculture are investigated based on a number of microclimatic and agronomic parameters including crop performance, crop yield and crop quality of the harvested products as well as the impact on biodiversity. Microclimate monitoring is performed by 32 stations allocated to the different cultures and treatments. They record PAR, soil moisture, soil temperature, humidity and air temperature in half-hour intervals, thus providing a high temporal resolution. Observations from the first crop year are discussed in the next section. Data on yield and quality of harvested products cannot be presented until after the second crop year. Additional accompanying research is being performed by the Fraunhofer ISE and the Institute for Technology Assessment and Systems Analysis (ITAS) to assess the electrical and economic performance of the APV system and also its social acceptance.

2.3 Agronomic aspects

This section discusses the impacts of APV technology on agriculture. Its utilization will most likely not only affect farming in terms of crop cultivation, but also agricultural practice. For this reason, we distinguish between its impact on technical aspects and operating procedures in field management, as well as the effects of APV on microclimate conditions and its consequences for crop cultivation. The usage of crop models to evaluate the effects of environmental impacts on crop production is currently also investigated for its application in APV research and thus, will also be discussed within this section.

2.3.1 Field management implications

The application of APV systems imposes several requirements on crop production and its technical management. First of all, the mounting structure of APV arrays needs to be adjusted to the requirements of the agricultural machinery used. As already mentioned, the PV panels have to be raised to an adjusted overhead clearance to permit conventional agricultural machines to pass. For cereal cropping with its large combined harvesters in particular, a clearance of at least 4–5 m is required. To prevent the loss of utilizable land, the distance between the pillars needs to be suitable for planting distances and working widths of the machinery. Our APV field trial showed that driving machinery underneath the APV facility and the arrangement of driving lanes require some experience and the driver's increased attention to prevent damage to the facility. In addition, the working width needs to be adjusted to the distance between the stilts. Given the fast development of autonomous driving and precision-farming applications, we expect these restrictions to be of minor importance for future large-scale arable farming. However, a certain loss of production areas between the stilts that are difficult to reach by agricultural machinery is inevitable and should be considered when predicting impacts on agricultural yields. As stated by Praderio and Perego (2017), at least 2% of the land will be occupied by the pillars of the mounting structure. Their anchorage can be accomplished in several ways. In the APV facility at Heggelbach, a special anchoring system (Obergfell et al. 2017; Spinnanker GmbH) was used to avoid the construction of concrete foundations in order to protect the soil and facilitate the complete removal of the construction.

Various construction modifications should be anticipated to minimize alterations in microclimatic conditions (discussed in next section). The application of PV panels can lead to increased water runoffs, causing an unbalanced water distribution with distinct moist patches under the lower panel edge and sheltered areas directly under the panel (Elamri et al. 2017). During heavy rainfall, strong runoffs from the PV modules can lead to soil erosion (Elamri et al. 2017) and the formation of gullies. The latter was also observed in our own APV trial. However, the problem only occurred in early development stages of wheat, potato and root celery i.e. when the soil was either not covered or barely covered by the crops. In a recent study dealing with the effects of solar panels on unirrigated pasture, Hassanpour Adeh et al. (2018) found higher amounts of soil moisture retained underneath the panels of a ground-mounted PV system. The heterogeneity of rain distribution in APV systems was recently described by Elamri et al. (2017). Their results reveal that technical features need to be considered to improve rain distribution or for the collection of run-offs from the panels. Their study used PV panels with adjustable tilt angles and found rain distribution to be most heterogeneous with flat panels (0° tilt angle) and least heterogeneous with panels in an either directly facing the wind or in the opposite direction. A strategy using a time-variable tilt angle depending on wind direction was found to be most effective at achieving a virtually uniform rainfall distribution (Elamri et al. 2017). In a model (see also Section 2.4), Elamri et al. (2017) also found the angle of incidence of rainfall to be a key variable in the determination of rainfall distribution heterogeneity. If the APV facility is implemented on a hillside, one approach for both, the utilization of the inaccessible area between the stilts and the mitigation of the soil erosion mentioned above, can be the planting of hedges or of perennial biomass crops in between the stilts.

Several technical and mechanical adjustments can be made to minimize the reduction in solar radiation by the PV panels and the resulting disadvantages for crop cultivation. The density of the PV arrays needs to be lower than for conventional ground-mounted PV facilities in order to maintain acceptable agricultural yields. A row distance of about 3 m is assumed to be adequate to allow sufficient quantities of light to reach the crop canopy while still achieving satisfactory energy yields. As part of a patent development (Fraunhofer ISE patent EP 2811819 B1), Beck et al. (2012) observed in their simulation that directing the PV arrays towards southwest or southeast was most suitable to achieve uniform light conditions under the panels. This also resulted in a predicted reduction in electricity yield of 5% compared to conventional south-oriented arrays. The optimum module tilt angle depends on the geographical location; in Central Europe it is around 20–25° (Beck et al. 2012; Dupraz et al. 2011a; Obergfell et al. 2017). It should be noted that a small inclination angle can lead to increased dust depositions as these are not washed off by the rain so easily. The same applies to snow covering in regions with regular snowfall. Dupraz et al. (2011a) have also suggested modifying the panel tilt during certain periods of the year that correspond to light-sensitive stages of crop development. For example, during emergence and pre-anthesis, wheat has been shown to be very sensitive to shading in terms of grain yield (Fischer 1985). Mobile PV modules allow sun tracking to be automatically controlled to accommodate both the specific needs of crops as well as diurnal and seasonal variations in light intensity (Valle et al. 2017).

Further technical innovations to current technology include semi-transparent (Cossu et al. 2016; Park et al. 2010), wavelength-selective (Loik et al. 2017) and bifacial PV modules (Schmid and Reise 2015). Li et al. (2018) recently combined some of these technical innovations in a greenhouse study using bifacial semi-transparent PV-modules with an adjustable tilt angle instead of conventional blinds. Depending on the solar irradiance level, the PV modules can be either tilted parallel to the greenhouse ceiling to generate electricity and shade the cultivated crops, or vertical to maximize crop intercepted radiation when solar irradiance level is low (Li et al. 2018). One concern is the decline in electrical performance through dust deposition on the panel surface as a consequence of agricultural management e.g. tillage and harvesting (Dinesh and Pearce, 2016). Notably in regions with low precipitation or extended dry periods (e.g. monsoon climates), the occasional cleaning of the module surface should be considered to avoid declining electricity yields through dust deposition (Dinesh and Pearce 2016). As suggested by Ravi et al. (2016), this could be managed by integrating irrigation systems and PV cleaning to avoid additional water consumption (Fig. 3). Another preliminary result observed in the APV trial in Heggelbach, is the slight delay in development of crops grown under APV, which has also been observed in other

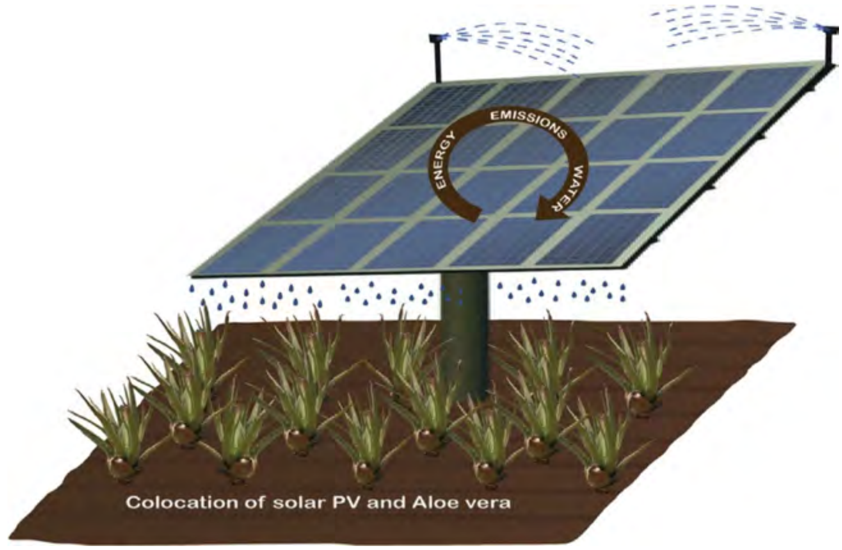

Fig. 3 Integration of PV module surface cleaning with irrigation system. Its application is also conceivable in APV systems. Run-off water of the PV module cleaning system can be collected or directly used to irrigate crops cultivated underneath (source: Ravi et al. (2016))

studies dealing with the impacts of APV and shade on crop production (Elamri et al. 2018; Rotundo et al. 1998). This is probably due to altered microclimatic conditions and also has an influence on field management as well as the marketing strategy of some crops (Elamri et al. 2018; Rotundo et al. 1998).

2.3.2 Microclimatic alterations and their impact on crop cultivation

In addition to the field management aspects mentioned above, one of the most important issues for agricultural practice underneath an APV array is the alteration of microclimate conditions and the resulting consequences for crop cultivation. While the reduction in solar radiation underneath the APV canopy is expected to be the most apparent change, several other microclimate factors may also be altered. One microclimate factor that is directly influenced by solar radiation is air temperature. Marrou et al. (2013c) did not find any significant changes in daily mean temperatures and thermal time between an APV trial and an unshaded control plot at the French location of Montpellier. On a few days with low wind speed or high solar radiation, the temperatures underneath the panel tended to be higher (Marrou et al. 2013b). However, other studies found that soil temperature (Ehret et al. 2015) and maximum air temperature (Pang et al. 2017) decreased under shaded compared to full-sun conditions. This inconsistency may be due to the direct effects of the solar panels on air temperature observed in studies with ground-mounted solar parks (Barron-Gafford et al. 2016; Hassanpour Adeh et al. 2018) and the heterogeneous shading conditions underneath APV facilities. In contrast, Armstrong et al. (2016) found mean air temperature under PV panels to be unaffected, with diurnal variation in air temperature under the panels being lower due to higher minimum temperatures and lower maximum temperatures. Nevertheless, these results should not be directly transferred to APV systems where the PV modules are high above the crop canopy. However, potential impacts of air and canopy temperature changes through shading on crop cultivation need to be considered, particularly in regions with high solar irradiation. Excessive heat may have negative effects on crop yields, as has been shown for example for potatoes, where marketable tuber yields decreased (Kim et al. 2017). Temperature and radiation — described by the photothermal quotient — are in general two of the most important determinants of cereal grain yields (Fischer 1985). In addition, temperature can affect nutritional quality, for example fatty acid composition of oilseed rape (Gauthier et al. 2017; Izquierdo et al. 2009) and starch content of potatoes (Krauss and Marschner 1984). While air temperatures tended to be higher, soil temperatures decreased underneath APV, whereas crop temperatures of durum wheat, lettuce and cucumber cultivated under APV decreased during the day-time and increased during the night-time (Marrou et al. 2013b).

As described in the preceding paragraph, the use of a solar panel canopy inevitably leads to an altered water distribution underneath (Dupraz et al. 2011a; Elamri et al. 2017; Hassanpour Adeh et al. 2018). After heavy rainfall, direct water runoffs onto the soil surface can increase the risk of soil erosion, while in more sheltered parts, unevenly distributed rainfall can lead to diminished water availability (Elamri et al. 2017). Beside these drawbacks, this sheltering by the PV panels could also help reduce the infestation of fungal diseases after persistent rainfall. The severity of anthracnose, one of the major post-harvest diseases in mangos grown in humid regions that often occurs after rainy seasons (Arauz 2000), has been found to decrease under a plastic roofing (Jutamanee et al. 2013). Comparable results have been observed by Du et al. (2015), who also found the severity of several fungal diseases to be reduced in sheltered grapevines in rainy regions of China. However, it should be noted, that in these studies completely sheltered crop stands are compared with non-sheltered crop stands. As only about one third of the total area is covered in APV systems (depending on configuration, size and density of installed modules), it remains doubtful whether the sheltering will have significant effects on disease infestation of the cultivated crops. In addition to the potential problems concerning water distribution, water balance in general may change under an APV system. Marrou et al. (2013a) reported that evapotranspiration is reduced under PV arrays due to both diminished evaporation and transpiration as a consequence of the light reduction. However, they found that the effect depended on the crop species cultivated, as evaporation is driven by crop cover rate. Under APV, the crop cover rate increased for lettuce, for example, but decreased for cucumber. Marrou et al. (2013a) concluded that APV systems can improve water use efficiency (WUE) and help prevent water losses under dry climates, if suitable crop species are chosen. This is in accordance with findings for citrus grown under shading nets, where WUE increased with lower solar irradiation (Medina et al. 2002). In simulations based on data from a 40-year period, Amaducci et al. (2018) found that cultivating maize under APV in non-irrigated conditions reduced soil evaporation and also increased average yield. The highest yield variation was obtained under full-sun conditions. Thus, they concluded that APV may lead to yield stabilization, mitigating yield losses in dry years (Amaducci et al. 2018).

2.3.3 Effect of shading on yield and quality

The extent of the reduction in solar radiation under an APV canopy very much depends on the seasonal solar altitude, the position underneath the array and the technical implementation of the facility. The latter includes orientation, tilt angle and size of the panels as well as the distance between them (Beck et al. 2012; Dupraz et al. 2011a). Due to the arrangement of the PV modules, shading underneath the facility is not uniform and varies during the day depending on solar altitude. In studies with APV systems adapted for crop production, for example through a reduced module density, crop-available radiation was predicted to reach values ranging between 60 and 85% of that in open-field conditions (Dupraz et al. 2011a; Majumdar and Pasqualetti 2018; Obergfell et al. 2017; Praderio and Perego 2017). This effect will be less distinct in smaller APV facilities due to border effects, especially when the sun is low and can reach the ground from the sides. In a field experiment where different lettuce varieties were cultivated under an APV facility, Marrou et al. (2013c) found that with reduced PV module density with a panel row distance of 3.2 m, up to 73% of incoming radiation was available at plant level. On average, the lettuce yields were 81–99% of the full-sun control yields, with two varieties even exceeding the control values. In simulations performed with climate data from the last 37 years (1975–2012), Praderio and Perego (2017) found that average yields of maize and wheat grown under APV would only be reduced by about 0.5–1.5%. However, it remains doubtful whether such yields can be achieved in practice. In a modified crop model adapted to the shading conditions underneath APV, Homma et al. (2016) found a 20% reduction in solar radiation led to a 20% reduction in rice yields. They concluded that sufficient light availability during early growth periods is an important yield factor.

Apart from the studies mentioned above, there is very little information on the effects of APV on crop production. Hence, information on the issue can only be taken from studies with comparable conditions, such as agroforestry experiments or studies with artificial shade. A brief summary of the existing literature addressing the impact of shading on plant development and yield is shown in Table 2. For reasons of comparability, only field experiments with artificial shade (mostly created by shading cloths or nets) were considered. As in most of these studies shade was provided by netting over the entire study area, the achieved uniform shading conditions are not the same as the dynamic shading patterns underneath an APV facility. Hence, the results of these studies should be treated with caution and cannot be directly transferred to APV systems. In most of the studies, different shading intensities were applied. In order to distinguish between intensities, we use the terms "moderate shading" (up to 50% reduction compared to full sunlight) and "severe shading" (more than 50% reduction compared to full sunlight) in the following text. These terms are only used to divide the shading intensities applied into two categories and are not intended as an assessment of the impact on crop production. For example, moderate shading conditions can potentially lead to severe results with regard to crop yield and quality as shown for potatoes (Sale 1973). As crop-available radiation under APV is reduced by about 15–40%, these light conditions correspond to moderate shading (Amaducci et al. 2018; Dupraz et al. 2011a; Marrou et al. 2013b).

There is a strong correlation between grain yield and irradiance in cereals such as wheat (Artru et al. 2017; Dufour et al. 2013; Jedel and Hunt 1990; Li et al. 2012; Mu et al. 2010), rice (Islam and Morison 1992) and maize (Jia et al. 2011; Reed et al. 1988). The extent of yield reduction depends on the shading intensity, time period, and at which stage of crop development the shading is applied. For example, in rice, the yield reduction can reach up to 73% under severe shading conditions with a reduction of incoming radiation up to 77% (Islam and Morison, 1992). In previous experiments with wheat, Fischer (1985) showed that this decrease in yield is due to both, a reduced number of grains per spike and spikes per unit area and also varies with the crop phenological stage at which shading is applied. While the wheat crops were most sensitive to shading in the period 30 days prior to flowering, treatments ending 45 days before anthesis did not show any significant effects. These results are in agreement with findings in rice, where a slight shift in light intensity during the

Table 2 Overview of existing literature on the effects of shading on different crops

Crop	Shade effect	Effect on yield	Further effects	Reference	RSR[b] [%]	Type/time of shade application	Study site
Field crops							
Sunflower	−/+	•Decreased seed set and number in all shading treatments	•Altered fatty acid composition	Cantagallo et al. (2004)	80	At various periods[a]	Buenos Aires, Argentinia
				Izquierdo et al. (2009)	50/80	During grain filling[a]	Santamari-ne, Argentinia
Oleiferous plants	−/+	•No details given	•Altered fatty acid composition	Izquierdo et al. (2009)	50/80	During grain filling[a]	Santamari-ne, Argentinia
Potato	−/+	•Decreased tuber yield and number •Increased yield at some locations and shading times	•Increased plant height and leaf area	Kuruppuarachchi (1990)	50	Non-uniform shading; at various periods	Kalpitiya, Sri Lanka
				Sale (1973)	21/34	During entire growth period[a]	Australia
				Midmore et al. (1988)	50/67	At various times of the day[a]	Peru
Wheat	−/+	•Decreased grain yield and grain size •Increased yield for some cultivars under moderate shading conditions	•Increased protein content	Artru et al. (2017)	55	Non-uniform shading; Starting at flowering	Gembloux, Belgium
				Dufour et al. (2013)	25–60	Various; increasing intensity[a]	Montpellier, France
				Fischer (1985)	50–67	At various periods[a]	Various
				Jedel and Hunt (1990)	50±5 (of PAR)	Various[a]	Toronto, Canada
				Li et al. (2012)	8/15/23	From jointing to maturity[a]	Nanjing, China
				Mu et al. (2010)	22/33 (of PAR)	From jointing to maturity[a]	Nanjing, China
Maize	−/+	•Decreased grain yield due to reduced grain weight •Increased stover yield	•Increased fat and protein content •Decreased starch content	Reed et al. (1988)	50	At various growth stages[a]	Missouri, USA
				Jia et al. (2011)	55	For 2 weeks at different times[a]	Shadong, China
				Mbewe and Hunter (1986)	65	At various growth stages[a]	Ontario, USA
Rice	−	•Reduced grain yield through shading during reproductive and ripening stages	•Shading during vegetative stage had no effect	Islam and Morison (1992)	22/52/77	At various growth stages[a]	Joydebpur, Bangladesh
Cotton	−	•Decreased lint yield	•Decreased fibre strength •Increased fibre length	Chen et al. (2017)	21/38	Starting at flowering[a]	Nanjing, China
Horticultural crops							
Tomato	+	•Increased fruit yield under moderate shading conditions	•Increased plant height with increasing shade •Reduced number of fruits with sunscald •Decreased content of ascorbic acid, carotenoids and phenolics	Baharuddin et al. (2014)	25/50/75	Unknown	Bogor, Indonesia
				El-Gizawy et al. (1993)	35/51/63	Starting 1 month after transplanting[a]	Egypt
				Nangare et al. (2015)	35/50/75	Starting after transplanting[a]	Abohar, Punjab, India
Sweet pepper	+			Rylski and Spigelman (1986)	12/26/47		Negev desert, Israel

Table 2 (continued)

Crop	Shade effect	Effect on yield	Further effects	Reference	RSR[b] [%]	Type/time of shade application	Study site
		•Highest yield under moderate shading conditions	•Increased plant height and quantity of flower nodes •Reduced number of fruits with sunscald			During entire growth period[a]	
Tree fruit and berry crops							
Kiwi	+	•Highest fruit yield under moderate shading conditions	•Decreased fruit drop and leaf fall in all cultivars •Increased storage quality •Reduced heat stress assumed	Wang et al. (2007)	70	During summertime[a]	Changsha, China
				Allan and Carlson (2003)	15/30/40/55	Unknown timing[a]	Pietmaritz-burg, South Africa
Mango	+	•No details given	•Decreased severity of postharvest diseases and thus increased fruit quality •Decreased anthracnose infestation through rain reduction during rainy season	Jutamanee et al. (2013)	26	Starting at beginning of flowering[a]	Nakhon Phanom, Thailand
Coffee	+	•Highest yields under moderate shade conditions	•Decreased yields under severe shading (> 50% reduction of incoming radiation)	Soto-Pinto et al. (2000)	30–70	During whole investigation period[a]	Chilón, Chiapas, Mexico
Black-berries	+	•Increased yield	•Extended harvest period	Rotundo et al. (1998)	40	From June–October[a]	Basilicata region, Italy
				Makus (2010)	40	Starting after third harvest[a]	Monte Alto, Texas, USA
Blue-berries	+/−	•Both increased and decreased yields depending on geographic location and shading period	•Extended harvest period	Lobos et al. (2013)	25/50/75	Starting 1 month after fruit set[a]	Gobles, Michigan, USA
				Retamales et al. (2008)	35/50	Starting at fruit set[a]	Miraflores, Chile

Plus signs indicate beneficial, minus signs indicate adverse shading effects on yield and quality of harvested crop

[a] Shade was applied uniformly by shading cloth, nets or similar

[b] RSR [%] = Reduction in solar radiation; multiple numbers indicate the application of various shading intensities

vegetative stage did not have any effects on yields (Islam and Morison 1992). In contrast, Li et al. (2012) found that grain yields of two wheat cultivars increased under mild shading conditions when applied from jointing to maturity (8% reduction of full sunlight). In maize, the extent of yield reductions was also linked to the growth stage at which shading was applied. Reed et al. (1988) found grain yield to be reduced by 12% when shading (50% reduction of incoming radiation) was applied during the vegetative stage. When applied during flowering or grain filling, yields were reduced by 20% and 19%, respectively (Reed et al. 1988). Mbewe and Hunter (1986) found similar results, with grain yield reductions in maize being most affected during the reproductive stage. Interestingly, while grain yields were reduced by 52% under shading (65% reduction of incoming radiation), stover yield was almost unaffected by shading during the reproductive stage (Mbewe and Hunter 1986).

In potatoes, tuber number and tuber yield were generally decreased by shading (Kuruppuarachchi 1990; Midmore et al. 1988; Sale 1973), but in regions with a high solar irradiation, yields were increased when shading was applied either during early plant development (Kuruppuarachchi 1990) or around noon (Midmore et al. 1988). This effect was explained by an enhanced plant survival rate through shading. However, depending on the climate, potential effects of the PV canopy on microclimate e.g. observed changes in evapotranspiration, need to be taken into account when interpreting data (Marrou et al. 2013a). This applies, for example, to the findings of Marrou et al. (2013c), which resulted from experiments carried out under a dry Mediterranean climate. In tomatoes, fruit yield increased under moderate shading conditions (25–36% reduction of full sunlight) in semi-arid conditions with high light intensities (Baharuddin et al. 2014; El-Gizawy et al. 1993; Nangare et al. 2015). Plant height also increased under these conditions. However, a higher degree of shading (50–75% of full sunlight) had adverse effects and led to decreased fruit yields. Similar results were found for sweet peppers grown in the Negev desert where moderate shade (12–26% reduction of full sunlight) led to increased yields and plant heights (Rylski and Spigelman 1986).

Moreover, the impact of shading on yields seems to depend on the plant component harvested. For lettuce, harvestable yield of some varieties was found to be hardly affected by shading, whereas for other varieties the yield exceeded that of plants grown under full-sun conditions (Marrou et al. 2013c). Marrou et al. (2013c) concluded that this was linked to different mechanisms of how the varieties adapted to shaded conditions. Shade-tolerant varieties showed a number of adaption strategies including an increased total leaf area, an altered leaf orientation, and a modified morphology with longer, wider, thinner but lower number of leaves. In wheat, the maximum leaf area index was found to be unaffected by shading (Artru et al. 2017; Dufour et al. 2013), while the straw biomass of some varieties increased (Artru et al. 2017). For certain temperate grassland species, pot experiments with shading cloths showed that, depending on the variety, consistent or even higher yields can be achieved under moderate shade conditions (Pang et al. 2017; Semchenko et al. 2012). These findings were confirmed in the first year of our own APV experiments, where shading to the extent of about one third of PAR led to an increased vegetative plant biomass in wheat and celeriac, but barely affected total yields of clover grass. In maize, Mbewe and Hunter (1986) found stover yield to be almost unaffected depending on the growth stage at which shading was applied. Hence, the effect of shading on vegetative plant components should also be considered; potential benefits may be derived by selecting appropriate crop species and varieties. In particular, forage crops and leaf vegetables such as cabbage and lettuce may benefit from diminished solar irradiation by increasing leaf area and thus total plant biomass.

In addition to yield factors, shading influences the quality of the harvestable products. In wheat, shading correlated with increasing grain protein content (Artru et al. 2017; Dufour et al. 2013; Li et al. 2012); in maize kernels, both fat and protein content increased (Jia et al. 2011). One study also addressed the impact of shading on the baking quality of two different wheat cultivars (Li et al. 2012): The glutenin content, wet gluten content, falling number and sedimentation value were all increased under moderate shading conditions, whereas mild shading (8% reduction of full sunlight) led to opposite results. These findings were explained by a dilution effect due to changes in grain weight, which was decreased by moderate and increased by mild shading (Li et al. 2012). In oil crops, oil quality was found to be modified through an altered fatty acid composition in response to changes in intercepted solar radiation (Gauthier et al. 2017; Izquierdo et al. 2009). The oleic acid content of maize, rape, soy and sunflower decreased with decreasing light intensity, whereas the content of polyunsaturated fatty acids such as linoleic and linolenic acid increased (Izquierdo et al. 2009). This result was recently confirmed by Gauthier et al. (2017) who also found the linolenic acid concentration of different oilseed rape genotypes to be negatively correlated with solar radiation. However, the effect of solar radiation was the reverse during the first 100–300 degree days after the beginning of flowering. Apart from the oil composition, shading was also associated with a reduced oil concentration (Gauthier et al. 2017). In purple- and red-fleshed potatoes, the content of anthocyanins and phenolics increased with higher light intensity (Reyes et al. 2004). This is in accordance with findings in tomatoes, where the content of various secondary plant metabolites, such as carotenoids (McCollum 1954), ascorbic acid (Hamnner et al. 1945) and phenolics (Dumas et al. 2003; Wilkens et al. 1996), increased with light intensity. For other quality-relevant factors of tomatoes, the results given in the literature are quite diverse. For example, El-Gizawy et al. (1993) found an increasing percentage of titratable acid and a decreasing content of both ascorbic acid and total soluble solids (TSS) with increasing shade, whereas Nangare et al. (2015) found no significant changes in acidity, TSS and ascorbic acid content. The occurrence of sunscald in tomatoes (El-Gizawy et al. 1993) and sweet peppers (Rylski and Spigelman 1986) grown in Egypt and Israel (Negev desert), respectively, was found to be reduced under shaded compared to full-sun conditions, showing that shading most notably acts as protection from excessive solar radiation and high temperatures in the studied regions. For fruit trees such as kiwi and mango, moderate shade has been found to increase fruit quality (Jutamanee et al. 2013; Wang et al. 2007) and partly even yields (Allan and Carlson 2003). These findings have been associated with enhanced protection against adverse climatic conditions such as high temperatures and excessive rainfall.

As described above, altered microclimate conditions in an APV cultivation system may trigger several effects on crop yield and quality of the harvestable products. However, there are no data available for a large number of crop species. Moreover, as the results mainly stem from netting and agroforestry experiments, there are limits to their transferability to APV systems. This emphasizes the need for distinct investigations for crop cultivation under APV. Nevertheless, the most prevalent change affecting plant cultivation will be the restricted light availability, which will most likely lead to yield losses in the majority of cultivated crops. The extent of the losses will very much depend on the local climatic conditions, particularly solar radiation, and the technical implementation of the APV system. Especially in arid regions, where the negative effects of high solar irradiance and excessive water losses predominate, additional shading may be advantageous and lead to yield stability (Amaducci et al. 2018). As shading patterns and microclimatic conditions under APV differ between the seasons, the impact on crop production will also depend on whether the crops are cultivated in spring or summer (Dupraz et al. 2011b; Marrou et al. 2013c). It can be assumed that, in species that are well adapted to shade or respond with an enhanced vegetative biomass production, yields can be maintained or even increased. This could be the case for forage crops, herbaceous plants and leaf vegetables such as cabbage and lettuce. For some species, it may be possible to alleviate the predicted yield losses through shading by deferring the harvest and thus extending the vegetation period. This has recently been confirmed by Elamri et al. (2018), who found a slight delay in development of lettuce grown under APV. Comparable results have been found for blueberries and blackberries grown under shading nets, where shading led to extended harvest periods, and thus also potential benefits in terms of marketing, as higher market prices can be achieved (Lobos et al. 2013; Rotundo et al. 1998). Several medicinal and spice crops such as cardamom and pepper, which are traditionally grown in forests and thus well adapted to shade, are currently being investigated for cultivation in agroforestry systems. These could also be considered for cultivation in APV systems (Rao et al. 2004; Reyes et al. 2009; Singh et al. 1989). Coffee, one of the most important tropical cash crops worldwide, has been shown to benefit from the additional shade provided by cultivation in agroforestry systems (Jezeer et al. 2018; Soto-Pinto et al. 2000). Similar results have been found for speciality crops like blackberry and blueberry, which naturally occur in habitats with moderate light conditions (Lobos et al. 2013; Makus 2010; Retamales et al. 2008; Rotundo et al. 1998). While blackberry yields increased from 9 up to 34% (Makus 2010; Rotundo et al. 1998), the results for blueberries are less distinct and seem to depend on climatic conditions and the period shading is applied (Lobos et al. 2013; Retamales et al. 2008). Even though the results from the various shading studies provide first insights into the shade tolerance of different crop species, they lack transferability due to the heterogeneity of climatic conditions and experimental set-up. In this context, crop models can be a more universal approach; they allow influencing variables to be varied without the time and effort required for extensive field experiments.

2.4 Modelling approaches in APV research

As outlined in the previous sections, the impact of APV on agronomic aspects is a quite complex topic and is influenced by many different factors. PV technology is steadily being refined, offering various options for the configuration of APV facilities adjusted to crop production. While the electrical performance of PV systems can nowadays be more or less easily calculated using existing software and models (Lalwani et al. 2010), the impacts on crop cultivation are more complex and thus, difficult to estimate. As seen in Section 2.3.3 and the corresponding Table 2, a number of studies have already addressed the topic of the impact of shading on crop cultivation. However, these studies were performed in different regions of the world and most were characterized by specific local climatic conditions. In this context, different solar radiation levels, temperatures, water availability etc. may also have affected the observed effects of shading. In addition, the manner in which the shading was applied also differs between the studies. While some apply uniform shading for the whole cropping period (e.g. Chen et al. 2017; Nangare et al. 2015), others use scattered shade limited to specific stages of crop development (e.g. Artru et al. 2017; Islam and Morison 1992). Therefore, the results of the cited studies are quite difficult to compare and even more in regard to the dynamic shading patterns in APV systems.

One approach to addressing the complexity and dynamism of APV systems is the development of crop models. This has already been initiated and further developed by a number of researchers (Dinesh and Pearce 2016; Dupraz et al. 2011a; Elamri et al. 2018; Elamri et al. 2017; Marrou et al. 2013a; Marrou et al. 2013c; Valle et al. 2017). The first modelling approach was introduced by Dupraz et al. (2011a). It consists of two different types of models to capture the complexity of APV. The so-called STICS model (Brisson et al. 2002) was used to simulate the impact of environmental variables on crop development, allowing the incorporation of crop specific parameters and the interaction of the crops with abiotic factors like microclimate, soil and farming practice (Dinesh and Pearce 2016; Flénet et al. 2004). A second model was used to predict light availability and distribution underneath an APV array. As shown by Dupraz et al. (2011a), crop modelling can be a useful tool for the simulation of crop performance under APV and, when combined with PV modelling and the LER approach, also allows the land productivity of the APV systems to be evaluated. However, they also revealed potential limits to the STICS model in the simulation of crop development under dense shading conditions (Dupraz et al. 2011a). The modelling approach has since been further developed by Marrou et al. (2013a, 2013b, 2013c), who adapted various models to the microclimatic dynamics underneath an APV system based on data obtained from their APV field trial. They implemented a comprehensive microclimatic monitoring system to measure incident radiation, air temperature, humidity, soil temperature and soil moisture at hourly intervals, thus achieving a high temporal resolution (Marrou et al. 2013a; Marrou et al. 2013b; Marrou et al. 2013c). In addition, wind speed, precipitation and crop specific parameters, such as stomatal conductance, crop cover rate and crop temperature were measured (Marrou et al. 2013b). They showed that the correlation of field data and their radiation model can be improved by increased spatial and temporal resolution of the measurements (Marrou et al. 2013c). To better understand the driving forces of water balance underneath APV, Marrou et al. (2013a) developed a theoretical model that identifies and calculates its components. Although rain distribution was observed to be quite heterogeneous under APV in these studies, rainwater inputs in the models were assumed to be similar to the unsheltered treatment (Marrou et al. 2013a). This was recently taken up by Elamri et al. (2017), who used data obtained from a field experiment addressing the rain distribution underneath an APV facility to design a rain distribution model. This enabled them to identify the key determinants of rain distribution caused by the PV panels and obtain a higher resolution of spatial heterogeneities in water supply underneath an APV system (Elamri et al. 2017; see also Section 2.3.1). In a follow-up study, Elamri et al. (2018) complemented this model with previous modelling approaches (Marrou et al. 2013a, 2013b, 2013c; Valle et al. 2017) giving a more complex model that incorporates a number of aspects including the impact of rain distribution, water and land use efficiency, as well the optimization of shading strategy (Elamri et al. 2018). They concluded that the model produced satisfactory results with some room for improvement in the temporal resolution and incorporation of soil surface conditions to assess soil water distribution. Elamri et al. (2018) consider their model a useful tool for the dimensioning of APV systems as well as the optimisation of irrigation and panel adjustment, but for further evaluation of its universal applicability a sensitivity analysis is necessary (Elamri et al. 2018).

In recent years, the modelling approach in APV research has been developed and refined by several studies. It enables the simulation of the impacts of APV for specific local climatic conditions and the technical implementation. To improve the validity of simulated results, further field experiments are required to obtain sufficient data on microclimatic heterogeneities. First steps in this direction have already been made by Marrou et al. (2013c) and Elamri et al. (2017) who already have acquired data on several microclimatic factors. For a more precise spatial and temporal resolution, further variables e.g. soil surface status (Elamri et al. 2018), need to be incorporated and predicted values validated from field experiments with comprehensive microclimate monitoring. In this context, measurements should also be taken transverse to the solar panels of the APV facility, as already implemented by Elamri et al. (2017), to gather data on rain distribution. Although the microclimatic modelling of APV systems is already quite sophisticated, the modelling of crop performance is still insufficient. Most studies published so far only discuss the shade adaptive responses of lettuce during its vegetative phase (Elamri et al. 2018). There is a lack of information on more complex crops (Valle et al. 2017) and their light requirements during various stages of development, and this is neither addressed in modelling approaches nor validated under field conditions (Dinesh and Pearce 2016; Marrou et al. 2013a, 2013b, 2013c). For a better understanding of crop specific morphological traits and their response to altered light conditions during different stages of development, further field experiments with various crop species are necessary to obtain additional data on crop performance, which then can be used to improve validity of the crop models. Ultimately, this information needs to be gathered in overarching models that simulate both energy and crop performance as well as microclimatic impacts, taking into consideration the local climatic conditions, selected crops and technical implementation of the APV facility.

3 Outlook and future application opportunities

APV systems are still at an early stage of development and there is plenty of scope for technical improvements and further fields of application. As already described in Section 2.3.1, there have recently been several innovations in PV technology. Valle et al. (2017) have shown that dynamic PV modules with controlled tracking can optimize the availability of incident radiation on the plant canopy, allowing more efficient crop production and increasing both electricity and biomass yield. The application of wavelength-selective PV modules in horticulture is currently being investigated with the aim of further adjusting PV systems to the specific requirements of crops in co-productive systems (Loik et al. 2017). Electricity yield may also be increased by upgrading APV plants with wind turbines to combine wind and solar energy production (Rem Tec 2017b).

In addition to technical optimizations, there are various implementation opportunities for APV, depending on the local climatic conditions and the scale of the facility. For example, the power generated could be used to optimize the farm's existing operation flows e.g. processing of harvested products or energy-consuming processes such as cooling and ventilation (Mekhilef et al. 2013). Another possibility is the electrification of farm machinery or vehicles in general. The self-consumption of electricity could be further increased by storage facility upgrades. In developing countries and other regions with only a rudimentary electrical grid, APV could act as a decentralized energy source for the electrification of rural areas (Malu et al. 2017; Silva Herran and Nakata 2012). This was also taken up by Harinarayana and Vasavi (2014), who see great potential for APV to meet future renewable energy targets in India, both improving rural off-grid energy production and saving on high expenditure for the expansion of the electricity grid. At farm level, the power could be utilized directly for irrigation and water-pumping systems or stored by pumping water into a reservoir to be used later for irrigation purposes (Burney et al. 2010; Mekhilef et al. 2013), thus helping to improve food security and water supply. Campana et al. (2016, 2017) recently investigated the potential of photovoltaic water-pumping systems for forage production in China. They concluded that these pumping systems provide great potential for the improvement of grassland productivity, while mitigating adverse effects of climate change and grassland desertification. In addition, the positive knock-on effects on CO_2 emission reduction and sequestration are conceivable, when diesel-driven water-pumping systems are replaced (Campana et al. 2016, 2017). APV could also provide a useful contribution to the holistic agricultural approaches of organic farms or large-scale projects such as Sekem (Sekem 2017) and the Sahara Forest Project (Sahara Forest Project 2017), both of which strive to re-cultivate desert areas through agricultural production using innovative and sustainable technologies. As these projects are located in arid regions (Egypt and Jordan, respectively) potential synergistic effects of the APV panels on crop production can be expected through the mitigation of evaporation and excessive solar radiation (Marrou et al. 2013a; Ravi et al. 2016). This approach is also being pursued and practically implemented in large-scale projects in China (Tonking New Energy 2018). Thus, APV could be an approach for sustainable desert agriculture. The described effects on crop production may also counteract the severe climatic conditions related to climate change, such as drought and heat. In the EU and other industrial countries, the development of renewable energies currently forms one of the key components of a sustainable climate and energy policy. Sustainability goals, combined with the limited agricultural land area in these countries, have led to an ethical conflict about land use for food or bioenergy production. This could be alleviated by the implementation of APV.

Another opportunity would be to exploit synergistic effects in cultivation systems that already use supporting structures, such as hop growing, horticulture (shade net houses and greenhouses), viticulture and intensive fruit production. The implementation of PV greenhouses is one focus of current research (Cossu et al. 2014; Kadowaki et al. 2012; Ureña-Sánchez et al. 2011) and has already been realized in several projects worldwide (Akuo Energy 2018; Reden Solar 2018; Tenergie 2018). Even though yields of horticultural crops, such as tomatoes and green onions, decrease, the economic benefits of these co-productive systems probably outweigh potential yield losses (Cossu et al. 2014; Kadowaki et al. 2012). As concluded in Section 2.3.3, the effects of shading will differ between crop species and local climatic conditions. The use of anti-hail nets is quite common in wine and fruit cultivation (Gandorfer et al. 2016; Kiprijanovski et al. 2016) and nettings are also applied as protection from other climate impacts such as excessive radiation, high temperatures (Ilić and Fallik 2017) and frost (Teitel et al. 1996). In these systems, synergistic effects can be achieved by the direct protection from adverse climatic effects through the PV panels themselves or by using the same supporting structures for both panels and netting. The impact of climate change on wine quality has recently been investigated, with canopy structures being one of the suggested solutions for protection against intense irradiation (van Leeuwen and Darriet 2016). This approach is already being pursued by the French company Sun'Agri (2018), one of the project partners in the French APV projects. They expect the application of APV in intensive fruit production and viticulture to lead to water savings, protect fruit against sunscald, and maintain or even increase yields by reducing losses due to weather extremes (frost, hail, strong wind). This aspect could become even more relevant in future in major wine-producing regions, as the area suitable for viticulture is predicted to decrease dramatically by 2050 due to the effects of climate change (Hannah et al. 2013). Another positive aspect in this context is that scaffolding is already accepted in these cultivation systems. A recent modelling study assigned these considerations to grape farming in India to ascertain its potential for APV (Malu et al. 2017). Malu et al. (2017) concluded that the annual income of grape farms using APV could be increased about 15 times through the additional energy production, while maintaining grape yields. However, it first needs to be proven that such predicted agricultural yields can really be achieved in practice.

The implementation of APV technology is likely to meet some obstacles. The introduction of new technologies is always accompanied by a certain amount of public controversy and this should also not be underestimated in the case of APV systems. In Germany, the uncontrolled expansion of ground-mounted PV arrays has led to a diminishing acceptance within the population followed by legal restrictions concerning the construction of PV facilities. In addition, the installation of ground-mounted PV plants leads to the irreversible conversion of arable into surfaced land and consequently a loss of area payments granted by the EU Common Agricultural Policy (European Commission 2003). In this context, legal regulations for the construction of APV facilities need to be clarified to provide a clear distinction between ground-mounted PV arrays and APV arrays. For APV, a certain minimum agricultural yield needs to be achieved in order to ensure sufficient crop production and avoid competition with energy production. Any kind of "pseudo agriculture" needs to be avoided, particularly with regard to agricultural subsidies. In our practical APV project, the farmers stated that they could tolerate crop yield reductions up to 20%. However, as subjective perceptions and opinions will differ, limits for tolerable yield reductions have to be defined. Although there is a clear call within society for the development of renewable energies, there is often a lack of social acceptance at local level, particularly when a loss of visual landscape quality, damage to cultural landscapes or consequences for the environment are feared (Poti et al. 2012; Zoellner et al. 2008). Even though APV avoids the loss of arable land and the resulting conflicts between food and energy production, a change of landscape scenery cannot be denied and will inevitably lead to societal debates, especially in the case of large-scale plants, as seen in China (Huawei FusionSolar 2017). However, in contrast to ground-mounted PV facilities, APV will not be accompanied by a loss of wildlife as fencing is not necessary and would indeed be obstructive for agricultural practice (Turney and Fthenakis 2011). In cultivation systems with scaffolding structures, an extension by APV will probably be less controversial, as the presence of supports is already established. Another approach to improving social acceptance could be the selective embedding into the existing scenery, paying attention to local circumstances (Scognamiglio 2016). This can be achieved in several ways including specific designs, the usage of organic materials or dyeing of the PV cells (Scognamiglio 2016). As Zoellner et al. (2008) concluded from case studies in Germany, the acceptance of renewable energies can be improved by involving the general public in decision-making processes.

4 Conclusion

The application of APV systems offers a number of opportunities, which differ depending on regional and climatic conditions. The real added value of the APV technology is that it enables the simultaneous production of food and energy, providing undeniable economic benefits for farmers, with additional potential synergistic effects. This is of particular interest in densely populated industrial countries, where the expansion of renewable energies is becoming increasingly important, but productive farmlands need to be preserved. APV will inevitably lead to altered microclimatic conditions, notably a reduced solar radiation and resulting changes in water balance. As radiation is one of the most important factors affecting crop performance, a decline in agricultural yields is the most likely consequence of cultivation underneath an APV array. However, due to microclimatic heterogeneities under APV, results from shading experiments are only transferable to a limited extent. In dry years, microclimatic alterations under APV can contribute to yield stabilization, compensating for seasonal climatic and crop yield fluctuations. This may become even more important in the future with the anticipated change in climatic conditions. Furthermore, benefits are possible for shade-adapted crops and in hot, arid climates where enhanced water savings and protection against adverse effects of high temperatures and excessive radiation are of advantage. As only very few studies address the impact of this technology on crop yields and quality, further investigations incorporating different climatic conditions, crop species and varieties are indispensable for the evaluation of its applicability in prospective agricultural systems. Such investigations should also consider synergies with current innovations in PV technology and agriculture, as well as the inclusion of APV into different cultivation systems and processing cascades. In this context, modelling can be an efficient approach to process the results from field experiments into universal models, which then can be adapted to specific climatic conditions and technical implementations of APV systems, thus finding appropriate solutions for respective locations. However, APV can be an important component of future agricultural systems, addressing some of the major current and prospective societal and environmental challenges, such as climate change, global energy demand, food security and land use.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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2.2. Effects on Crop Development, Yields and Chemical Composition of Celeriac (*Apium graveolens* L. *var. rapaceum*) Cultivated Underneath an Agrivoltaic System

This section addresses the impacts of AV on the cultivation of celeriac (*Apium graveolens* L. *var. rapaceum*) as indicated by the results from the two-year field experiment at the AV research facility in Herdwangen-Schönach. To assess the effects of AV on crop productivity, different parameters of crop development like growth stage, crop height and leaf area index have been monitored. At harvest, fresh matter bulb yields as well as above ground biomass have been ascertained. To further examine how chemical composition of the Celeriac bulbs was altered by AV, different compounds have been analyzed. Correspondingly, this section addresses research questions 3 and 4.

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Effects on Crop Development, Yields and Chemical Composition of Celeriac (*Apium graveolens* L. *var. rapaceum*) Cultivated Underneath an Agrivoltaic System

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Abstract: Agrivoltaic (AV) systems increase land productivity through the combined production of renewable energy and food. Although several studies have addressed their impact on crop production, many aspects remain unexplored. The objective of this study was to determine the effects of AV on the cultivation of celeriac, a common root vegetable in Central Europe. Celeriac was cultivated in 2017 and 2018 as part of an organically managed on-farm experiment, both underneath an AV system and in full-sun conditions. Under AV, photosynthetic active radiation was reduced by about 30%. Monitoring of crop development showed that in both years, plant height increased significantly under AV. Fresh bulb yield decreased by about 19% in 2017 and increased by about 12% in 2018 in AV, but the changes were not significant. Aboveground biomass increased in both years under AV, but only increased significantly in 2018. As aboveground biomass is a determinant of root biomass at harvest in root vegetables, bulb yields may be further increased by a prolonged vegetation period under AV. Compound analysis of celeriac bulbs did not show any clear effects from treatment. As harvestable yields were not significantly reduced, we concluded that celeriac can be considered a suitable crop for cultivation under AV.

Keywords: agrivoltaic; agrophotovoltaic; Agri-PV; shading; crop performance; yields; product quality; organic agriculture; biodynamic agriculture; land productivity

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1. Introduction

Agrivoltaic (AV) systems are currently being implemented in a number of countries as an approach for the dual use of arable land for renewable energy and agricultural production [1,2]. It has been shown that both land productivity and farm income can be increased by the additional energy generated through AV [1–5]. Recently, first concepts for the integration of AV into prospective farming systems—e.g., in combination with farming robots—have been proposed [6]. However, considering the land use conflict between food and energy production, a sustained adequate agricultural yield needs to be guaranteed if AV systems are to be used. This necessitates further field studies on the performance of agricultural crops under AV. The implementation of AV is currently being investigated in field trials by several researchers [2,5,7–9]. So far, a number of crops have been assessed for their suitability for cultivation underneath AV, including lettuce [8], corn [10], potatoes, winter wheat [9], and fruit vegetables (such as cherry tomatoes and chili peppers) [7]. Additionally, grass-clover has been investigated as a perennial forage crop [9]. These studies have shown that sufficient crop yields can be achieved in the partial shade of the photovoltaic (PV) modules of AV systems, but agricultural yield reductions of up to 20% can occur [8,9,11]. By contrast, in hot and dry weather conditions, reduced solar radiation and microclimatic alterations under AV (e.g., lower soil [8,9] and air temperatures [9] and potential advantages in water use efficiency [12]) can be beneficial for crop production and lead to increased yields [7,9].

The present study was conducted on-farm within a field trial with four different crops (celeriac, grass-clover, potato and winter wheat) cultivated underneath an AV system. The crops were cultivated as part of a crop rotation under organic management. This setup was chosen because, to date, no AV studies have been conducted under organic field management conditions. Furthermore, organic farming generally strives to reduce external inputs “by reuse, recycling and efficient management of materials and energy in order to maintain and improve environmental quality and conserve resources”, as a matter of principle—as described by the International Federation of Organic Agriculture Movements (IFOAM) [13]. Thus, organic farming also addresses energetic self-sufficiency and the replacement of fossil energy resources. As such, AV would appear an appropriate approach in this context. Further details on the field trial were reported by Weselek et al. [9]. Harvestable crop yields decreased by 18.7% (wheat), 18.2% (potatoes) and 5.3% (grass-clover) in 2017, but increased by 2.7% (wheat) and 11% (potatoes) in 2018. Grass-clover yields in 2018 were reduced by 7.8% [9]. The results were linked to quite distinct climatic differences between the years; 2018 brought lower precipitation, higher temperatures and greater solar irradiance. In the same time frame, 246 MWh of energy were generated by the AV facility in the first cropping year, which corresponds to about 83% of the electrical yield a conventional ground-mounted PV installation covering the same area would have achieved [14]. Hence, even with a reduction of harvestable crop yield of 18.7% for winter wheat in 2017, overall land productivity was increased by about 56% in comparison to single crop and PV production [14]. The results further emphasized findings from previous studies [3] on the benefits of AV regarding land use and land productivity.

As a recent study showed, long term land productivity and market certainty are often seen as the main arguments favoring the implementation of AV from farmers' perspective [15]. This emphasizes the need for agricultural field trials. However, experimental data on the impact of AV on crop production are scarce; few data are available for field vegetables and, in particular, root vegetables. In 2017, vegetables were cultivated on a total area of 2.2 million hectares in Europe [16]. As comparatively high market revenues can be achieved with vegetables, the impacts of AV on cultivation and harvestable crop yields will be of major interest. Celeriac (*Apium graveolens* L. var. *rapaceum*), also known as turnip-rooted celery or knob celery, is a celery variety cultivated primarily in Central and Eastern Europe [17,18]. In contrast to common celery (*Apium graveolens* var. *graveolens*) and leaf celery (*Apium graveolens* var. *secalinum*), this biennial crop forms large bulbs in the first cropping year—which consist of hypocotyl, tap root and stem in equal proportions [17]. Celeriac bulbs have white flesh and can be used both cooked and raw. In 2018, organic celeriac was cultivated on a total of about 219 hectares in Germany, producing 6853 tons of harvested celeriac bulbs [19].

The aim of our study was to investigate how celeriac (a common field vegetable) would be affected if it were cultivated underneath the solar panels of an AV system (Figure 1). In addition to examining parameters such as crop development and yields, the study examined, for the first time, how altered microclimatic conditions in the partial shade of the AV facility affected the chemical composition—and consequently, the quality—of celeriac.

Figure 1. Celeriac plants growing underneath the agrivoltaic (AV) facility in 2017. The reference site is located behind the facility. (source: Bauerle/University of Hohenheim).

2. Material & Methods

2.1. Site Description & Field Experiment

Celeriac was cultivated as part of an on-farm field experiment using a four-year crop rotation (along with winter wheat (*Tricticum aestivum*), potato (*Solanum tuberosum*) and grass-clover) [9]. The field trial was performed on a commercial farm managed according to biodynamic principles (Demeter) as described in [9]. Details on the design of the AV facility were described by Trommsdorff et al. [14]. In both 2017 and 2018, celeriac was grown on a strip 24 m long and 19 m wide under an AV system, with a total size of 0.3 ha. Additional celeriac was grown on an adjacent reference area (REF) without solar panels (Figure 2). To avoid any shading of the REF site, it was located at a distance of 20 m from the AV facility. On both sites, four trial plots of 1 m^2 were defined. To reduce border effects—in particular under the AV facility—the plots were located at least 4 m from the sites' borders. Celeriac plantlets (*Apium graveolens* L. var. *rapaceum*, Goliath variety) were sown in seed trays and planted out around development stage 13 (according to BBCH (Biologische Bundesanstalt, Bundessortenamt und CHemische Industrie) scale for root and stem vegetables [20]) at a density of 45,000 plants per hectare. In both years, planting took place on 5 May. The celeriac cropping area was fertilized with 15 t composted cow manure per hectare between mid-February and mid-March. Biodynamic preparations (20 l per hectare each of horn manure and horn silica) were sprayed according to Demeter guidelines twice a year. Weed control was mainly conducted by currycombing before planting (twice) and hoeing after planting (up to four times). Additional hand weeding was performed if weed pressure became high within the rows. In 2017, the preceding crop was perennial grass-clover; in 2018, it was potato. For further information on field management, see [9].

2.2. Microclimate

Microclimate was monitored via eight microclimate stations (i.e., four per treatment) on the celeriac cropping area, each assigned to one of the trial plots. Each microclimate station was equipped with different sensors and recorded various microclimatic parameters. Air temperature and humidity were measured at a height of 2 m using a VP-4 sensor. Soil temperature and moisture were measured at a depth of approximately 25 cm using a 5TM sensor. Due to tillage operations, soil sensors were only installed during the celeriac cropping period from 8 June to 10 October in 2017, and from 9 May to 22 October 2018.

Photosynthetic active radiation (PAR) was estimated by photosynthetically active photon flux density (PPFD) using a QSO-S sensor. All parameters were recorded with data loggers (EM50G). Data loggers (and the sensors mentioned above) were obtained from METER Group AG (Munich, Germany). In addition to the data collected in the field trial, meteorological data for comparison were obtained from Agricultural Meteorology Baden-Wuerttemberg, published by the Agricultural Technology Centre Augustenberg (LTZ) [21]. The weather station nearest to the field trial was located at Billafingen (47.83° latitude 9.13° longitude), 2 kilometers away. Mean monthly temperature and accumulated precipitation are shown in Figure 3 (data taken from Billafingen weather station [21]). Note that values recorded in the field trial cannot be directly compared with those recorded at the weather station, as they are located at different spots and their instruments have not been calibrated. Furthermore, in 2018, no values were recorded at our field trial from 11 to 13 December due to a power outage.

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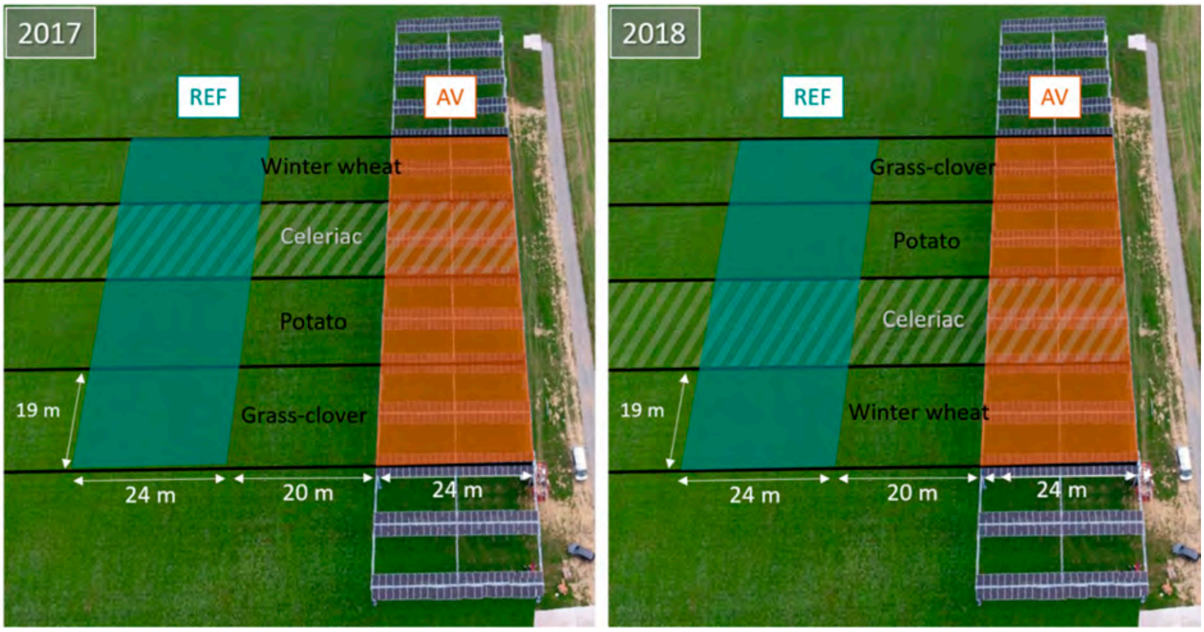

Figure 2. Setup of the field experiment in 2017 and 2018 with location of celeriac within the crop rotation. The experimental site was split into a reference (REF) and agrivoltaic (AV) site. The diagram is a schematic illustration and not to scale. (image source: BayWa r.e., modified).

Figure 2: Setup of the field experiment in 2017 and 2018 with location of celeriac within the crop rotation. The experimental site was split into a reference (REF) and agrivoltaic (AV) site. The diagram is a schematic illustration and not to scale. (image source: BayWa r.e., modified).

Climatic conditions varied greatly between the two years. In 2017, annual accumulated precipitation was 1351 mm, annual solar was radiation 1180 kWh/m^2, and mean annual temperature was 8.6 °C. In 2018, accumulated precipitation was 916 mm, annual solar radiation was 1204 kWh/m^2, and mean annual temperature was 9.7 °C.

2.3. Crop Monitoring & Harvest

Crop development was monitored over two growing seasons, beginning in May (both years) immediately after the celeriac was planted and lasting until shortly before final harvest. The last monitoring dates were 26 September in 2017 and 18 October in 2018. In each of the defined plots, 12 individual plants were selected and tagged. Of these, 10 plants were monitored and two were kept as backup in case of plant losses. Crop development was monitored every two weeks. Crop height was measured using a folding rule. Leaf area index (LAI) was measured using a plant canopy analyzer (LAI-2200C, LI-COR Biosciences, Lincoln, Dearborn, MI, USA). On each monitoring date, twelve single measurements were taken per plot: six measurements between plants within the rows, and six measurements between rows. The final harvest was performed on the farm's actual harvest dates. The 12 selected plants in each plot were harvested manually. Each celeriac plant was separated into aboveground and belowground biomass. Remaining roots were roughly removed from

2.2. Microclimate

Microclimate was monitored via eight microclimate stations (i.e., four per treatment) on the celeriac cropping area, each assigned to one of the trial plots. Each microclimate station was equipped with different sensors and recorded various microclimatic parameters. Air temperature and humidity were measured at a height of 2 m using a VP-4 sensor. Soil temperature and moisture were measured at a depth of approximately 25 cm using a 5TM sensor. Due to tillage operations, soil sensors were only installed during the celeriac cropping period from 8 June to 10 October in 2017, and from 9 May to 22 October 2018. Photosynthetic active radiation (PAR) was estimated by photosynthetically active photon flux density (PPFD) using a QSO-S sensor. All parameters were recorded with data loggers (EM50G). Data loggers (and the sensors mentioned above) were obtained from METER Group AG (Munich, Germany). In addition to the data collected in the field trial, meteorological data for comparison were obtained from Agricultural Meteorology Baden-Wuerttemberg, published by the Agricultural Technology Centre Augustenberg (LTZ) [21]. The weather station nearest to the field trial was located at Billafingen (47.83° latitude 9.13° longitude), 2 kilometers away. Mean monthly temperature and accumulated precipitation are shown in Figure 3 (data taken from Billafingen weather station [21]). Note that values recorded in the field trial cannot be directly compared with those recorded at the weather station, as they are located at different spots and their instruments have not been calibrated. Furthermore, in 2018, no values were recorded at our field trial from 11 to 13 December due to a power outage.

the bulbs. The aboveground biomass from each plot was weighed and subsequently dried for 48 h at 60°C to determine dry matter yield. Diameter and weight of each celeriac bulb was measured. For the analysis of chemical composition, bulbs were peeled, washed with distilled water and ground (Thermomix, Vorwerk, Wuppertal, Germany). The resulting fibrous pulp was freeze-dried at 0.34 mbar and −32°C until completely dry and then stored at −20°C for further analysis.

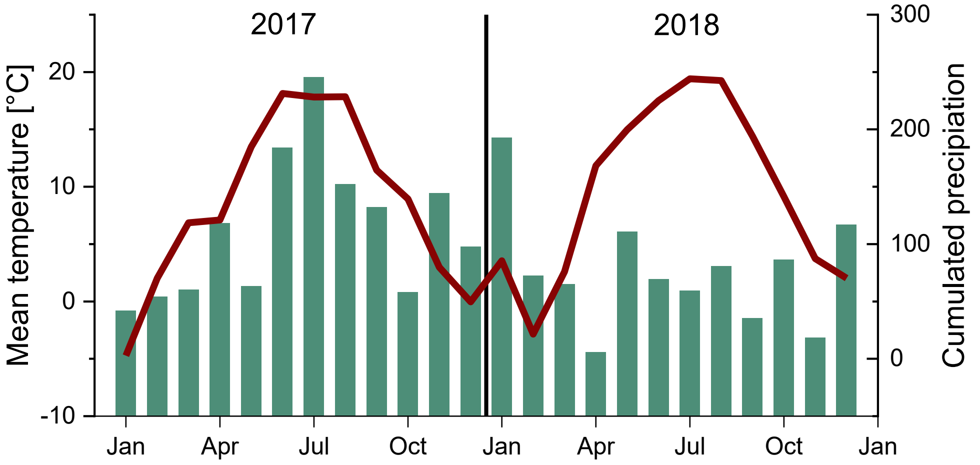

Figure 3. Monthly mean temperature (red curve) and monthly accumulated precipitation (cyan bars) in 2017 and 2018. Data from Agricultural Meteorology Baden-Wuerttemberg, Billafingen weather station.

2.4. *Analysis of Chemical Composition*

For chemical analysis, the freeze-dried samples were ground to a fine powder (MM400, Retsch, Haan, Germany) using ceramic grinding jars to avoid any heavy metal contamination. Before analysis by ICP-OES and ICP-MS, samples were digested by microwave pressure digestion (UltraCLAVE III, MLS, Leutkirch, Germany) according to method 10.8.1.2 of the Association of German Agricultural Analytic and Research Institutes (VDLUFA) [22]. For analysis of Al and Si, samples were additionally digested with 0.5 M hydrofluoric acid to avoid silicate formation. The minerals Al, B, Ba, Ca, Cu, Fe, K, Mg, Mn, Na, P, Zn, and Si were analyzed by ICP-OES (5100 ICP-OES, Agilent, Santa Clara, USA) according to EN standard 15621:2017-10 [23]. The trace elements and heavy metals Cd, Co, Cr, Mo, Ni, Pb, Se, Fe, Cl, and I were analyzed by Inductively Coupled Plasma Mass Spectrometry ICP-MS (NexION 300X ICP-MS, PerkinElmer, Waltham, MA, USA) according to the VDLUFA (Verband deutscher landwirtschaftlicher Untersuchungs- und Forschungsanstalten) method 17.9.1 [24]. For Cl analysis, samples were extracted in simmering water according to VDLUFA method 2.2.2.2 [25]. For iodine analysis, samples were extracted with 0.5% ammonium hydroxide according to VDLUFA method 2.2.2.3 [26]. Carbon and sulfur were analyzed based on the Dumas combustion method [27]. Crude protein, crude fat and crude fiber were determined (using a Fibertherm apparatus, C. Gerhardt, Königswinter, Germany) following the European Commission (EC) regulation No. 152/2009 III [28]. For the calculation of crude protein, the N concentration was multiplied by a conversion factor of 6.25. Neutral detergent fiber (amylase treated, after ashing, aNDFom), acid detergent fiber (after ashing, ADFom), and acid detergent lignin (ADL) were determined according to VDLUFA methods 6.5.1, 6.5.2 and 6.5.3 [29–31], respectively, using a Fibertherm apparatus (Fibertherm, C. Gerhardt, Königswinter, Germany). In 2017, aNDFom, ADFom and ADL were not analyzed due to insufficient sample material.

2.5. *Statistical Analysis*

Statistical analysis was conducted according to the method of Wesselak et al. [9]. The experimental set-up can be considered a single replicate of a strip-plot design with two treatments, AV and REF. Note that a replicate of each treatment would require another

Figure 3. Monthly mean temperature (red curve) and monthly accumulated precipitation (cyan bars) in 2017 and 2018. Data from Agricultural Meteorology Baden-Wuerttemberg, Billafingen weather station.

Climatic conditions varied greatly between the two years. In 2017, annual accumulated precipitation was 1551 mm, annual solar was radiation 1180 kWh/m², and mean annual temperature was 8.6 °C. In 2018, accumulated precipitation was 916 mm, annual solar radiation was 1204 kWh/m², and mean annual temperature was 9.7 °C.

2.3. *Crop Monitoring & Harvest*

Crop development was monitored over two growing seasons, beginning in May (both years) immediately after the celeriac was planted and lasting until shortly before final harvest. The last monitoring dates were 26 September in 2017 and 18 October in 2018. In each of the defined plots, 12 individual plants were selected and tagged. Of these, 10 plants were monitored and two were kept as backup in case of plant losses. Crop development was monitored every two weeks. Crop height was measured using a folding rule. Leaf area index (LAI) was measured using a plant canopy analyzer (LAI-2200C, LI-COR Biosciences, Lincoln, Dearborn, MI, USA). On each monitoring date, twelve single measurements were taken per plot; six measurements between plants within the rows, and six measurements between rows. The final harvest was performed on the farm's actual harvest dates. The 12 selected plants in each plot were harvested manually. Each celeriac plant was separated into aboveground and belowground biomass. Remaining roots were roughly removed from the bulbs. The aboveground biomass from each plot was weighed and subsequently dried for 48 h at 60°C to determine dry matter yield. Diameter and weight of each celeriac bulb was measured. For the analysis of chemical composition, bulbs were peeled, washed with distilled water and ground (Thermomix, Vorwerk, Wuppertal, Germany). The resulting fibrous pulp was freeze-dried at 0.34 mbar and −32°C until completely dry and then stored at −20°C for further analysis.

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AV system. The data analysis was carried out with SAS software version 9.4 (SAS Institute Inc., Cary, NC, USA) using the following model for crop development:

$$y_{ijkl} = \mu + b_{kij} + \tau_i + \varphi_j + (\tau\varphi)_{ij} + e_{ijkl}, \quad (1)$$

where b_{kij} is the fixed effect of lane k in treatment i at day j, τ_i is the i-th treatment effect, φ_j is the j-th day effect and $(\tau\varphi)_{ij}$ is the interaction effect of day j and treatment i. e_{ijkl} is the repeated measurement error of observation y_{ijkl} with a first-order autoregressive variance-covariance structure of error effects from the same measuring point. Note that the variance of repeated measurements on the same plot underestimates the true error variance, and thus all tests are too liberal.

As harvestable crop yield was measured in two successive years but only once per year, an analogous model to (1) can be fitted replacing day j by year n:

$$y_{inkl} = \mu + b_{kin} + \tau_i + \rho_n + (\tau\rho)_{in} + e_{inkl}, \quad (2)$$

where ρ_n and $(\tau\rho)_{in}$ are the effects of the n-th year and its interaction effects with treatment. All other effects are defined analogously to model (1).

Analysis of chemical composition was conducted accordingly for each parameter:

$$y_{inkl} = \mu + b_{kin} + \tau_i + \rho_n + (\tau\rho)_{in} + e_{inkl} \quad (3)$$

where significant differences were found via an F test, a multiple t-test (Fisher′s LSD test) was performed. Results of multiple t-tests are presented as a letter display.

3. Results & Discussion

3.1. Microclimate

An overview of the results of microclimate monitoring is presented in Table 1. Photosynthetic active radiation was, on average, reduced by about 29.5% under AV, which is within the range of the results from previous modeling and field studies, where reductions of irradiance ranged from 12% up to more than 60%, depending on the setup of the AV system [3,32,33]. Soil temperature was reduced by 1.2 °C in 2017 and 1.4 °C in 2018. This is in accordance with findings from Marrou et al. [32], who also found soil temperature to be reduced under AV. In 2017, yearly mean soil moisture was 1.9% higher under AV, while it decreased by about 3.1% in 2018. In both years, yearly mean air humidity was 2.8% higher in AV compared to REF. No differences between the treatments were found in yearly mean air temperature. In contrast, Marrou et al. [32] did not find any differences in aerial microclimate (temperature and humidity) between AV and unshaded control. The results also reflect the differences between the years—as also shown by the weather data recorded at the weather station in Billafingen (see Section 2.2.)—with comparably high temperatures and dry conditions in 2018. The yearly mean air temperature was 1.7 °C higher in 2018 compared to 2017. Air humidity and soil moisture were lower in both treatments compared to 2017. Additionally, photosynthetic photon flux density was slightly increased in 2018. Further details on microclimate monitoring have been reported [9].

Table 1. Yearly averages of air temperature and humidity, soil temperature and moisture as well as photosynthetic active radiation expressed by photosynthetic photon flux density (PFD) under the agrivoltaic system (AV) and on the reference site (REF) in 2017 and 2018.

		Air Temperature [°C]	Humidity [%]	Soil Temperature [°C]	Soil Moisture [%]	PPFD [μmol/m^{2}s]
2017	REF	8.7	79.1	18.4	25.2	469.4
	AV	8.7	81.9	17.2	27.1	336.7
2018	REF	10.4	71.6	19.2	20.9	497.9
	AV	10.4	74.4	17.8	17.8	344.5

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2017	REF	8.7	79.1	18.4	25.2	469.4
	AV	8.7	81.9	17.2	27.1	336.7
2018	REF	10.4	71.6	19.2	20.9	497.9
	AV	10.4	74.4	17.8	17.8	344.5

3.2. Crop Development

Celeriac growth and development was monitored on 10 days in 2017 and 11 days in 2018 (due to later harvest date).

After planting in May, the plantlets established quite slowly in 2017 in both treatments, which may be explained by the subsequent low precipitation of about 50 mm in May (Figure 4a). This also led to a certain amount of plant loss (not quantified). Consequently, crop development was delayed for several weeks until shoot growth started: mean plant height remained constant on the first four monitoring days and had even decreased slightly at the end of June. After the pronounced period of drought in May, monthly precipitation was between 150 and 250 mm from June to August. Nevertheless, it took until the middle of July before the celeriac plantlets had recovered, at which point shoot height gradually increased, reaching a maximum crop height of 35.7 cm under AV and 29.4 cm for REF 130 days after planting (DAP).

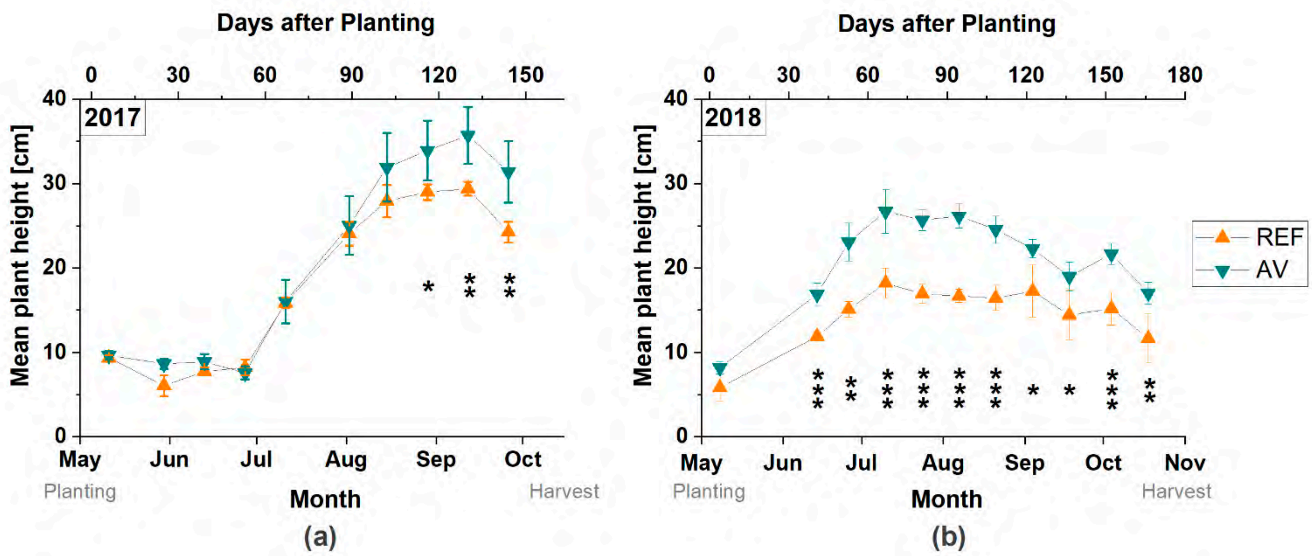

Figure 4. Mean plant height under AV (cyan triangles) and on REF (orange triangles) in 2017 (**a**) and 2018 (**b**). Significant differences are indicated by stars (* $p < 0.05$; ** $p < 0.005$; *** $p < 0.0005$). Standard deviation is depicted by error bars.

By contrast, in 2018, plants had already doubled their height by the second monitoring date in mid-June (Figure 4b). At this point, the celeriac cultivated under AV was 30% higher than on the REF site, while in 2017 growth had just begun in both treatments. The mean maximum crop height of 26.6 cm in AV and 16.7 cm in REF was recorded at 66 DAP. Plant height then decreased until final harvest. In May 2018, accumulated precipitation was 100 mm—more than twice as high as in May 2017. After that, however, monthly precipitation in 2018 remained below 100 mm until December (Figure 2) and consequently aboveground plant growth had stopped by mid-July in both treatments.

As a result, final plant development was better in 2017 than in 2018, although plantlet establishment was less problematic in 2018. The potatoes, which were planted shortly before the celeriac, were also found to have a lower initial plant height during the first weeks after emergence in 2017 than in 2018 [9].

In addition to year-related effects, crop height was also affected by treatment: celeriac plants were significantly higher under AV than in REF on three monitoring dates in 2017 and ten of the eleven dates in 2018 (Figure 4a,b). Differences in crop height between the treatments were more pronounced in 2018 than in 2017: averaged over all monitoring dates, crop height in AV was 30.6% higher than REF in 2018, but only 14% higher in 2017. In 2017, the mean difference in crop height between the treatments slowly increased from the 5th monitoring date (67 DAP) onwards, reaching a maximum (at final harvest, 144 DAP) of +7.2 cm in AV. In 2018, mean difference in crop height between the treatments was highest on the 6th monitoring date (94 DAP) at +9.5 cm in AV and then slowly decreased to +5.4 cm at final harvest (166 DAP). These treatment-related differences within the years corresponded to the general crop development, as described above. In 2017, crop height (and also difference between the treatments) increased from July onwards; meanwhile, in 2018, the crop reached maximum height by the middle of the growing season and then decreased until final harvest. However, the results show that crop height was increased by AV in both years. Similar results have been found for potatoes and winter wheat [9], where crop height was significantly increased by AV in both 2017 and 2018. As discussed by [9], increases in crop height are most probably due to shading; under AV, PAR was reduced by 30% on average in both years [9] (Table 1). These findings are in line with results from experiments with artificial shading, in which the canopy height of wheat [34,35] and potato [36] was increased by shading. Increased elongation growth under decreased light intensities can be interpreted as a shade-adaptive response by the plants in order to capture more light [37,38].

Leaf area index (LAI) was measured on seven monitoring days in 2017 and ten monitoring days in 2018. In 2017, no measurements were possible until the end of June as the plantlets were too small. LAI values differed only slightly between the years (Figure 5). As discussed above, the LAI values also indicated delayed development of the plantlets in 2017, which began to grow slowly from the end of June onwards (Figure 5a). On the other hand, in 2018, LAI values of approximately 2.5 had already been recorded in June (Figure 5b). Variations in LAI between the monitoring dates may be explained as an artifact caused by the occasional occurrence of weeds and the senescence of outer leaves—which may have led to lower LAI values being recorded from time to time. In 2017 in particular, leaves showed clear signs of Septoria leaf spot infection caused by the fungus *Septoria apiicola*, which led to early leaf senescence and consequently to a certain amount of loss of outer, older leaves. This explained the trend of declining LAI values from September onwards. As a similar effect of premature leaf senescence was observed in both treatments, the impact of uneven rain distribution under AV [9] can be excluded as the cause of the infestation by fungal leaf disease, based on the present data. However, infestation and pathogenesis were not monitored explicitly, and should be addressed in more detail in future—particularly as humidity was shown to be slightly higher under AV (Table 1). In 2018, celeriac leaves were still green at final harvest and did not show any signs of Septoria leaf spot infection. This can be seen from the LAI values, which were more or less constant until harvest. Similarly to crop height, LAI increased under AV, but the increase was only significant on one monitoring date in 2017 (166DAP) and four monitoring dates in 2018 (66, 94, 136 and 166 DAP). An increased leaf area under AV has also been found in lettuce [8], winter wheat, potatoes and grass-clover [9]. In lettuce, changes in total leaf area were linked to an increment in individual leaf area (width and length), as well as to altered leaf angles. However, the number of leaves was reduced by shading and depended on the level of shading applied [8]. In our experiment, the determinants of increased LAI could not be clearly specified, as leaf number and other leaf morphology characteristics were not monitored. In general, an increase in leaf area can be interpreted as a further physiological adaptation to diminished light availability under AV, in addition to increased crop height. Both strategies focus on intercepting more light to maintain sufficient photosynthetic performance [37].

As discussed above, both crop height and LAI of celeriac cultivated under AV were increased. Enhanced vegetative growth, as a consequence of decreased light intensities, can be interpreted as a shade-adaptive response aimed at enhancing light adsorption [37,38]. At the same time, increased elongation growth in response to shading is considered a shade-avoidance strategy, predominantly found in species less adapted to shaded environments [37,38]. Increased specific leaf area and leaf area ratio—both of which describe the relation of leaf area to plant biomass—can enhance the shade tolerance of plants [37,39]. Although the specific leaf area and leaf area ratio could not be deduced from the LAI measurements in our trial, the results indicated that the celeriac—and also crops like potatoes dates in 2018 (60, 91, 130 and 160 DAP). An increased leaf area under AV has also been found in lettuce [8], winter wheat, potatoes and grass-clover [9]. In lettuce, changes in total leaf area were linked to an increment in individual leaf area (width and length), as well as to altered leaf angles. However, the number of leaves was reduced by shading and depended on the level of shading applied [8]. In our experiment, the determinants of increased LAI could not be clearly specified, as leaf number and other leaf morphology characteristics were not monitored. In general, an increase in leaf area can be interpreted as a further physiological adaptation to diminished light availability under AV, in addition to increased crop height. Both strategies focus on intercepting more light to maintain sufficient photosynthetic performance [37].

and wheat [9]—adapted to the reduced irradiation underneath the PV panels of the AV facility through a combination of shade-adaptive mechanisms.

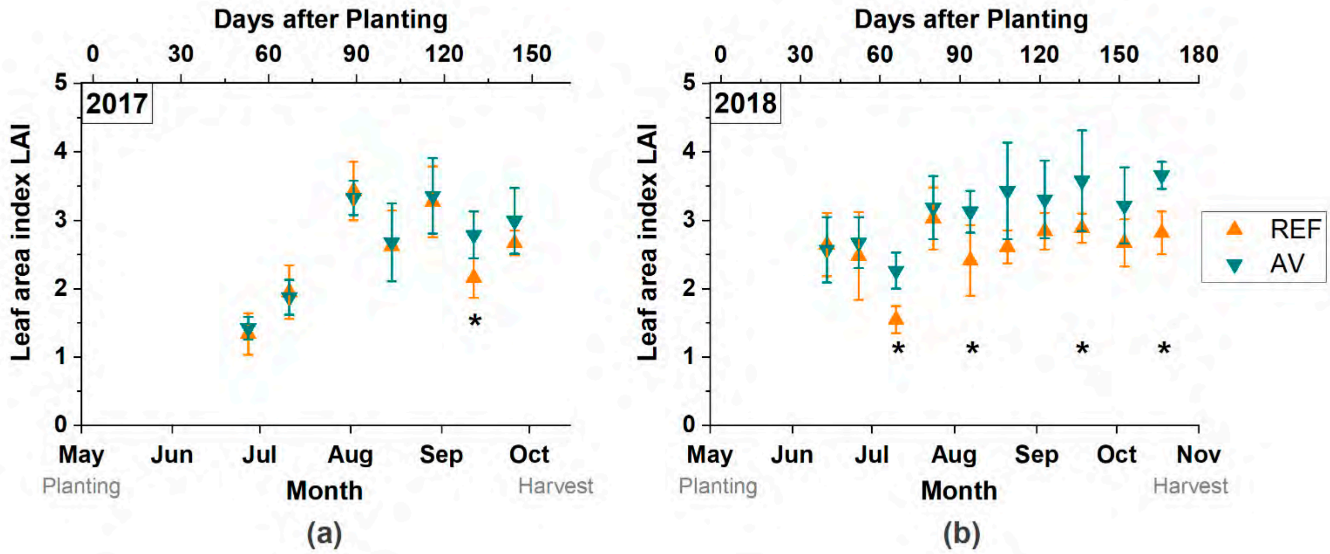

Figure 5. Leaf area index (LAI) of plants grown under AV (cyan triangles) and in REF (orange triangles) in 2017 (**a**) and 2018 (**b**). Significant differences (* $p \leq 0.05$) are indicated by stars. Standard deviation is depicted by error bars.

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3.3. Bulb Yields and Yield Components

The celeriac was harvested on 10 October in 2017 and 22 October in 2018 in both treatments. The early harvest date in 2017 was due to the fact that no further yield increases were to be expected on account of early leaf senescence (see also Section 3.2.). However, the date was still within the common celeriac harvest period. Aboveground biomass was increased by AV in both years, but only significantly in 2018 (Figure 6a). Dry matter yield of aboveground biomass was 0.37 t ha^{-1} in REF and 0.55 t ha^{-1} in AV (+48%; $p = 0.082$) in 2017, and 1.1 t ha^{-1} in REF and 1.4 t ha^{-1} in AV in 2018 (+31.9%; $p = 0.0045$). Interestingly, aboveground biomass was higher in 2018, although crop height was higher in 2017. We postulate that this was caused by the very distinct weather conditions in the two years, which affected both aboveground biomass and crop height in different ways. First, initial shoot growth was virtually zero in the first few weeks after planting in 2017. We assume that this period conferred a crucial growth advantage in 2018, leading to higher final shoot biomass in that year. Second, the dry weather conditions in summer 2018 may have led to a decrease in turgor pressure as a response to drought stress, leading to more wilting of leaves. As crop height was measured without lifting up individual leaves, this will also have led to lower crop heights being recorded. This explanation is supported by the finding that, in 2018, crop heights had decreased by the middle of July with the onset of drought stress. Furthermore, hanging leaves will also have led to an enlarged leaf rosette, explaining why LAI was higher in 2018 despite lower crop heights. The third—and presumably most crucial—factor was disease; aboveground biomass was lower in 2017 due to infection with Septoria leaf spot, leading to early leaf senescence and consequently a certain loss of matured leaves.

Celeriac bulb yield was 11.9 t ha^{-1} in REF and 9.7 t ha^{-1} in AV (−18.9%; $p = 0.15$) (Figure 4) in 2017, and 9.6 t ha^{-1} in REF and 10.8 t ha^{-1} in AV (+11.8%; $p = 0.49$) in 2018 (Figure 6b). Neither the differences between the treatments nor those between the years were significant. The yields in both years and treatments were low in comparison with the national average for organically cultivated celeriac, which was 29.6 t ha^{-1} in 2017 and 31.1 t ha^{-1} in 2018 [19]. In general, celeriac is considered drought-sensitive, with drought stress leading to small, poorly developed bulbs [17,18]. Therefore, it can be assumed that the dry weather conditions in spring 2017 and especially summer 2018 probably led to comparatively low bulb yields. This is particularly probable given that the celeriac plants in our trial were not irrigated. The bulbs were poorly developed in both years and treatments (Figure 7). Average individual bulb weight was 196 g (REF) and 158 g (AV) in 2017, and 186 g (REF) and 197 g (AV) in 2018. Average bulb diameter was 7.3 cm (REF) and 6.6 cm (AV) in 2017 and 7.5 cm (REF and AV) in 2018. Both average weights and diameters can be considered undersized. To meet the criteria of the wholesaler the farm supplies, celeriac must fulfill the class 1 UNECE (United Nations Economic Commission for Europe) standard for root and tubercle vegetables [40]. In addition, the bulbs must have a minimum weight of 350 g if only the bulbs are sold, or a minimum size of 60 mm if whole plants (bulb including leaves) are sold. Taking these criteria into consideration and assuming only bulbs (without leaves) are sold: of the 48 bulbs harvested from each treatment in 2017, only one (AV) and four (REF) were actually marketable. In 2018, the respective numbers were zero (AV) and one (REF). Extrapolated to a hectare, marketable bulb yields would consequently have been only 0.5 t ha^{-1} (AV) and 2 t ha^{-1} (REF) in 2017, and 0 t ha^{-1} (AV) and 3.6 t ha^{-1} (REF) in 2018. If sold as whole plants, marketable bulb yield would have been 7.8 t ha^{-1} (AV) and 10.6 t ha^{-1} (REF) in 2017, and 10.3 t ha^{-1} (AV) and 8.8 t ha^{-1} (REF) in 2018.

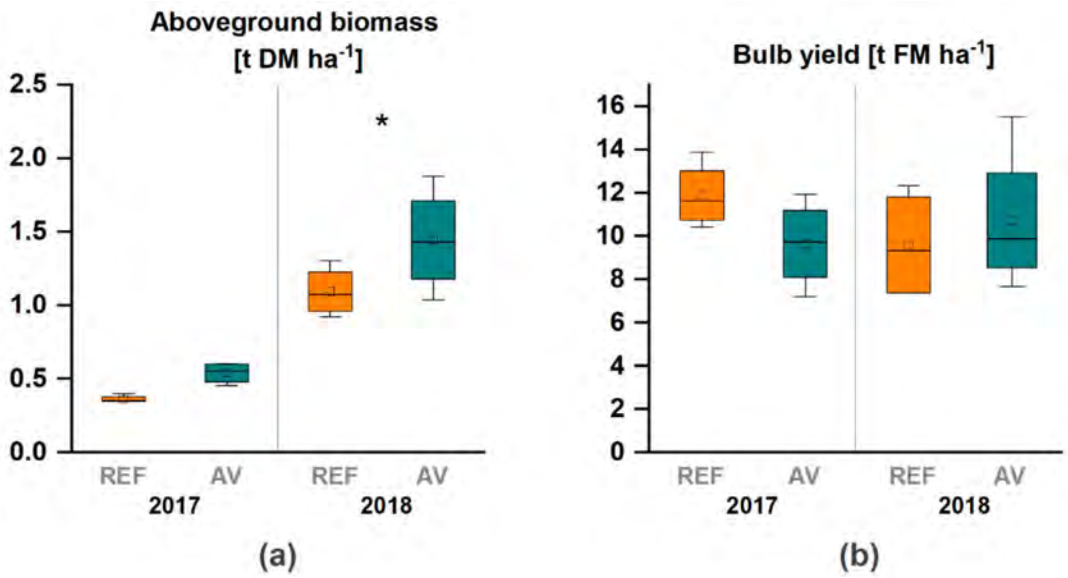

Figure 6. Celeriac aboveground biomass (t dry matter ha^{-1}) (**a**) and bulb yield (t fresh matter ha^{-1}) (**b**) in REF and AV in 2017 and 2018. Significant differences are indicated by stars (* $p < 0.005$).

As mentioned above, yield variations within the years differed between the treatments. Averaged over both treatments, bulb yield was higher in 2017 (10.8 t ha^{-1}) than 2018 (10.2 t ha^{-1}). While bulb yields from the REF site were 2.3 t ha^{-1} lower in 2018 than 2017, yields on the AV site actually increased by about 1.1 t ha^{-1}. Lower yields under AV in 2017 were most probably caused by the reduction in solar radiation (about 30%) (Table 1). In contrast, the yield increases under AV in 2018 indicate that the celeriac plants benefitted from shading that year. It can be assumed that, in 2018, drought, intensive solar radiation, and high temperatures counterbalanced the adverse effects of shading on celeriac productivity. However, it remains unclear whether this was caused directly (by attenuating irradiation) or indirectly (by altering microclimatic conditions to provide a more favorable microclimatic environment for celeriac growth). It was expected that soil moisture would increase under AV, as a reduction in evapotranspiration in the partial shade of AV panels was already reported [12]. However, soil moisture under AV only increased in 2017; it was actually reduced in 2018 (Table 1). Therefore, soil moisture can be excluded as a potential explanation for increased crop yields under AV in 2018.

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Figure 7. Celeriac harvested in 2017. The plants all come from one plot. In each treatment, four plots (with 12 plants each) were harvested. Most bulbs are comparatively small and some leaves are already senescent. (Source: Bauerle/University of Hohenheim).

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As shown, soil temperature was reduced by AV (Table 1). Although this was the case in both years, we assumed that reduced soil temperature and a direct reduction in solar radiation under AV were the determining factors that diminished the adverse effects of excessive irradiation, heat, and drought on crop yields in 2018. Furthermore, increases in aboveground biomass, as mentioned above, may also have led to higher bulb yields in 2018 through higher amounts of assimilates being translocated from the shoots to the bulbs.

While no comparable data is available for celeriac, studies with other root vegetables (e.g., carrot, parsnip, radish and beetroot) have shown that shoot and storage-root weights are linearly correlated, with slight differences between species [41–43]. Biologically, celeriac is comparable to beetroot and radish, species in which the storage organ also develops from the hypocotyl. We therefore hypothesized that the significantly higher aboveground biomass under AV in 2018 was a determining factor for the higher bulb yield compared to REF. As the vegetation period in 2018 was prolonged due to the later harvest date, the period for the translocation of assimilates from the shoot to the storage root was also extended. This raises the question of whether delaying the harvest could have facilitated mobilization of the full assimilate potential stored in the shoot, increasing bulb weights and yields under AV. A study with lettuce cultivated underneath an AV system found that a delayed harvest date led to yields comparable to the unshaded control [44]. However, in the case of celeriac, a further increase in bulb yields through a prolonged vegetation period would be limited by environmental conditions. Mild autumnal temperatures are required for translocation of assimilates to the storage organ to continue. In addition, the 2017 results showed that infestation with fungal diseases can also become a limiting factor, leading to premature leaf senescence and preventing further yield increases.

Relative changes in harvestable yields of winter wheat and potatoes cultivated under AV were comparable to those of celeriac in the present study. While in 2017, yields decreased by about 18–19%, they increased by about 3% (wheat) and 11% (potato) in 2018 [9]. Accordingly, all annual crop species investigated in the field trial showed comparable responses to cultivation in the altered environment underneath the AV facility. Moreover, yield fluctuations between the years were less pronounced under AV, as was the case with celeriac. This supports the hypothesis that cultivation under AV can be advantageous in dry weather conditions and may have yield-stabilizing effects in the long term [9,33], but further trial years are needed for validation. The results indicated that—outside of dry climates where a general reduction in sun exposure can be beneficial and certain crops adapted to shaded conditions—leaf vegetables may be particularly suitable for cultivation under AV [2]. The increases found in above ground biomass and in growth parameters like crop height and LAI will become directly relevant for harvestable yields. This is supported by findings in lettuce, where cultivation under AV led to increased yields of some cultivars, and was also linked to increased leaf area [8].

3.4. Chemical Composition

Chemical composition analysis of celeriac bulbs revealed that most of the parameters analyzed were affected more by year than by treatment (Tables 2 and 3). The test of fixed effects revealed that all determined parameters were significantly affected by year, except S, Mg, Mn, and Se. No significant differences were found for Si, Co, and I, as the concentrations were below the detectable thresholds of 150 mg kg^{-1} (Si), 0.02 mg kg^{-1} (Co), and 0.5 mg kg^{-1} (I) given in Table 3. Dry matter (DM) content was significantly lower ($p < 0.0005$) in 2017 than in 2018 (9.9% (both AV and REF) in 2017 compared to 14.4% (AV) and 13.6% (REF) in 2018). In 2018, DM content was significantly lower in REF ($p = 0.002$) than in AV. No significant differences between treatments were found for crude protein and crude fat (Table 2). Crude protein was slightly higher in AV than in REF in 2017. However, crude protein in AV was lower than in REF in 2018, which may be explained by a dilution effect, as yields in AV were lower in 2017 and higher in 2018. Crude fat was affected by year, but virtually unaffected by treatment. Both crude fat and protein were significantly higher in 2018 than in 2017. Fresh matter (FM) protein content (2017: 0.99% AV, 0.94% REF; 2018: 1.17% AV, 1.20% REF, data not shown) was lower than the reference values of 1.2–1.5% stated in the literature [17,18]. FM crude fat content (2017: 0.22%, AV and REF; 2018: 0.28% AV and REF) was also slightly lower than literature values (0.3–0.4%) [17,18]. Carbon content was significantly lower under AV in both years, indicating that less carbon was allocated from the shoots to the bulbs, despite higher shoot biomass. This may be due to generally lower photosynthetic assimilation of carbon dioxide as a consequence of lower irradiance and/or diminished translocation to the storage organs, which would support the hypothesis that maturation is delayed under AV (see Section 3.3). This would also explain the higher C content in 2018: prolongation of the vegetation period, increased irradiation (and consequently photosynthetic performance), and increased aboveground biomass (and consequently translocation potential) may have led to higher amounts of assimilates being translocated to the bulbs. The C/N ratio was higher in 2017 than in 2018 in both treatments (data not shown), which can be explained by the higher N content in 2018. The C/N ratio under AV was at 24.7, significantly lower ($p = 0.012$) than in REF (26.6), in 2017, and at 21.7, slightly higher ($p = 0.45$) than REF (21.3) in 2018.

Table 2. Concentration of crude protein, crude fat, neutral detergent fiber (aNDFom), acid detergent fiber (ADFom), acid detergent lignin (ADL) and macroelements C, S, Ca, K, Mg, Na, P (in % dry matter DM). Significant differences ($p < 0.05$) are indicated by different letters. *p*-values correspond to the test of fixed effects year, treatment (Trt) and their interaction. SEM = Standard error of means.

Treatment	[% DM]												
	Crude Protein	**Crude Fat**	**$aNDF_{om}$**	**ADF_{om}**	**ADL**	**C**	**S**	**Ca**	**K**	**Mg**	**Na**	**P**	**Cl**
						2017							
AV	10*a*	2.25*a*	-	-	-	39.5*a*	0.09*a*	0.31*a*	4.09*a*	0.2	0.31*a*	0.58*a*	0.08*a*
REF	9.4*a*	2.18*a*	-	-	-	40.1*b*	0.09*a*	0.34*b*	3.9*a*	0.21	0.31*a*	0.59*a*	0.08*a*
						2018							
AV	11.7*b*	2.78*b*	13.3	9.5*a*	2.06	40.7*c*	0.08*b*	0.28*c*	2.19*b*	0.19	0.16*b*	0.33*b*	0.05*b*
REF	12.1*b*	2.83*b*	16.1	10.5*b*	3.0	41.1*d*	0.08*ab*	0.3*ac*	2.25*b*	0.18	0.22*c*	0.3*b*	0.06*ab*
SEM	0.196	0.075	1.348	0.072	0.327	0.149	0.002	0.005	0.076	0.01	0.018	0.01	0.009
						p-value							
Year	<0.0001	<0.0001	-	-	-	<0.0001	0.0612	0.0001	<0.0001	0.082	<0.0001	<0.0001	0.0152
Trt	0.6643	0.8713	0.1918	0.0002	0.0985	0.0048	1.0	0.0021	0.4225	0.9	0.0844	0.3628	0.7760
Trt∗Year	0.0397	0.4254	-	-	-	0.6843	0.3166	0.2009	0.1221	0.7071	0.1065	0.1832	0.2694

Table 3. Concentration of microelements (ppm dry matter (DM)). Significant differences ($p < 0.05$) are indicated by different letters. p-values correspond to the test of fixed effects year, treatment (Trt) and their interaction. SEM = Standard error of means.

Treatment	[ppm DM]															
	Al	**B**	**Ba**	**Cu**	**Fe**	**Mn**	**Zn**	**Si**	**Cd**	**Co**	**Cr**	**Ni**	**Mo**	**Pb**	**Se**	**I**
								2018								
AV	3.16*a*	33*a*	8.04*a*	16*a*	21.3*a*	36.4*a*	29.3*a*	<150	0.67*a*	<0.02	0.23*a*	0.92*a*	0.05*a*	0.08*a*	0.03	<0.50
REF	3.02*a*	30.8*a*	11.1*b*	17.4*a*	21*a*	60.2*b*	31.2*a*	<150	1.33*b*	<0.02	0.08*ab*	1.49*b*	0.04*a*	0.11*b*	0.03	<0.50
								2017								
AV	1.28*b*	27*b*	2.47*c*	14.1*b*	30*b*	42.1*ac*	25.9*b*	<150	0.5*a*	<0.02	0.02*b*	1.19*a*	<0.02*b*	0.06*c*	0.02	<0.50
REF	2.7*ab*	24.6*b*	3.8*c*	12.8*b*	28.4*b*	48.1*c*	25.7*b*	<150	0.96*c*	<0.02	0.03*b*	2.15*c*	<0.02*b*	0.1*ab*	0.02	<0.50
SEM	0.53	1.02	0.876	0.515	1.404	2.462	1.069	-	0.079	-	0.059	0.089	0.003	0.006	0.007	-
								p-value								
Year	0.0626	0.0001	<0.0001	<0.0001	0.0001	0.2261	0.0019	-	0.0064	-	0.0484	0.0004	<0.0001	0.0029	0.163	-
Trt	0.2705	0.0467	0.0299	0.8685	0.6533	0.0001	0.4452	-	<0.0001	-	0.2875	<0.0001	0.2872	0.0002	0.9202	-
Trt∗Year	0.1818	0.8578	0.3487	0.0225	0.6657	0.0046	0.3385	-	0.231	-	0.1996	0.0521	0.2872	0.4191	0.7898	-

Fiber content ($aNDF_{om}$, ADF_{om}, ADL) was lower under AV, but only significantly for ADF_{om} (1.0% absolute decrease). For $aNDF_{om}$ and ADL, the standard error between the plots was comparatively high. As data on $aNDF_{om}$, ADF_{om} and ADL only exist for one year, the results should be treated with care; year or yield effects cannot be excluded. However, this may provide further evidence that carbon metabolism is affected by AV through altered carbon assimilation as well as delayed translocation to the bulbs. Apart from Na and Ca, none of the macroelements were significantly affected by treatment. Concentration of Ca was increased by 0.03% (absolute) in 2017 and Na by 0.06% (absolute) in 2018 on the REF site. Concentration of all macroelements was higher in 2017 than 2018 in both treatments. This effect was significant for all elements, except S and Mg. As the trace elements Si, Co, I, and Mo (2018 only) were under the detectable thresholds (Table 3), no differences were detected. Al, B, Ba, Cu, Fe, Zn, Cr, Mo, and Cl were affected by year, but not by treatment. In 2018, lower concentrations were found throughout, except for Fe, which increased. No differences were found in Se concentrations. Mn content was lower in AV in both years but only significantly so in 2017. Ni decreased in AV in both years. Both Cd and Pb content were significantly lower under AV in both years. In general, celery is known to accumulate heavy metals such as Cd and Pb [45]. However, the detected concentrations were far below the acceptable maximum concentrations (0.20 mg kg^{-1} FM (Cd) and 0.1 mg kg^{-1} FM (Pb)) [46]. The treatment-related differences in Cd and Pb concentrations may be explained by differences in soil levels. Soil sample analyses showed that Cd and Pb soil levels were slightly lower on the AV site (data not shown). Overall, concentrations of most minerals and elements analyzed for both treatments were within the range stated in the literature [18].

However, this was only the case in 2017; in 2018 significant reductions were found, as described above. It is generally known that nutrient uptake (and, consequently, concentrations of various minerals and trace elements) is reduced under drought [47]. Hence, the significantly lower mineral content in 2018 was most probably caused by low soil water status as a consequence of dry weather conditions in summer, leading to impaired root uptake and translocation to the shoots.

The results show that cultivation underneath an AV system had only a slight effect on the chemical composition of celeriac. Concentrations of C, Ni and Mn were decreased by AV; all other parameters were mainly affected by year. The fiber fractions $aNDF_{om}$, ADF_{om} and ADL were only measured in 2018. Apart from the results shown here, no comparable data on the effects of microclimatic alterations (particularly shading) on the quality characteristics of celeriac are available. Most studies featuring celeriac and celery focus on the accumulation of furanocoumarins [48–50] and quality parameters such as content of vitamins and secondary plant metabolites [51–54]. These were not the subject of our study. In general, celery is considered to be nitrate-accumulating [55]. Nitrate is thought to have a negative effect on human health [55,56]. Nitrate concentrations in crops are affected by a number of factors, including N fertilization and environmental factors (e.g., light intensities) [55,57,58]. In several crops, including blade celery (*Apium graveolens* L. var. *dulce*), nitrate concentrations have been shown to be correlated with shading intensity [57–59]. In celeriac, nitrate accumulation is also cultivar-dependent [60]. Therefore, future trials should investigate whether nitrate concentrations in vegetables like celeriac are affected by cultivation underneath AV. Our results show that crude protein content was affected by AV, indicating that protein and N metabolism were altered in some way. However, this effect was not significant and differed between the years. Carbohydrate concentration, as a relevant constituent with respect to the nutritional quality of celeriac bulbs, should also be analyzed in the future. This could offer further evidence on how carbon assimilation is affected by AV. According to the values stated in the literature, total carbohydrate content in celeriac ranges from approximately 2.0% to 3.0% of fresh matter [18,61]. Apart from celeriac, no other studies on the effects of AV on crop production have addressed their impact on the chemical composition of the harvested crops. In wheat, cultivation under AV was found to shift grain size distribution towards smaller classes [9]. Although the chemical composition of the grains was not analyzed, alterations in quality parameters can be assumed to be a consequence of an altered bran/endosperm ratio [9].

4. Conclusions

The production of celeriac was found to be affected in several ways by cultivation underneath an AV system. Under AV, photosynthetic active radiation was reduced by about 30% in both years studied. Both crop height and leaf area index increased in response to shaded conditions, leading to significantly higher aboveground biomass in 2018. Neither bulb yields nor their chemical composition were significantly affected by AV. In 2017, yields tended to be lower under AV, whereas in 2018 they increased slightly. The results were linked to lower soil temperatures and reduced PAR under AV, which may have become advantageous in the hot and dry weather conditions of 2018. We therefore conclude that celeriac can be considered a suitable crop for cultivation under AV. However, as climatic conditions were quite extreme in both years, leading to comparably low yield levels in general, further field trials are necessary to investigate how yields would develop under more optimal conditions and over a longer term. Chemical analysis of C and fiber content provided evidence of an altered carbon metabolism and potentially delayed ripening under AV. Thus, further studies are required to examine whether a prolongation of the celeriac vegetation period can be beneficial for final bulb yields through exploitation of the full potential stored in the increased shoot biomass under AV. Furthermore, quality parameters such as carbohydrate and nitrate content should be assessed. The impact of altered water distribution and increased humidity under AV on infestations with fungal disease should be examined. As a coproductive system, the advantages of AV clearly predominate: increased income through additional energy production, conservation of limited land resources through increased land productivity, and potential benefits for crop production in dry climates. Nevertheless, in view of the land use conflict between energy and food production, these benefits need to be weighed up against potential losses in agricultural productivity. This emphasizes the need to define criteria for assessing the extent to which potential drawbacks in agricultural use can be tolerated in such dual-use systems.

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2.3. Agrivoltaic system impacts on microclimate and yield of different crops within an organic crop rotation in a temperate climate

In order to examine how solar irradiation and microclimate are altered under AV, this section presents and discusses the findings from the microclimatic measurements that have been carried out within the AV field experiment in the years 2017-2018. In addition to the findings from celeriac presented in section 2.2, the impacts of AV on crop development and yields of grass-clover, potato and winter wheat, are presented and discussed. Thus, research questions 1 to 4 are addressed.

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RESEARCH ARTICLE

Agrivoltaic system impacts on microclimate and yield of different crops within an organic crop rotation in a temperate climate

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Abstract

Agrivoltaic (AV) systems integrate the production of agricultural crops and electric power on the same land area through the installation of solar panels several meters above the soil surface. It has been demonstrated that AV can increase land productivity and contribute to the expansion of renewable energy production. Its utilization is expected to affect crop production by altering microclimatic conditions but has so far hardly been investigated. The present study aimed to determine for the first time how changes in microclimatic conditions through AV affect selected agricultural crops within an organic crop rotation. For this purpose, an AV research plant was installed near Lake Constance in south-west Germany in 2016. A field experiment was established with four crops (celeriac, winter wheat, potato and grass-clover) cultivated both underneath the AV system and on an adjacent reference site without solar panels. Microclimatic parameters, crop development and harvestable yields were monitored in 2017 and 2018. Overall, an alteration in microclimatic conditions and crop production under AV was confirmed. Photosynthetic active radiation was on average reduced by about 30% under AV. During summertime, soil temperature was decreased under AV in both years. Furthermore, reduced soil moisture and air temperatures as well as an altered rain distribution have been found under AV. In both years, plant height of all crops was increased under AV. In 2017 and 2018, yield ranges of the crops cultivated under AV compared to the reference site were −19 to +3% for winter wheat, −20 to +11% for potato and −8 to −5% for grass-clover. In the hot, dry summer 2018, crop yields of winter wheat and potato were increased by AV by 2.7% and 11%, respectively. These findings show that yield reductions under AV are likely, but under hot and dry weather conditions, growing conditions can become favorable.

Keywords Agrophotovoltaic · Agrivoltaic · Shading · Crop performance · Crop yield · Organic agriculture · Photovoltaics · Land productivity · Winter wheat · Potato · Grass-clover

1 Introduction

Agrivoltaic (AV) systems are currently discussed as an approach for the co-productive utilization of agricultural land by combining food production and photovoltaic (PV) energy production on the same land area (Dinesh and Pearce 2016; Dupraz et al. 2011; Weselek et al. 2019). As the PV modules are raised several meters above the ground, agricultural production can be performed below the modules using standard land machinery. By further technical adaptations of the PV facility construction to the specific needs of crop cultivation, up to 60–70% of crop-available radiation can be maintained underneath the modules (Dupraz et al. 2011; Schindele et al. 2020; Trommsdorff et al. 2021; Weselek et al. 2021). At the same time, sufficient electrical yields can be achieved to increase both land productivity and farm income (Dinesh and Pearce 2016; Dupraz et al. 2011; Marrou et al. 2013c; Schindele et al. 2020; Trommsdorff et al. 2021). However, when evaluating the suitability of AV application in agricultural systems, its impact on microclimatic conditions and crop productivity is of major concern. To date, there are almost no

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references to microclimatic heterogeneities under AV in the scientific literature, and thus their impacts on crop yields remain uncertain (Weselek et al. 2019). So far, most studies dealing with AV systems have focused on simulations and modelling (Amaducci et al. 2018; Dinesh and Pearce 2016; Elamri et al. 2018; Homma et al. 2016), while actual data obtained from real field experiments is still scarce (Marrou et al. 2013a; Marrou et al. 2013b; Marrou et al. 2013c; Weselek et al. 2021; Weselek et al. 2019). In one of the very few studies based on a real field trial, several lettuce cultivars were grown under AV. Harvestable yields were virtually unaffected by AV, depending on the cultivar and the spacing between the PV modules mounted above (Marrou et al. 2013c). With a distance of 3.2 m between the solar panel rows, solar radiation was reduced by about 30% (Marrou et al. 2013b; Marrou et al. 2013c). Water losses through evapotranspiration were decreased in the partial shade of the AV facility (Marrou et al. 2013a). However, besides solar radiation and soil temperature, which were decreased under AV, no significant differences were observed with regard to other microclimatic conditions, e.g. air temperature and humidity (Marrou et al. 2013b). Apart from crops like lettuce (Marrou et al. 2013c), corn (Sekiyama and Nagashima 2019) and horticultural crops like chiltepin pepper and cherry tomatoes (Barron-Gafford et al. 2019), the impacts of AV can only be taken from modelling studies (Amaducci et al. 2018; Homma et al. 2016). In simulations performed with a 40-year climate dataset, Amaducci et al. (2018) found increased maize grain yields under AV in non-irrigated conditions. Under irrigated conditions, however, grain yields decreased. By contrast, Homma et al. (2016) predicted a 20% decrease in rice grain yields due to shading by 20%. As a reduction in solar radiation is expected to be one of the most limiting factors for crop production under AV, results can be transferred from experiments with cultivation in artificial (Dufour et al. 2013; Schulz et al. 2019) or natural shading conditions as occur for example in agroforestry systems (Artru et al. 2017). For winter wheat, grain yield reductions of up to 50% have been found, depending on shading intensity and point of time when shading was applied (Artru et al. 2017; Dufour et al. 2013). However, also, grain yields were increased in wheat under mild shading conditions as shown by Li et al. (2010). Comparable results have been observed for potatoes, where tuber number and total tuber yields were decreased with increased shading (Kuruppuarachchi 1990; Midmore et al. 1988; Sale 1973; Schulz et al. 2019). In regions with high solar radiation, however, shading was found to be beneficial for potato tuber yields when applied during specific stages of development or at specific times of the day (Kuruppuarachchi 1990; Midmore et al. 1988). For forage crops, yield responses to shading are more divergent with both yield reductions and increases being found, indicating the dependence on the studied species and climatic region (Pang et al. 2017).

As most of these studies apply shade using netting constructions, the transferability of the results to AV is limited, since shading patterns and microclimatic heterogeneities will differ (Weselek et al. 2019). Hence, to obtain solid data on the impacts of AV technology on crop production, field experiments are required. Accordingly, the aim of our study was to determine how microclimatic conditions and crop production are altered under an AV facility. To examine the technology under practical conditions, the study was performed on a commercial farm under organic management (Demeter certified). This farm was chosen, in particular, as organic farming in general strives for reducing external inputs and for an efficient and resource-conserving management (Weselek et al. 2021). In this context, AV seems to be an appropriate approach to improve electrical self-sufficiency and independency from fossil fuels.

2 Material & methods

2.1 Site description

The research site (47.85° latitude, 9.14° longitude, approx. 660 m above sea level) is located on a field near Herdwangen-Schönach in south-west Germany in the region Lake Constance-Upper Swabia. Average annual air temperature is 8.7 °C and average annual rainfall 905 mm (climate data taken from the nearest weather station at Billafingen, less than 2 km away, 47.83° latitude 9.13° longitude, 537 m above sea level) (source: Agricultural Meteorology Baden-Wuerttemberg, published by the Agricultural Technology Centre Augustenberg (LTZ); accessible at www.wetter-bw.de).

The soil texture is classified as sandy loam. The AV facility extends from 656 to 667 m above sea level.

2.2 AV plant

The AV research plant was installed in August and September 2016 and has a total size of 0.3 ha and capacity of 194 kWp. In order to enable uniform light distribution for optimization of both PV and photosynthetic yield, the AV plant has been designed with several technical features (Fraunhofer ISE patent EP 2811819 B1; Trommsdorff et al. 2021). The facility is oriented in south-west direction. Bifacial solar panels with a row width of 3.4 m are installed on steel columns with a tilt angle of 20° at a row distance of 6.3 m and a clearance height of 5 m. Further technical details can be found in previous publications (Schindele et al. 2020; Trommsdorff et al. 2021; Weselek et al. 2019).

2.3 Setup and implementation of field experiment

To assess the impacts of the AV system technology on crop performance and harvestable crop yield, four different crop species were selected as part of the farms common crop rotation (Fig. 1): winter wheat (*Triticum aestivum* var. "Elixer C", fodder wheat), potato (*Solanum tuberosum* var. "Regina"), grass-clover ("Siloprofi", 10% *Lolium perenne*, 6% *Dactylis glomerata*, 38% *Phleum pratense*, 12% *Poa pratensis*, 8% *Festulolium*, 5% *Medicago sativa*, 9% *Trifolium pratense*, 12% *Trifolium repens*) and celeriac. These crops were selected as they represent different types of crops: winter wheat and potatoes as two of the most relevant cash crops worldwide, celeriac as typical local vegetable and grass-clover as perennial forage crop and important element of organic crop rotations, which is cut several times a year. In addition, the selected crop species represent different plant physiological types for which different reactions to the cultivation under AV may be expected: winter crops (wheat), spring crops (celeriac and potatoes) and perennials (grass-clover). All crops were managed according to usual farm practice. Celeriac is not considered within the study as first results have recently been published by Weselek et al. (2021). Sowing, planting and harvest dates, along with other relevant agronomic measures, are provided in Table 1. The crops were grown in 19-m-wide strips. Each strip is subdivided into a plot under the AV system ("AV") and into a plot used as adjacent reference area ("REF") without solar panels on the same field. There was a distance of 20 m between the two plots to avoid shading of the reference area by the panels. Four 1-m^2 sampling areas were defined for each crop and treatment, resulting in a total of 24 sampling areas for data collection each year (Fig. 1a). The sampling areas beneath AV were each set in the middle of two panel rows, at a 4-m distance to the upper and downer edge of the growing strips (Fig. 1a, black lines) and a 5-m distance to the left and right edge of the AV facility to minimize border effects, particularly when solar altitude was low.

2.4 Microclimate

Measurements of microclimatic conditions included air humidity and temperature at a height of 2 m above the ground (VP-4 sensor), soil moisture and soil temperature approx. 25 cm below ground (5TM sensor) and photosynthetic active radiation (PAR; QSO-S sensor), estimated by photosynthetically active photon flux density. The values were logged in 30-min intervals by 24 separate microclimate stations, each assigned to one of the sampling areas. The microclimate stations were placed in the non-processable area between the cropping strips on the same level as the steel columns of the AV facility (Fig. 1), to enable field processing with conventional land machinery without any restrictions. To provide homogenous light conditions underneath the facility, the AV construction has been designed according to preliminary simulation studies (Trommsdorff et al. 2021). Accordingly, the positioning of the QSO-S sensors recording PAR can be considered as representative for the whole facility. Soil sensors for the recording of soil moisture and temperature were placed next to the sampling areas (Fig. 1a, boxes) and only installed during the cropping season of each crop. All soil sensors were removed after final harvests of the crops to avoid any damage by tillage operations. Data loggers (EM50G) and all the sensors mentioned above were obtained from METER Group AG (Munich, Germany). For statistical analysis, the daily (24 h) values of each parameter and treatment were averaged. Rain distribution was recorded from June to October in 2017, and from July to October in 2018, using 28 rain gauges (70 mm volume; TFA Dostmann, Wertheim-Reicholzheim, Germany) mounted on wooden poles 2 m above the ground. Rain gauges were set up on the grass-clover cultivation area only, as this crop requires the fewest number of agronomic measures. Here, they were positioned in transect lines, each with seven gauges and two transects per treatment (AV/REF), to provide data for different areas underneath AV and on the REF site. The gauges were removed temporarily during the data acquisition period each year to allow agronomic measures to be carried out. Hence, the recorded precipitation does not match the actual rainfall amounts during this period. To compare the weather conditions, data on annual rainfall, solar radiation and temperature were taken from the weather station in Billafingen (see also Sect. 2.1).

2.5 Monitoring and harvest of crops

Monitoring of crop performance and crop yields was carried out over two growing seasons from December 2016 until October 2018. No monitoring was carried out between November 2017 and April 2018 due to unfavorable weather conditions. During this period, the soil was either so wet that it was impossible to access the field without damaging the crops or the field site was covered with snow. However, due to low temperatures, crop growth can be regarded to be virtually zero during that time.

Crop development was monitored every fourth week and from flowering onwards every second week. On each of the wheat and potato plots, ten single plants were selected and tagged for monitoring. For a better comparison between the 2 years, the results are presented with days after sowing (DAS) for wheat, day of year (DOY, with January 1st defined as 1 DOY) for grass-clover and days after planting (DAP) for potato. Monitoring included non-destructive measurements of plant height (using a folding ruler) and growth stage (BBCH scale) of the tagged plants. Non-destructive measures were taken from each plant and averaged across plants within each sampling area. Leaf area index (LAI; LAI-2200C Plant Canopy Analyzer, LI-COR Biosciences, Lincoln, USA) was

Table 1 Agricultural management of the on-farm trial during the data collection period 2016–2018.

Crop	Seeding/planting density	Season	Preceding crop	Sowing/ planting	Harvest dates	Agronomic measures	Amount/frequency
Winter wheat (Variety: Elixer C)	200 kg ha^{-1}	1st season 2016/2017	Grass-clover (perennial)	22.10.2016	08.08.2017	Application of biodynamic preparations (horn manure and horn silica)	20 l ha^{-1} each; 2 times per season
						Application of cow slurry	10 m^3 ha^{-1}; 2 times per season
		2nd season 2017/2018	Grass-clover (annual)	25.10.2017	31.07.2018	Application of compost tea preparation	20 l ha^{-1} in 200 l water; 2 times per season
						Comb harrowing	1–2 times per season
Potato (Variety: Regina)	3,000 kg ha^{-1}	1st season 2016/2017	Grass-clover (perennial)	22.04.2017	29.08.2017	Application of biodynamic preparations (horn manure and horn silica; 2×/season)	20 l ha^{-1} each; 2 times per season
						Application of composted cow manure	15 t ha^{-1}
						Application of compost tea	20 l ha^{-1} in 200 l water
		2nd season 2017/2018	Celeriac	27.04.2018	04.09.2018	Ridging	3 times per season
						Harrowing	1–2 times per season
						Spraying against colorado beetle (*Leptinotarsa decemlineata*) with a neem (*Azadirachta indica*) based product (Neem Azal)	2.5 l ha^{-1} in 400 l water; 1–2 times per season
Grass-clover (Variety: Siloprofi)	35 kg ha^{-1}	1st season 2016/2017	Grass-clover (perennial)	Spring 2015	11.05.2017 13.06.2017 02.08.2017 12.09.2017	Application of cow slurry	10 m^3 ha^{-1}; 2 times per season
	30 kg ha^{-1}	2nd season 2017/2018	Winter wheat	23.08.2017	08.05.2018 26.06.2018 21.08.2018 23.10.2018	Application of biodynamic preparations (horn manure and horn silica)	20l ha^{-1} each; 2 times per season

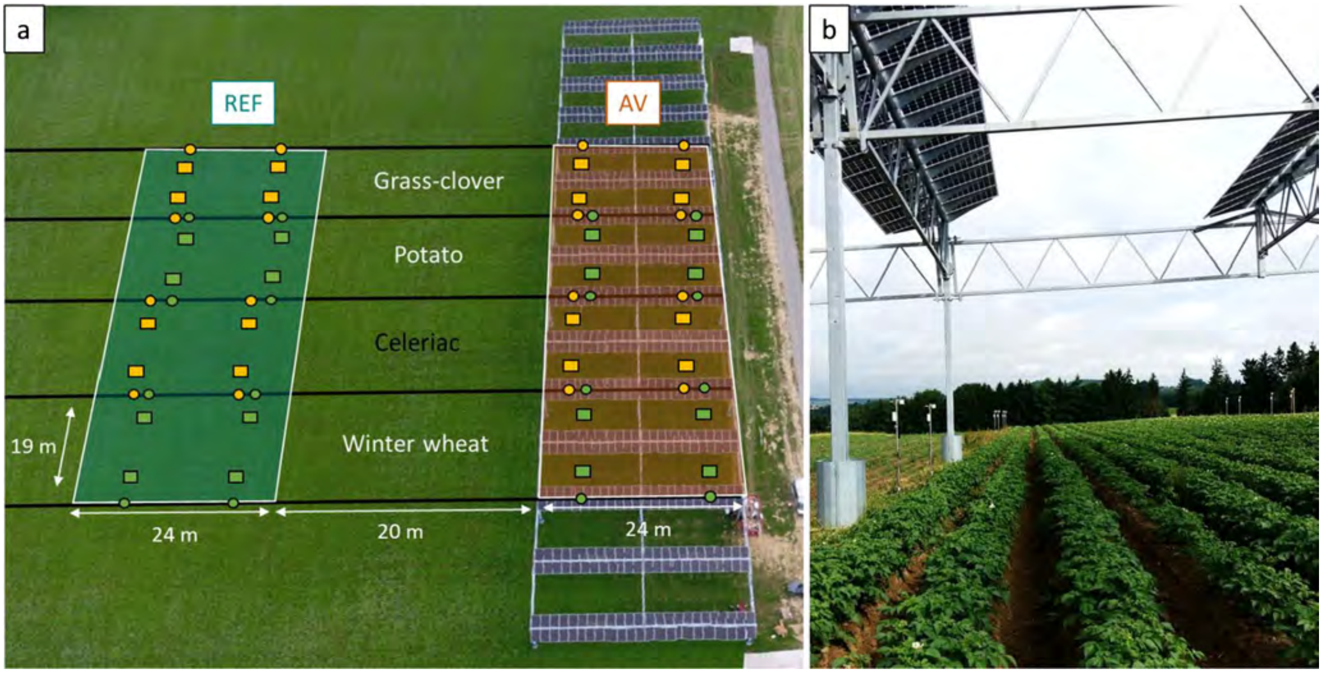

Fig. 1 Field trial design of the first cropping season 2017 with reference (REF) and agrivoltaic (AV) sites (**a**). Crops are grown in strips. Sampling areas are indicated by boxes, positions of microclimate stations by circles. Soil sensors were placed next to the sampling areas. Celeriac was part of the crop rotation but is not considered within this study. (**b**): Potatoes growing under the AV panels (front) and on the REF site (back). Microclimatic stations have been placed in line with steel columns of the facility. (Source: (**a**) modified after BayWa r.e; (**b**) Bauerle/ University of Hohenheim).

measured at four different positions of each sampling area and averaged for each area. The measurements were taking in exactly the same way in the grass-clover plots, but without tagging individual plants. Here, crop height was estimated at ten random positions within the sampling areas. In addition, the proportions of grass and clover were determined by estimating surface coverage ratio.

Each sampling area was harvested manually immediately before the farm's usual harvest dates. Wheat was harvested at maturity, and the aboveground biomass was separated into stems, leaves and ears. Dry weight was determined after drying for 48 h at 30 °C (ears) or 60 °C (leaves and stems). Ears were threshed to determine the grain yield. Thousand grain weight was determined using a seed counter (Contador, Pfeuffer GmbH, Kitzingen, Germany). For the estimation of grain size classes (<1.8 mm; 1.8–2.0; 2.0–2.2; 2.2–2.5; 2.5–2.8; >2.8), 100 g grains were sorted (Sortimat K5, Pfeuffer GmbH, Kitzingen, Germany) and weighed back to estimate the share of each class. Potatoes were washed and sorted according to diameter (<35 mm, 35–50 mm, >50 mm) before determining the fresh weight. Grass-clover was cut four times per year, and dry matter yield was determined by drying the biomass at 60 °C to constant weight.

2.6 Statistical analysis

The experimental setup can be considered as a single replicate of a strip-plot design where treatment (AV and REF) and crop rotation were allocated to columns and rows, respectively. A plot (a combination of treatment and crop rotation) was further divided into two lanes with two measurements taken per lane (resulting in four sampling areas per plot and two per lane, respectively). Lanes were created by the working widths and the working direction of the machinery for processed in crop-specific working steps and coded as south and north. Repeated measures were taken on each plot. Note that a true replicate for treatment would require another AV system. The data analysis for traits of crop development was carried out with SAS software version 9.3 (SAS Institute Inc., Cary, NC, USA) using the following model:

$$y_{ijkl} = \mu + b_{kij} + \tau_i + \varphi_j + (\tau\varphi)_{ij} + e_{ijkl}, \quad (1)$$

where b_{kij} is the fixed effect of lane k in treatment i at day j, τ_i is the i-th treatment effect, φ_j is the j-th day effect and $(\tau\varphi)_{ij}$ is the interaction effect of day j and treatment i. e_{ijkl} is the repeated measurement error of observation y_{ijkl} with a first-order autoregressive variance-covariance structure of error effects from the same measuring point. Note that the variance of repeated measures on the same plot under-estimates the true error variance, and thus, all tests are too liberal. Further note that the considered traits are crop-specific; thus, analysis was performed for each crop separately.

As harvestable crop yield was measured in two successive years but only once per year, an analogous model to (1) can be fitted replacing day j with year n:

$$y_{inkl} = \mu + b_{kin} + \tau_i + \rho_n + (\tau\rho)_{in} + e_{inkl}, \quad (2)$$

where ρ_n and $(\tau\rho)_{in}$ are the effects of the n-th year and its interaction effects with treatment. All other effects are defined analogous to model (1).

The microclimate data were evaluated in all crops. Thus, another linear mixed model was used:

$$y_{ijklm} = \mu + b_{kijn} + \tau_i + \varphi_j + \vartheta_m + (\tau\varphi)_{ij} + (\tau\vartheta)_{im} + (\varphi\vartheta)_{jm} + (\tau\varphi\vartheta)_{ijm} + e_{ijklm}, \quad (3)$$

where ϑ_m is the effect of the m-th crop and $(\tau\vartheta)_{im}$, $(\varphi\vartheta)_{jm}$ and $(\tau\varphi\vartheta)_{ijm}$ are the corresponding interaction effects with the m-th crop. Residuals were checked graphically for homogeneous variances and normal distribution. After finding significant differences via F test, a multiple t test (Fisher's LSD test) was performed. Results of multiple t tests were presented as a letter display. Note that care should be taken with the interpretation of letter displays as these tests are too liberal.

3 Results and discussion

3.1 Microclimate

No microclimate data could be recorded from 11 October until 23 November in 2017 and from 11 until 14 December in 2018 for technical reasons. Therefore, yearly mean values have been taken from the weather station in Billafingen: The weather conditions in the years were quite different with an extraordinary dry and hot summer in 2018. In 2017, accumulated precipitation was 1351 mm, annual solar radiation 1180 kWh/m^2 and mean temperature 8.6 °C; in 2018, they were 916 mm, 1204 kWh/m^2 and 9.7 °C, respectively (source: weather station Billafingen). In 2018, the 1.1 °C higher average annual temperature compared to 2017 was mainly due to increased air temperatures during summertime: From July to September, monthly average temperature was on average 2 °C higher in 2018 compared to 2017. The mean daily PAR was significantly reduced ($p < 0.05$) by about 30% underneath AV in both 2017 (n = 359 days) and 2018 (n = 363), with only slight variations between months (Fig. 2a). In 2017, daily mean PAR on the REF site was highest on 11 June at 678.9 μmol m^{-2} s^{-1} and lowest on 10 December at only 19.9 μmol m^{-2} s^{-1}. Interestingly, the dates with maximum and minimum values were slightly different on the AV site at 480.9 μmol m^{-2} s^{-1} on the 10 June and 14.4 μmol m^{-2} s^{-1} on 25 November. In 2018, daily mean PAR was highest on 20 June at 683.7 μmol m^{-2} s^{-1} (REF) and 471.8μmol m^{-2} s^{-1} (AV), and lowest on 4 January at 15.8 μmol m^{-2} s^{-1} (REF) and 6.7 μmol m^{-2} s^{-1} (AV) on 10 December. These findings are comparable with results from previous AV experiments, in which predicted and measured light reductions ranged from 12 to 40%, depending on the density and orientation of the PV modules mounted above (Amaducci et al. 2018; Majumdar and Pasqualetti 2018; Marrou et al. 2013b; Weselek et al. 2019). With on average 70% available PAR underneath the AV facility in Heggelbach, even more radiation was available than predicted in preliminary simulations (Trommsdorff et al. 2021).

Soil moisture was significantly decreased under AV on 26 days in 2017 and on 133 days in 2018. In 2017, significant differences only occurred during wintertime from the end of November onwards. Similar results were observed in 2018, where daily mean soil moisture was significantly lower under AV until the middle of April and from the end of October onwards. This result is surprising since soil moisture was expected to be higher under AV during summertime due to lower evapotranspiration (Amaducci et al. 2018; Marrou et al. 2013a). However, the studies by Amaducci et al. (2018) and Marrou et al. (2013a) were performed in irrigated systems with spring crops like maize, lettuce and cucumber, and therefore the results are difficult to compare with ours. Furthermore, the results of the rain distribution measurements (see next section) indicated that the plots were placed in the rain-sheltered area of the facility between the panel rows, corresponding to rain gauge positions P3 and P5 (Fig. 2b).

Mean daily soil temperature under AV was on average about 1.2 °C lower in 2017 (n = 201; $p < 0.05$) and 1.4 °C lower in 2018 (n = 205; $p < 0.05$) on almost every day from the beginning of March to the middle of October (Fig. 2c). Also, Marrou et al. (2013b) found reduced soil temperatures under AV, ranging from −0.5 °C in irrigated lettuce to −2.3 °C and −1.9 °C in wheat at 25-cm and 5-cm depth, respectively. In addition to crop-related variations and depths, soil temperature was also affected by the density of the modules mounted above: Increased module density led to lower temperatures, except in wheat at 25-cm depth (Marrou et al. 2013b). Our results further indicated that the soil underneath AV is heating up more slowly and less strong compared to open field conditions. This may be advantageous during summertime but can also become adverse, especially in spring when quick soil heating is demanded in terms of nitrogen mineralization.

In both, 2017 (n = 132 days) and 2018 (n = 112 days) daily mean air temperature was significantly lower by about 1.1 °C on average. This effect was found across the whole year but was most prevalent during summertime. However, on 7 days in 2017 and 18 days in 2018, measured air temperature was higher under AV. In contrast, Marrou et al. (2013b) found that air temperature tended to be higher underneath the AV facility on days with high solar radiation or low wind speeds. In our field trial, wind speeds have not been assessed. However, as the study of Marrou et al. (2013b) has been performed under different conditions (e.g. climatic region, design of the AV facility, crop selection and irrigation), multiple explanations for the opposing results are conceivable.

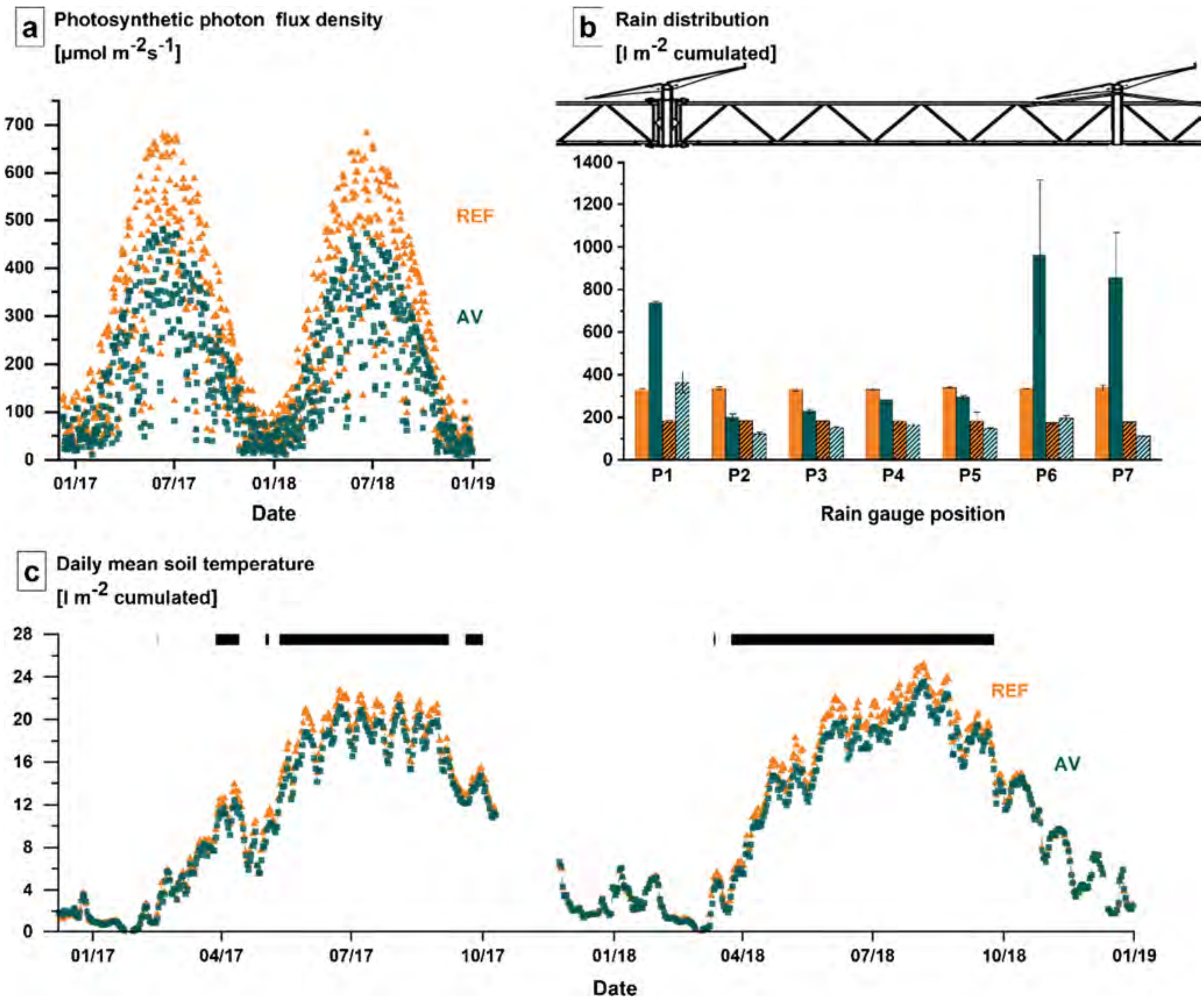

Fig. 2 (**a**) Daily means of photosynthetic active radiation (PAR) in 2017 and 2018 underneath agrivoltaic (AV, cyan squares) and on the reference site (REF, orange triangles). (**b**) Rainfall distribution underneath the AV panels (cyan bars) and on REF (orange bars) in 2017 (non-hatched) and 2018 (hatched bars). Error bars indicate standard deviation. Harvest and monitoring plots of the crops were placed between rain gauge positions P3 and P5. (**c**) Daily mean soil temperature in both years for AV (cyan squares) and REF (orange triangles). Significant differences ($p < 0.05$) between AV and REF in (**c**) are indicated by black horizontal bars.

In both years, air humidity was higher under AV on several days. In 2017, daily mean air humidity was on average 2% higher on 60 days and 2% higher on 44 days in 2018 under AV, respectively. The differences mainly occurred in wintertime from October onwards in 2017 and before April in 2018.

The accumulated precipitation was 439 mm lower in 2018 (912 mm) than in 2017 (1351 mm; source: weather station Billafingen), in particular due to low precipitation during summer (Weselek et al. 2021). As described in Sect. 2.4., in our trial, rain gauges had to be removed occasionally when agronomic measures were carried out. Therefore, the collected amounts in our field trial do not reflect the actual precipitation for that period. Consequently, the average accumulated precipitation of the rain gauges recorded in our trial was only 335 mm in 2017 and 181 mm in 2018 (Fig. 2c: a–g), while the accumulated precipitation at the weather station Billafingen for the same period (see also Sect. 2.4) was 771 mm in 2017 and 190 mm in 2018. However, as the Billafingen weather station is located almost 2 km away at a much lower sea level and rainfall events can be locally quite different due to a hilly landscape, measured rainfall amounts are not totally suitable for comparison. The local microclimates can be expected to be slightly different.

In addition, precipitation was unequally distributed underneath the AV facility. For example, in 2017, the average cumulated amount of rainfall collected at rain gauge positions "P2" and "P3" on the AV site was only 215 mm, whereas it was 335 mm on the REF site (Fig. 2b). The amounts collected by the gauges at positions "P1", "P6" and "P7" in the same period were 738 mm, 964 mm and 857 mm, respectively. The PV panels are divided into two parts: position "P1" and "P7" are under to the draining edge of the first panel, and position "P6" to that of the second panel. Consequently, a rain sheltering effect occurred in the areas between two panel rows ("P2"–"P5"), while directly underneath the panels, rain concentration effects led to increased amounts of water being collected in the rain gauges under the panel edges. However, as the high standard deviation at positions "P6" and "P7" in 2017 and less distinct results for 2018 indicate, the runoff from the panel edges is limited to a very small area and slight variations in rain gauge positions already led to deviating results. For this reason and due to low precipitation in general, differences between the rain gauge positions under the AV facility were less pronounced in 2018. Elamri et al. (2018) reported similar results, with rain to be distributed unequally underneath an AV system. As they have shown, such heterogeneities depend on the direction of the PV panels and may even be avoided in systems with mobile PV modules and time-dependent adjusting of panel tilt angles (Elamri et al. 2018).

As the sensors recording soil temperature and moisture have been placed at positions underneath the AV facility which are corresponding to rain gauge positions "P4" and "P5", further measurements are needed to investigate whether found alterations in soil microclimate are representative for the whole area underneath the AV plant. The slight slope of the experimental site in both a north-west and south-west direction will also affect water redistribution in the soil after rainfalls. In 2017, drainage gullies were observed after heavy rainfalls in the potato field directly underneath the panel edges of the AV facility. Consequently, an increased risk of soil erosion under AV can be assumed in particular in early stages of crop development with virtually bare soils.

As shown, microclimate was affected by AV in several ways. PAR, soil temperature and moisture, as well as air temperature, were significantly reduced under the AV facility, whereas air humidity partly increased. PAR was on average reduced by about 30% under AV and, hence, is considered to be the most relevant constraint for crop production. However, the results have also shown that alterations in microclimate and between the treatments are also affected by the crop cultivated underneath. As shown for celeriac, mean soil moisture on average increased under AV during celeriac vegetation period in 2017 (Weselek et al. 2021), which seems contradictory to the results of daily means, but may explain found differences between winter and summertime. Therefore, a more in-depth analysis of microclimatic data, also addressing spatial, temporal and crop-related differences is needed, to fully understand microclimatic alterations under AV. In this context, a high-resolution acquisition of microclimatic data, covering representing areas underneath the AV facility, is required to assess microclimatic heterogeneities. As the measurements of rain distribution indicated, precipitation is distributed unevenly under AV, and hence, also the technical design of prospective AV facility should be improved to ensure a more even rain distribution. Besides variations between the treatments, climatic conditions were quite different in the years 2017 and 2018, with low precipitation and high temperatures especially during summer 2018.

3.2 Crop development

Canopy height of winter wheat was significantly higher under AV than in REF from 201 DAS onwards in 2017 (+8.2–19.9%) and from 195 DAS onwards in 2018 (+16.4–19.1%) until final harvest (Fig. 3). This confirms earlier findings by McMaster et al. (1987), who also found increased winter wheat canopy height under shading. LAI of the wheat canopy was significantly higher under AV on one monitoring date (262 DAS; +24.5%) in 2017 and on four monitoring dates in 2018 (195, 232, 244 and 272 DAS; +23–35.9%; data not shown). Comparable results have been found by Li et al. (2010) and can be explained as morpho-physiological response of wheat plants in order to capture more light and compensate for reduced light incidence (Li et al. 2010). In contrast, no significant effects of shading on the LAI dynamics of winter wheat were found in agroforestry experiments (Artru et al. 2017; Dufour et al. 2013). However, in these experiments, shading was applied at late stages of development at which vegetative growth was almost completed (Artru et al. 2017). In 2017, no significant differences in growth stage were observed between the two treatments, although senescence had progressed further on the REF site at 262 DAS. In 2018, winter wheat was at a higher growth stage on the REF site than on the AV site at 232 and 244 DAS. This was clearly visible from the color of the crop canopy, which was still green under AV but already turning yellow on the REF site. Comparable results were described by Marrou et al. (2013b), who found crop development of wheat to be slightly delayed in the shade of PV modules. This may be explained by differences in the photothermal ratio between the two treatments leading to a delay in maturation under AV (Fischer 1985). However, in our trial, all visible differences had vanished by harvest.

Comparable results were found in potatoes, where canopy height was significantly higher under AV on several monitoring dates in 2017 (66 and 80 DAP; +12.4–19.3%) and 2018 (48, 60 and 74 DAP; +5.1–15.9%) (Fig. 3). This is in agreement with LAI, which was significantly higher under AV at two monitoring days in 2017 (80 and 102 DAP; +28.5–53.4%) and two in 2018 (60 and 74 DAP; +14.6–20%) (data not shown). At one monitoring date in 2017, LAI was lower under AV (66 DAP; −24.5%). These findings are in agreement with Kuruppuarachchi (1990) who found increased

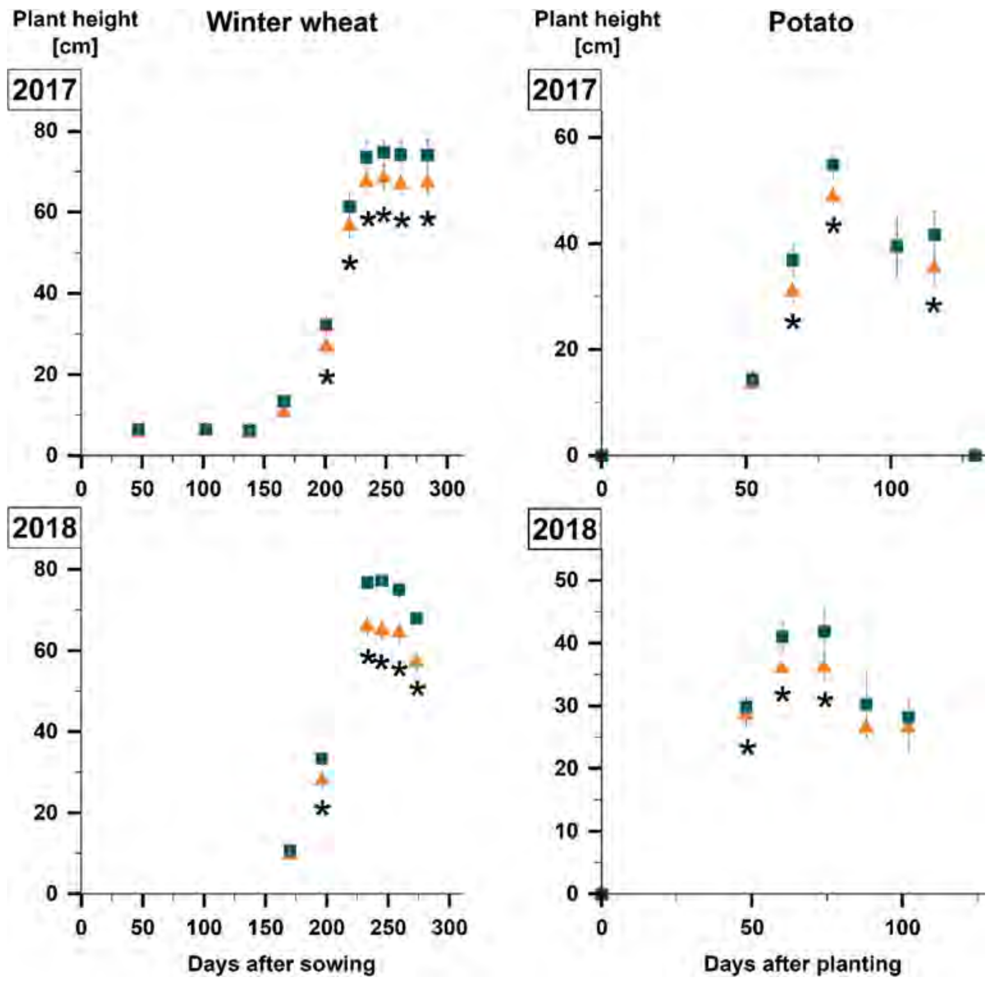

Fig. 3 Plant height of winter wheat (left) and potato (right) in 2017 and 2018 underneath agrivoltaic (AV, cyan squares) and on the reference site (REF, orange triangles). Significant differences ($p < 0.05$) are indicated by stars, standard deviation by error bars.

canopy height of potatoes under artificial shading. Besides canopy height and LAI, growth stages were also affected by AV in our experiment. In both years, flowering tended to start earlier on the REF site. In 2018, leaf senescence of potato plants started later under AV than on the REF site. At final harvest, however, differences in growth stages and tuber ripeness were no more visible. In 2017, no significant differences in growth stages were observed between the treatments.

In grass-clover, canopy height and LAI also differed significantly between AV and REF on several days in both 2017 and 2018 (Fig. 4). Apart from few exceptions shortly after the plots were cut, canopy height and LAI were always higher on AV than in REF. In addition, a trend of faster regrowth after cutting was observed on AV plots. This was particularly visible after the 3rd and 4th cut in 2017 (226 DOY and from 268 DOY onwards). The assumption that this was due to better water supply under AV was not confirmed as soil moisture actually tended to be lower under AV (see also Sect. 3.1). However, these findings may also be explained by species-specific growth differences. As the estimation of clover:grass ratio revealed, the average proportion of clover on the AV site was 62% in 2017 and 49% in 2018, compared to 57% and 45% on the REF site. Therefore, observed differences in canopy height and growth between the two treatments may be explained by deviating species proportions. In a comprehensive screening for shade adaptability of different forages, Pang et al. (2017) showed that some species (e.g. white clover) can be favored by shading. As these findings also affect biomass yields, they are discussed in more detail in Sect. 3.3.

Monitoring of crop development revealed that canopy height and LAI of winter wheat, potatoes and grass-clover increased under AV. Comparable results have been found for celeriac, where both LAI and crop height were significantly increased by AV (Weselek et al. 2021). The results may be explained as shade-adaptive response to increase light capture by increased vegetative growth, in order to compensate for reduced radiation in the shade of the AV panels. Furthermore, crop development was slightly delayed by AV, but all visible interim differences had disappeared at final harvest.

3.3 Harvestable crop yields

Differences in harvestable crop yields of winter wheat were found both, between treatments (AV and REF) and years (2017 and 2018) (Fig. 5a). Harvest index was significantly lower

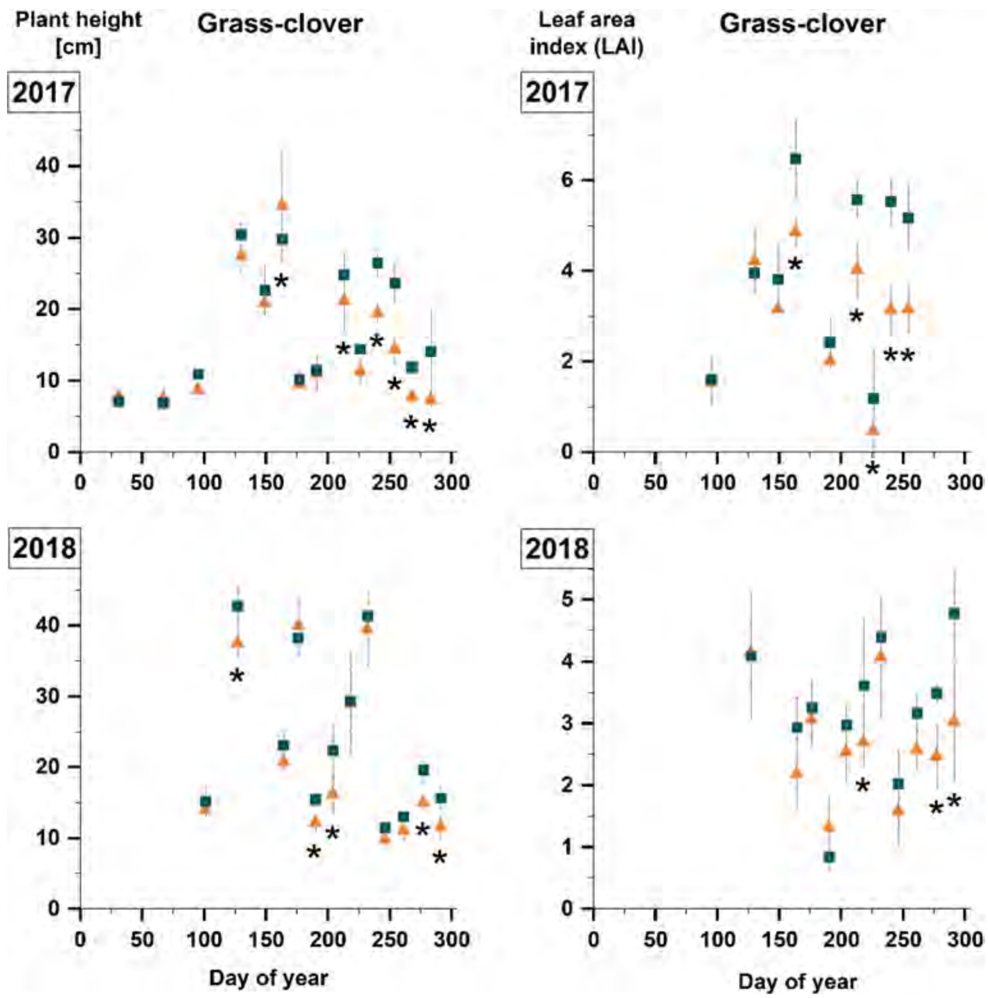

Fig. 4 Plant height (left) and leaf area index (right) of grass-clover in 2017 and 2018 underneath agrivoltaic (AV, cyan squares) and on the reference site (REF, orange triangles). Significant differences ($p < 0.05$) are indicated by stars, standard deviations by error bars.

under AV in both years, with 57. 2 (AV) compared to 59.8 (REF) in 2017 (p = 0.008), and 56.1 (AV) compared to 59.3 (REF) in 2018 (p = 0.002). Straw yield was 2.9 t ha^{-1} (REF) and 2.6 t ha^{-1} (AV) in 2017 (−7.1%; not significant), and 2.2 t ha^{-1} (REF) and 2.7 t ha^{-1} (AV) in 2018 (+22.1%; not significant). In 2017, higher straw yield in REF was mainly due to higher stalk weight (not significant). In 2018, both stalk (not significant) and leaf weight (p = 0.004) were higher under AV. In 2017, grain yield of winter wheat was 4.6 t ha^{-1} under AV compared to 5.7 t ha^{-1} on the REF site (−18.7%; p = 0.03). In 2018, it was 4.7 t ha^{-1} under AV compared to 4.6 t ha^{-1} in REF (+2.7%; not significant; p = 0.78). Grain yield of both AV and REF was significantly lower in 2018 compared to REF yields in 2017. In a study by Li et al. (2010), changes in grain yields ranged from +1.8% for a shade-adapted cultivar under 8% shade up to −7.2% for a shade-sensitive cultivar under 23% shade. In contrast, Dufour et al. (2013) found a reduction in grain yields as high as 50% under 31% shading due to a decline in both number of grains per ear and grain weight. The results show that the reduction in grain yields of winter wheat under shading is most likely due to decreased single grain weights, while its extent appears to depend very much on cultivar and climatic conditions. Under certain conditions, even increased grain yields are possible as shown by Li et al. (2010). Our results from 2018 in particular indicate that under hot and dry conditions, reduced sunlight will most probably not be a limiting factor for yield levels. Beside grain yields, also grain size distribution was affected. While in 2017, 89% (REF) and 88% (AV) of grains were bigger than 2.8 mm, in 2018 only 75% (REF) and 53% (AV) of grains were bigger than 2.8 mm (p <0.0001). Accordingly, the share of smaller grain size classes was higher under AV in 2018: Grains with a size of 2.5–2.8 mm had a share of 18% (REF) and 34% (AV) (p < 0.0001), and grains with a size of 2.2–2.5 mm a share of 6% (REF) and 11% (AV) (p < 0.0001). In both, 2017 (p = 0.03) and 2018 (p = 0.0002), thousand grain weight was significantly lower under AV. Reductions in harvest index and thousand grain weight have also been found in shading experiments of Artru et al. (2017). In our study, lower harvest index under AV most probably can be explained by lower grain yields in 2017, and increased straw yields in 2018, compared to the REF site

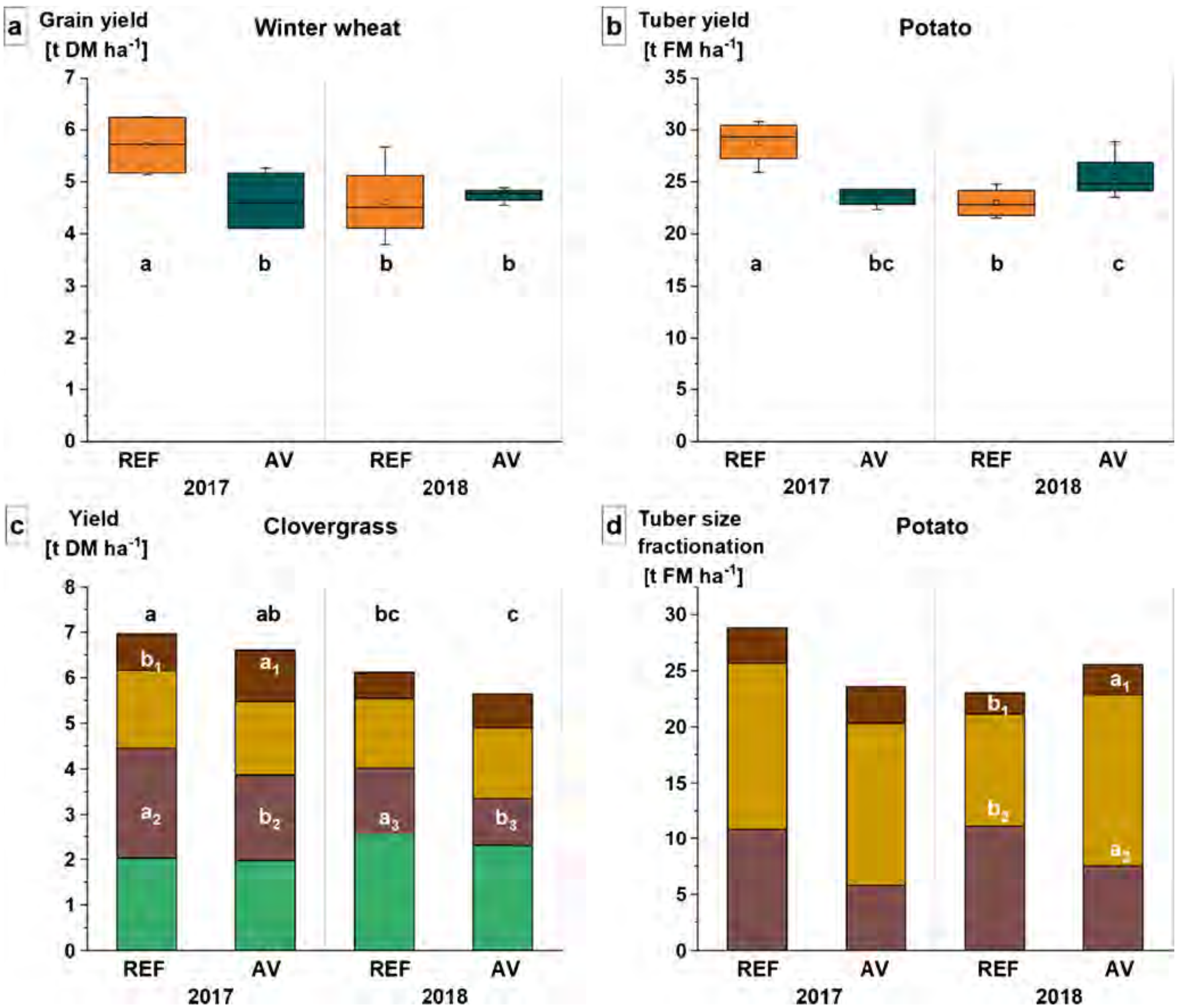

Fig. 5 Yields of winter wheat (**a**), potato (**b**) and grass-clover (**c**), as well as tuber size fractionation of potato (**d**) in the years 2017 and 2018 (DM = dry matter; FM = fresh matter). Different letters indicate significant differences between reference (REF) and agrivoltaic (AV), with a > b ($p < 0.05$). Whisker boxplots (25–75%) with whisker length of 1.5 interquartile range, mean (square) and median (center dash). Stacked bars in (**c**) represent grass-clover cuts (1st cut down to 4th cut top), and in (**d**) tuber size fractions: diameter >50 mm (bottom), 35–50 mm (middle), <35 mm (top).

respectively. Increases in straw biomass can be explained by a higher crop canopy and LAI in 2018 (see also Sect. 3.2.).

In 2017, the reduction of potato tuber yield under AV in 2017 was comparable to the reduction of grain yield of winter wheat. Fresh matter (FM) tuber yield was 23.6 t ha^{-1} for AV and 28.8 t ha^{-1} for REF in 2017 (−18.2%; $p = 0.005$), and 25.5 t ha^{-1} (AV) and 23.0 t ha^{-1} (REF) in 2018 (+11%; $p = 0.034$) (Fig. 5b). Average tuber yields of potatoes grown organically in Germany were on average 22.0 t ha^{-1} in 2017 and 25.0 t ha^{-1} in 2018. Thus, tuber yields in our trial from both years and treatments were comparable to the national average. The proportion of large potato tubers (> 50 mm) was higher on the REF site in 2017 ($p = 0.012$) and 2018 (not significant; $p = 0.052$), while the share of medium-sized tubers (35–50 mm) was increased under AV in 2018 ($p = 0.0031$) (Fig. 5d). In both years, the share of small-sized tubers (< 35 mm) slightly increased under AV ($p > 0.05$). A recent study by Schulz et al. (2019) investigated the effect of three different shading levels (12%, 26% and 50%) on the growth, yield and quality of potatoes in south-west Germany over a 3-year cultivation period (2015–2017). In accordance with our findings, the highest share of undersized potato tubers was found under 26% shading, while the highest share of oversized tuber was found under full sun conditions (Schulz et al. 2019). These results are of relevance as potato tuber size fractionation is important for the marketing of table potatoes, with small and large-sized tubers being regarded as less marketable. Assuming only medium-sized potato tubers (35–50 mm) are considered marketable, a higher share of tubers was marketable under AV in 2018 in our trial, whereas in 2017 the treatments did not differ significantly. Also, Schulz et al. (2019) found the highest share of marketable tubers under 50% shading. In experiments performed in New South Wales, Australia, shade application of 21% and 38% led to tuber yield reductions ranging from 9 to 27% (for 21% shade), and from 23 to 42% (for 38% shade), depending on year and irrigation treatment (Sale 1973). Both tuber number and weight were reduced by shading. Although these parameters were not assessed in our experiment, the smaller proportion of large tubers (> 50 mm) under AV indicates that average tuber weight was reduced, too. In the study by Schulz et al. (2019), none of the shading treatments led to significant dry matter (DM) tuber yield reductions in 2015, while in 2017 only the 50% shading treatment led to significant reductions (Schulz et al. 2019). In 2016, both the 26% and 50% shading treatments led to significant yield reductions in comparison with the full-sun control (Schulz et al. 2019). As they hypothesize, the main criterion for achieving sufficient tuber yields is reaching of the light saturation point of potatoes under given climatic conditions. Therefore, not only the level of shading but also yearly variations in solar irradiance and the latitude of the cultivation region need to be considered (Schulz et al. 2019). In contrast to Schulz et al. (2019), who did not find significant yield reductions under 26% shading, potato tuber yields in our trial were significantly reduced under AV in 2017. This may be explained by several factors like different potato varieties and altered microclimatic conditions, as the field experiment by Schulz et al. (2019) has been performed under irrigated conditions in the Rhine plain. In our trial, lower tuber yields in 2018 than in 2017 may be explained by low precipitation and high temperatures during summer 2018 (also see Sect. 3.1). Both drought and high temperatures are known to be negatively correlated with potato tuber yields (van Loon 1981).

As shown in Sect. 3.1, both air and soil temperature were significantly lower under AV in both years. We therefore hypothesize that, especially in the hot summer of 2018, lower air and soil temperatures under AV may have reduced plant stress, leading to higher tuber yields at harvest compared to the REF site. This is supported by findings of Midmore (1984), who found potato tuber yields to be positively affected by reduced soil temperatures under hot climatic conditions.

In grass-clover, cumulated annual yields of four cuts (DM) were slightly lower under AV: 6.6 t ha^{-1} compared to 7.0 t ha^{-1} in REF in 2017 (−5.3%; $p = 0.23$), and 5.6 t ha^{-1} compared to 6.1 t ha^{-1} in REF in 2018 (−7.8%; $p = 0.13$) (Fig. 5c). However, these differences were not significant. While harvestable yields on DM basis were reduced by AV, FM yields were higher: 40 t ha^{-1} (REF 35.7 t ha^{-1}) in 2017 (+12%; $p = 0.03$) and 22.7 t ha^{-1} (REF 22.1 t ha^{-1}) in 2018 (+2.5%; $p = 0.75$). These findings can be explained by the significantly higher DM content ($p < 0.0001$) of 19.5% (2017) and 28.7% (2018) in REF compared to 16.5% (2017) and 25.3% (2018) under AV. Ergon et al. (2016) have shown that, in grass/legume mixtures, grasses contribute proportionally more dry matter to the yield than clover, and therefore, our findings can be explained by the higher proportion of grasses in the REF plots (see also Sect. 3.2). As discussed in Sect. 3.2, the cultivation in the partial shade of the AV facility may favor shade-adapted species such as clover. This is in agreement with Pang et al. (2017), who found different forage grass and legume species to be unaffected by shading. Biomass yields of some of the species also used in our study, like *Poa pratensis*, *Trifolium pratense* and *Trifolium repens*, increased by up to 45% shading (Pang et al. 2017). In addition, DM production of grasses was found to be reduced by shade (Abraham et al. 2014). Apart from cumulated yields, also differences within the different cuts were found between the treatments: In both years, DM yield of the second grass-clover cut was significantly lower under AV. In 2018, DM yield of the fourth cut was significantly higher under AV. For all other cuts, no significant differences were found between the two treatments. However, in both years, DM yields in REF tended to be higher at the first two cuts and lower at the last two cuts, which can also be explained by the different species proportions in the two treatments. In grassland mixtures, grasses are known to produce more dry matter at the beginning of the year, while legumes are higher yielding at the end of the growing season (Ergon et al. 2016). These findings also need to be considered in terms of fodder quality, as higher protein and lower fiber contents can be expected as a result of higher shares of clover. In 2018, the proportion of clover did not become higher under AV until the end of the season. This may be due to dry weather conditions as well as a generally lower proportion of clover in the second year of the grass-clover mixture as a consequence of increased nitrogen levels (Ergon et al. 2016).

The results showed for the first time that harvestable yields of winter wheat, potatoes and grass-clover were significantly affected by AV. On a 2-year average, harvestable yields under AV decreased by about 6.5% (grass-clover), 7.2% (potato) and 8% (winter wheat). The results are comparable to the average yield reduction of 7.1% found in celeriac within the 2-year field trial (Weselek et al. 2021). Besides crop yield reductions, also a certain loss of cultivation area through the inaccessible areas between the stilts of the AV facility has to be taken into consideration. Its extent depends on whether the field is managed in a lengthwise or crosswise direction to the facility and also how the working widths of the machinery fit the distance between the stilts. In our field trial, the field was managed in a crosswise direction. In 2017, the mean width of the inaccessible strips between the different cultivation area segments was estimated and resulted in a total area loss of approximately 8.3%, which has to be considered in terms of crop yield reductions. Taking into account that at the same time, 246 MWh energy have been produced by the AV facility only in the first cropping year, leading to an improved land use of 56–86% (Trommsdorff et al. 2021), such reductions in agricultural yields seem to be tenable. In contrast to the REF site, harvestable yields of winter wheat and potatoes cultivated under AV were stable in both years. This supports findings of Amaducci et al. (2018) that in the long term, AV may have yield-stabilizing effects in non-irrigated systems: maximum yields are lower than for open field production in years with favorable weather conditions, but this is compensated by lower yield losses in less optimal years. However, to assess potential yield stabilizing effects of AV, further trial years are necessary. As indicated by the results of 2018, under dry conditions with high solar irradiance, beneficial effects of shading—either directly or indirectly through reduced soil temperatures—on crop productivity are possible. This has recently been confirmed by Barron-Gafford et al. (2019), who found chiltepin pepper and tomato production to be positively affected by the cultivation underneath an AV system under dryland conditions in Arizona, USA. However, the study does not provide sufficient data to assess the impacts on fruit yields, as only fruit number is presented, while information on fruit weights and marketable yields is missing. In addition, Barron-Gafford et al. (2019) found that water retention after irrigation was improved by AV, further emphasizing potential synergistic effects of AV on crop production in arid climates. Besides different climatic conditions in 2017 and 2018, effects of crop rotation also need to be considered in our trial, when comparing both years (Table 1). In 2017, the preceding crop of all treatments in the experiment was perennial grass-clover, which covered the study site for 3 years during the construction of the AV facility. Besides the impact of AV on crop development and yields, future research should also take crop quality into account. In celeriac, first results showed that chemical composition was only barely affected by AV (Weselek et al. 2021), but further studies are needed. As shown for winter wheat, the cultivation under AV led to decreased thousand grain weight as well as to a shift in grain size distribution. It can be assumed that this will also affect grain composition with an increased bran fraction and consequently altered chemical composition and flour yields. As crop quality is one of the most important factors in terms of marketing, potential effects of AV on quality parameters have to be regarded to fully assess its impact on crop production.

4 Conclusion

In this first comprehensive experiment on the effects of AV on crop production of winter wheat, potatoes and grass-clover, it has been shown that both crop development and harvestable yields have been affected by altered microclimatic conditions underneath AV. Measurements of canopy height and leaf area index have shown that shading led to increased growth of aboveground biomass of all investigated crop species, which can be considered as shade-adaptive strategy. However, these findings were not always accompanied by an increased dry matter production of aboveground biomass. While in 2017 all crops were negatively affected by AV with yield losses between −5 to −20%, winter wheat and potatoes grown under AV benefited in the hot and dry summer of 2018 in comparison to the cultivation under open field conditions. In agreement with other studies, the results indicate that the highest potential of AV systems can be seen in hot and dry climates, where beneficial impacts on crop production are likely. As AV systems are intended to be co-productive systems with dual use purposes for simultaneous energy and agricultural crop production, agricultural yields should not be considered in isolation but together with energy yields as well as potential benefits on land productivity, to evaluate AV systematically. However, this also arises the question, to what extent reductions in agricultural yields will be acceptable. This is in particular the case in temperate climates, where the adverse effects of AV on crop production will probably prevail, as well as in regions with limited cropland, where the preservation of agricultural productivity should be premised, to avoid the loss of agricultural land and further trade-off between food and energy production. Nevertheless, the results in 2018 have shown that AV can become advantageous for crop production even in temperate climates, in order to compensate for the prospective risk of more intensive drought periods as expected due to climate change.

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Authors' contributions Conceptualization, P.H., S.Z. and I.L.; Investigation, A.W. and A.B.; Formal analysis, A.W. and J.H.; Visualization, A.W.; Writing—original draft, A.W. Writing—review & editing, A.W., A.B., J.H., S.Z., I.L., P.H.; Supervision, P.H. and I.L. All authors read and approved the final manuscript.

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Data availability The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval Not applicable.

Conflict of interest The authors declare no competing interests.

Financial interests The authors declare they have no financial interests.

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3. General discussion

This section is divided into three subsections. In section 3.1. the impacts of AV on crop production are discussed. For this, at first the results from the field experiment presented in sections 2.1.-2.3. are summarized in section 3.1.1., with different aspects discussed more in detail. The findings are complemented with additional information from literature as well as with unpublished results from the year 2019 and observations that have been made within the field trial. Derived from this, the suitability of different crops for the cultivation under AV is discussed and potentially suited crop species are being identified in section 3.1.2. As the cultivation under AV not only affects crop growth but also management in general, at last certain aspects regarding the practical cultivation in an AV system are discussed in section 3.1.3. In section 3.2 conceivable improvements regarding the experimental set-up (section 3.2.1) as well as regarding the technical design of AV installations (section 3.2.2) are discussed. In addition, prospective research questions are identified section 3.2.1. The deliberations are summarized in each of the two sub-sections to give a short overview. As outlook, the implementation of AV in practice is discussed in section 3.3. First, some basic considerations regarding the definition of the term "agrivoltaic", its demarcation from conventional PV installations as well as the challenge of finding a balance between energy and food production are made. As case example, the status quo of the implementation of AV in Germany is reported and discussed in section 3.3.1.

3.1. Impacts of AV on crop production

3.1.1. Implications from the field trial

As shown in section 2.2 and 2.3, growth and development of all investigated crop species was comparably affected by the cultivation underneath AV with more or less distinct variations between the years: Both LAI and canopy height were significantly increased by AV, which is in line with previous results from shading experiments, where the application of shade led to increased growth of vegetative biomass of winter wheat and potatoes [1–3].

Increased vegetative growth as indicator for shade-sensitivity?

As discussed, both can be interpreted as shade-adaptive response in order to enhance light adsorption [4]. In general, shade-adaptive responses like an increased specific leaf area and photosystem (PS) II:I ratio, as well as a decreased Chlorophyll a:b ratio can be found in both shade-tolerant and shade-sensitive plant species [5]. In contrast, increased elongation growth is considered as shade-avoidance strategy, which can be mainly found in crop species occurring in open habitats like grasslands, where an increment of plant height can be beneficial in order to increase inter- and intraspecific competition for sunlight [5]. By contrast, an increment of plant height is unfavorable in naturally shaded habitats like forests, as surrounding trees cannot be overgrown, while at the same time also mechanical resilience of the plants is impaired [5]. Consequently, found increases in canopy height indicate, that all investigated crop species can be considered as shade-sensitive. The results are not surprising since these species like most common crop species do not originate from shaded environments, but from more open habitats and – in case of wheat and potatoes – from regions with comparably high solar irradiance like the Middle East and South America. However, since the study has been performed in a temperate climate, it should be noted, that found alterations in crop growth may be divergent in regions with higher solar irradiance. Correspondingly, other studies did not find any impact of shading on canopy height of species winter wheat [6,7], potatoes [8] and maize [8], indicating that climatic conditions, the duration and timing shading is applied, as well as species- and cultivar-related differences play a role.

Particularities of perennial forage production under AV

Although grass-clover was comparably affected with an increased canopy height found under AV, the results need to be regarded separately, as grass-clover exhibits substantial differences in comparison to typical crops of arable farming like potatoes and wheat: As perennial plantation, grass-clover is cultivated for a comparably longer period of time, so that further adaptions to the shaded conditions are conceivable within the time span. In addition, grass-clover – which is used as general term for forage mixtures of different grass and leguminous plant species – in our trial was composed of eight different grasses (perennial ryegrass, cocksfoot, common timothy, meadow grass and festolium) and leguminous plant species (alfalfa, red and white clover), of which each may respond differently to the altered climatic conditions under AV. Although the different species have not been evaluated separately during crop monitoring, the results indicated that in particular some of the leguminous species may have been favored by the shaded conditions. As shown in section 2.3, the proportions of grass and clover within the plant population were altered in the experiment with higher shares of clover found under AV in comparison to the REF site. An effect which has been found in both years and independently from the actual age of the grass-clover plant stand, which was multi-annual in the first year of the experiment, whereas it was just sown a few month before crop monitoring started in 2018. As discussed, these findings are in accordance with the results from previous shading studies, were different leguminous species like white and red clover, but also grass species have been shown to benefit from shading, while others did not [9]. It therefore can be assumed, that some type of forage species (e.g. white clover) may be more competitive in shaded environments. However, as the different species within the grass-clover mixture have not been monitored more in detail, it remains unclear, whether further species-specific adaptions occurred, in particular during the perennial vegetation period. This also applies for the found altered shares of grass and clover, as the estimation of species composition during crop monitoring has been generalized for the two types of species (leguminous and grass-like species), so that it cannot be assessed, how the individual leguminous species in the mixture performed. As shown, the found shift in species composition within the grass-clover cropping area under AV did not only affect crop development but also forage yields: Albeit both vegetative growth and also fresh matter yields of above ground biomass increased under AV, dry matter yields actually decreased, presumably due to reduced dry matter content (see also section 2.3). As discussed, this finding may be a consequence of a reduced share of grasses within the plant stand, leading to a reduced DM content and consequently DM yield in total. It therefore can be concluded, that regarding DM yields, increased vegetative growth of grass-clover under AV did not compensate for losses due to lowered grass and consequently DM content. In contrast, shading of pure stands of shade-tolerant forage crops can lead to increased DM yields, like shown for example for white clover [9]. The results further show, that the results from sole crop cultivation cannot unrestrictedly transferred to forage crop mixtures like grass-clover. Here, potential dynamics in species composition and adaption lead to less predictable results. It illustrates even more, why the results of grass-clover production in the present study cannot be compared with the results of crops like potato, celeriac and winter wheat.

Effects on harvestable yields and variances between the investigated crop species

Accordingly, found alterations of harvestable yields under AV were comparable for winter wheat, potato and celeriac in both 2017 (-18.7%, -18.2% and -18.9%) and 2018 (+2.7%, + 11.0% and +11.8%) (Fig. 3), whereas they were different in grass-clover with -5.3% in 2017 and -7.8% in 2018 (see also section 2.2 and 2.3). A finding which has also been confirmed in 2019 (unpublished), where the reduction of harvestable yields of winter wheat and celeriac ranged from -27.1 to -32.1%, whereas DM yields of grass-clover were only reduced by about -18.7% (Fig. 3). In this year, potato tuber yields have not been evaluated, since weed pressure was too high as a consequence of a suboptimal crop rotation within the field trial as described in section 3.2.1. However, beside grass-clover, also the alterations of grain yields of winter wheat in response to the cultivation under AV were slightly different compared to found alterations of potato tuber and celeriac bulb yields: While in 2017 and 2019, the relative reduction of grain yield of winter wheat under AV was comparable to found reductions in potato and celeriac, the yield increment in 2018 was less pronounced. A finding which may be explained by the fact, that winter wheat was already sown in fall 2017 and thus may have profited from higher soil moisture during fall and spring, leading to lower drought stress during the dry and hot summer season 2018.

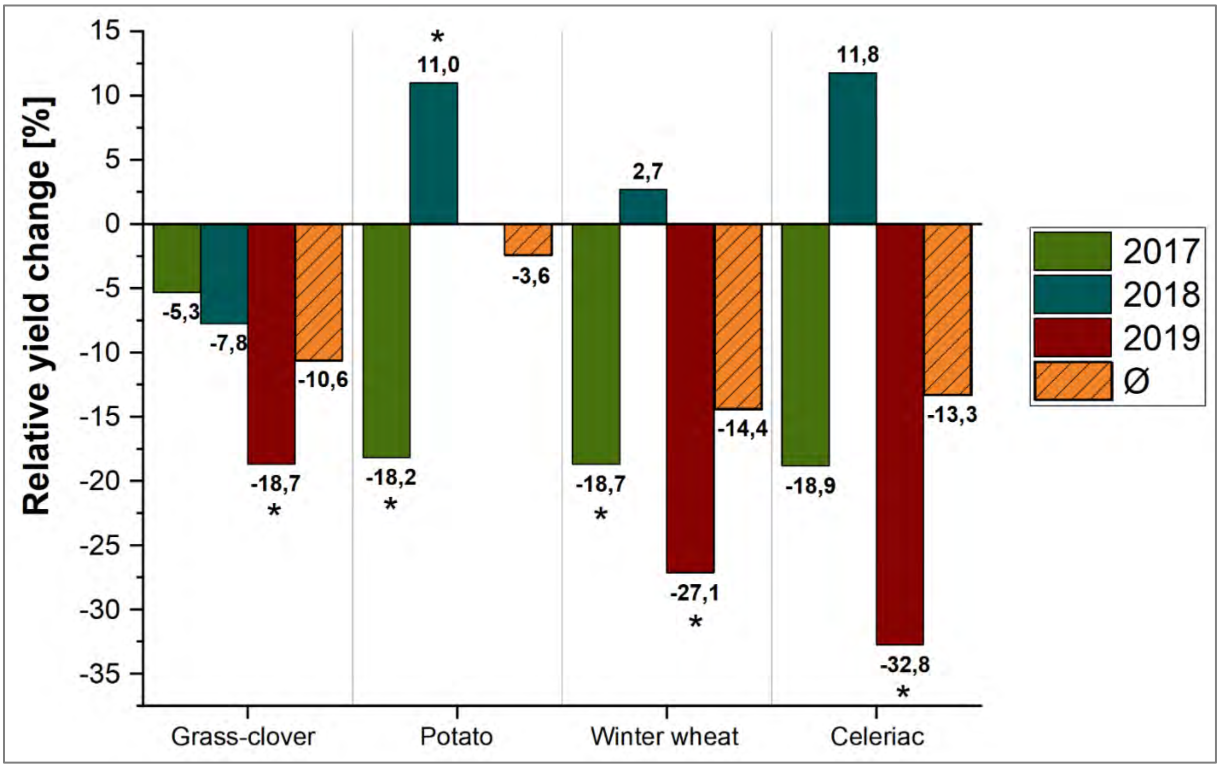

Figure 3: Relative changes in harvestable yields of grass-clover, potato, wheat and celeriac through AV in 2017-2019 and averaged for all three years (orange-striped bars). For potato, relative yield change has just been averaged for 2017-2018 as in 2019, potato yields have not been ascertained due to high weed pressure. Significant differences ($p<0.05$) are indicated by stars.

In contrast, celeriac and potato as summer crops have been planted during a period, when the soil was already dry. Consequently, the assumed mitigation of heat and drought stress and accordingly higher yields under AV in 2018 may have been more pronounced as in winter wheat. When comparing the effects on harvestable yields of the investigated crop species, it has to be noted that, apart from differences between the investigated crop species in vegetation period or species composition (in case of grass-clover), they also differ in which plant component is being harvested and at which stage of development: In grass-clover, above-ground biomass is generally cut (or grazed) several times a year between the development stages of heading and flowering, depending on cutting frequency and usage (hay or silage). In contrast, harvestable yields of winter wheat, potato and celeriac are determined by evaluating the yield of reproductive and/or storage organs like grains, tubers and roots/bulbs.

Effects on yield components and derived implications

Although formation and filling of such reproductive organs is driven by the supply with photosynthetic assimilates from the photosynthetic active parts of the plants (e.g. leaves) [10], an increased vegetative growth and biomass did not necessarily lead to an increment of harvestable yields as the results have shown. In this context, the consideration of how different yield components have been affected by AV may help to understand such coherencies more comprehensively. As shown, enhanced vegetative growth also led to an increased shoot biomass at final harvest in celeriac and winter wheat. Even though found increases in crop height and LAI of potatoes indicate, that vegetative growth was enhanced by the cultivation under AV, too, final shoot biomass could not be estimated in our trial as final harvest took place after complete senescence of potato haulms [4,11]. Straw yield of winter wheat increased in 2018, but decreased in 2017. However, as significant higher harvest indices indicated, the share of vegetative biomass at total shoot biomass was increased under AV in both years or vice versa, the share of grains decreased. In early shading studies with wheat, several authors already described, that spike weight decreased in response to shading through a reduction in grain weight and/or number [3,6,12]. The reductions have been assumed to be caused by a reduced assimilate supply to and within the spikes [3,13]. In our trial, spike weigth and grain number per spike were only decreased by AV in 2017, but actually increased jointly in 2018 with increasing grain yields. In both years however, thousand grain weight and accordingly also kernel weight was reduced under AV. In particular in 2018, reduced grain weight was also reflected by significantly lower grain sizes, which is also in accordance to findings of Artru et al. [6]. In summary, the results show that the cultivation under AV led to decreased grain weight and number in 2017 and to decreased grain weight and size in 2018, and thus are in line with above-mentioned results from shading experiments. However, it cannot be validated within the present study, whether these findings were caused by an decreased assimilate supply to and within the spikes, as well as if the results can also be transferred to potatoes. Here, the cultivation under AV led to a reduced tuber size [11], which may be due to a reduced assimilate supply to the tubers, too. Even if so, it remains unclear, whether assimilate translocation to generative organs like tubers and grains was impaired due to generally reduced assimilate supply, as consequence of lowered photosyntetic performance in the partial shade, and/or higher shares of assimilates being utilised for increased vegetative growth. As shown by Artru et al. [6], grain yields of wheat decreased even when shade was applied only shortly before anthesis. At that time, maximum LAI was already reached and thus, vegetative biomass was equal in both treatments. As they assumed, grain yield reductions most probably can be explained by a reduced production of photosynthetic assimilates during grain filling. This is in accordance with findings in early shading studies with wheat, which found the period shortly before anthesis to be most sensitive to shading, while shading 45 days prior to or after anthesis did not have any signficiant effects on grain number [12,13]. The findings indicate, that in particular during late stages of development, shading negatively affects harvestable crop yields, while the effects of early shading were found to be negligible [1,12]. A fact which also has to be considered when optimising agrivoltaic systems for crop production (see also section 3.2.2).

Yield stabilizing effects through AV?

Apart from species-specific yield differences, the results of 2019 have shown, that in years with less extreme climatic conditions and more balanced rainfalls during the growing season, yield reductions under AV can be expected to be more distinct as in years like 2017 and 2018 (Fig. 3). On average, harvestable crop yields under AV were reduced by 26.2% in 2019. A finding which is in line with modelling results of Amaducci et al. [14], who found yield differences between AV and unshaded conditions to be higher in years with more favorable climatic conditions. Furthermore, a yield stabilizing effect through AV as assumed by Amaducci et al. [14], has been confirmed in case of winter wheat, where mean grain yield under AV in 2017-2019 has only been fluctuating by 0.4 t TM ha^{-1}, while in the same period, they have been varying by 2.3 t TM ha^{-1} on the REF site. For grass-clover and celeriac however, yields within the years were quite distinct in both treatments, and thus, no yield stabilizing effect through AV has been observed. However, in comparison with a 40-year dataset used by Amaducci et al. [14], the here presented results of a three-year experiment can be regarded quite short to assess the effects on long-term crop yields.

Drivers of change: Climatic and microclimatic variances under AV

As shown, crop production under AV was affected in various ways. In this context, decreased light availability underneath the solar panels has been identified to be the most significant constraint for crop cultivation (see also section 2.1). A finding which has also been confirmed in recent studies with rice, showing that yield reductions were nearly linearly correlated with shading rates [15]. Apart from shading, different microclimatic parameters were found to be altered under AV, of which some may have been also beneficial for crop producitvity. This was in particular the case in 2018, in which decreased soil and air temperature were assumed to have lessened the adverse repercussions of heat and drought (see also section 2.2 and 2.3). However, while lowered soil temperatures during hot summers can be favorable for yield formation of for example potato tubers [16], it also can become disadvantageous. As N-mineralization in soils is driven by soil moisture and temperature, a delecerated warming of the soil can reduce N-mineralization rates in spring [17]. A fact, which can become yield-relevant in crops with a high nitrogen demand during spring, like for example oilseed rape or corn [18,19]. This applies even more for organic crop production, where crop growth is more dependent on nutrient mobilization from the soil than in conventional farming, where easily soluble mineral nitrogen fertilizers are available. Apart from nitrogen mineralization, another effect which was potentially induced by lowered soil and air temperature underneath the solar panels of the AV system was observed in 2019. In this year, a high number of celeriac plants has been sprouting. Although this effect was visible on both sites, it was distincly more pronounced underneath the AV system. In several biennal root vegetable species including celeriac, sprouting is known to be induced by vernalization [20,21]. Usually sprouting takes place in the second cropping year, while in the first cropping year it is undesirable as it is linked to losses in harvestable yields and quality. However, it can already be induced in the first cropping year by low temperatures during its juvenil phase [21]. Shortly after celeriac was planted by the end of april in 2019, temperatures in May dropped below zero for several days, which may have induced vernalization in some of the plantlets. It can be assumed, that this effect was more pronounced under AV due to lowered soil and air temperatures (see also section 2.3). In addition to temperature effects, also water supply has been discussed to be affected by AV due to heterogenous rain water distribution. Beside direct effects like an increased risk of erosion in the direct runoff of the panels, soil moisture has been assumed to be effected, too, though the arrangement of soil sensors only allowed limited conclusions (see also section 3.2.1). In 2019, first measurements have been conducted to allow drawbacks on spatial heterogenity of soil moisture underneath the AV facility. For that, soil moisture has been measured with mobile TDR probes at different spots in a transect in crosswise direction to the panel rows. The measurements confirmed, that soil moisture was slightly increased underneath the panel runoff, while it was reduced in the area in between two panel rows mounted above [unpublished; 22]. However, this effect has only been found in winter wheat, potato and grass-clover. In celeriac, the differences between the different measuring points were less pronounced, indicating that in row-crops like celeriac with relatively sparse crop stands, increased surface water flows along the slope gradients may have led to more balanced soil moisture across the field. In this context, the potato plant stand in 2019 can be considered exceptional due to high weed pressure as described in section 3.2.1. It therefore can be assumed, that further factors like crop density, weed pressure, slope gradient of the field and soil characteristics have to be considered, too, when regarding soil water redistribution. The results indicate, that uneven rain distribution under AV also affects soil moisture, further emphazising that technical solutions for an improved rain water distribution need to be integrated in the planning of AV systems (see also section 3.2.2). In this context, also the experimental set-up should be reassessed as consequently, soil sensors and also harvest plots of the investigated crops may have been placed in the rain sheltered part underneath the facility (see also section 3.2.1). Beside soil moisture, air humidity was shown to be slightly increased by AV, too. Although this effect was particularly found during winter time [11], the question arises, whether higher humidity under AV may also affect the incidence of fungal leaf diseases (see also section 3.2.1). It can be concluded, that shading is the most important constraint for production under AV, but further interaction effects of found microclimatic alterations should not be completely neglected.

3.1.2. Suitability of crops for the cultivation under AV

The results from the field trials discussed in the preceding section enable a valuable insight on the effects of microclimatic alterations under AV on the cultivation of different crop species. However, as discussed in section 2.1, such findings are strongly dependent on local climatic conditions, so that its transferability is only possible to a very limited extent. Apart from local climatic conditions and year-effects, the findings further depend on a number of influencing factors like soil characteristics, field management (including crop rotation, fertilization, crop protection, irrigation, etc.), crop varieties and in particular also the way and extent solar radiation is reduced by the AV facility. On an experimental level, shading e.g. can be varied in its intensity, uniformity, duration and stage of development being applied. In case of AV systems, these factors mainly depend on the technical design and set-up of the respective AV construction. Considering all these influencing factors as well as a very limited number of comparable studies on the effects of shading on crop production, universal recommendations regarding the suitability of crop species for the cultivation under AV are quite challenging.

Light saturation, CO_2 assimilation and shade tolerance

This raises the question, whether more universal parameters can be applied to identify potentially suited crops. One approach to evaluate shade tolerance of different crop species, can be to categorize crops regarding their light saturation point [8,23]. In plant physiology, the interrelationship of photosynthesis and irradiance is classically described by the light response curve [10]. At low irradiance, photosynthetic performance is notably limited by photon flux density (i.e. photosynthetic active radiation, PAR). With increasing photon flux density, photosynthetic performance is increasingly saturated until it reaches light saturation point. From this point on, a further increase in photosynthetic performance is not limited by irradiation, but CO_2 assimilation [10]. In comparison to sun pants, shade-adapted plants reach light saturation point already at comparably lower light levels, so that further increases in PAR will be less relevant in terms of crop growth or yields. In a recent study on the effects of shading on potato production, the authors concluded, that under shaded conditions, sufficient potato tuber yields comparable to the full sun control can be attained, depending on whether light saturation point (which was estimated around 400 µmol m^{-2} s^{-1} or 14.86 MJ m^{-2} day^{-1} for potatoes) could be achieved during potato growing period in the respective treatments [8]. In other words, if monthly average radiation during potato growth period was above 14.86 MJ m^{-2} day^{-1} in a certain treatment (e.g. 26% shade), tuber yields were not affected. According to this, Schulz et al. [8] extrapolated, to which extent shading can be tolerated in potato cultivation in Central Europe, based on long-term climatic data (Fig. 4). The figure shows, that with decreasing latitude, higher shading rates can be tolerated and may even become favorable at some point, as excessive radiation above light saturation point can lead to photoinhibition and declining photosynthetic rates [10]. However, while in the years 2016 and 2017 a non-attainment of light saturation point in the treatments with 26% (2016) and 50% (2016 and 2017) shade led to significantly reduced tuber yields, this was not the case in 2015. Here, tuber yields were unaffected, although light saturation point was not reached in the treatment receiving 50% radiation only [8]. The authors assumed, that after emergence a certain minimum of PAR has to be available to obtain sufficient yields and moreover, further microclimatic parameters like soil and air temperature have to be considered [8], which is in line with the above made assumptions.

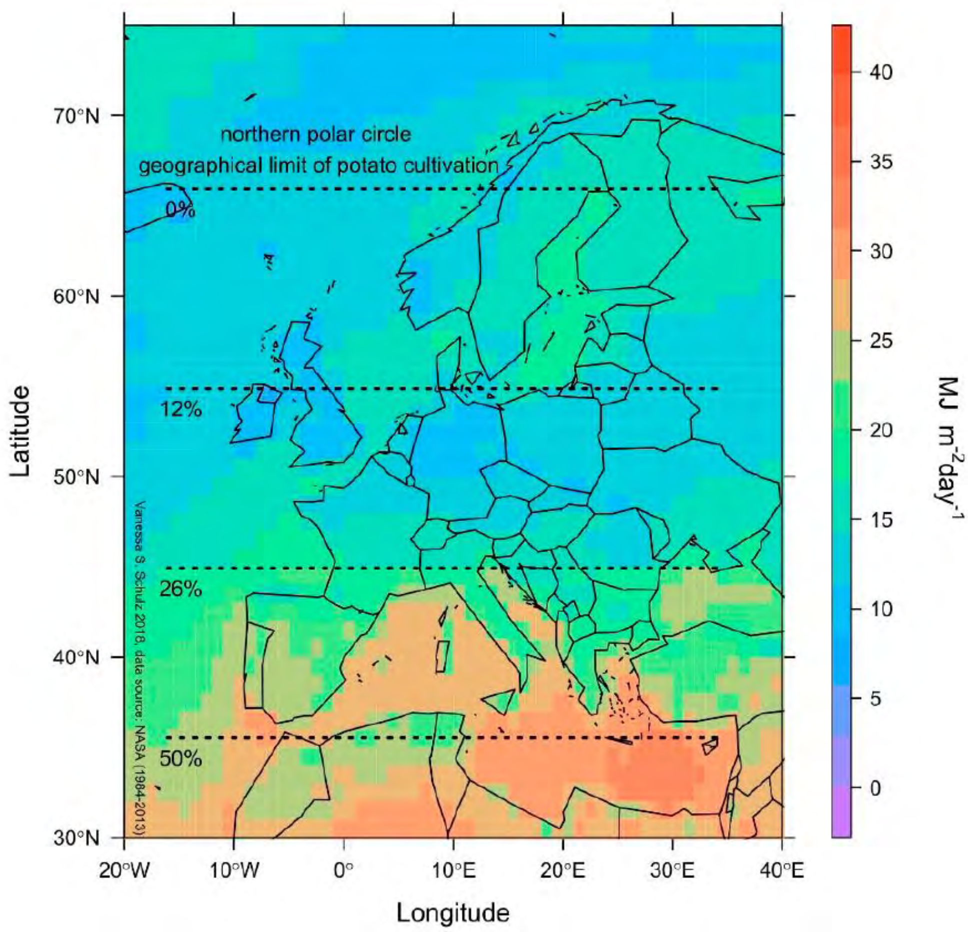

Figure 4: Mean total solar irradiance (MJ m^{-2} day^{-1}) during the potential potato growing season (March to October) in Europe from 1984–2013 and the limiting shading extents of 0, 12, 26 and 50% at different latitudes. (source: [8])

While in C3-plants like potatoes, high temperatures and excessive radiation can lead to declining photosynthetic rates and consequently impaired crop growth, C4-plants are quite well adapted to such conditions [24]: Through the spatial segregation of CO_2 assimilation and photosynthesis, photosynthetic ratio can be maintained and even increased at high temperatures, whereby likewise higher amounts of light can be absorbed and light saturation point is reached at comparably higher PAR levels in comparison to C3-plants [10,24].

Correspondingly, C4-plants can be expected to be more sensitive to shading and consequently, some of the most important cash and food crops like corn, millet and sugarcane which are C4-plants, can be considered as less suitable for the cultivation in AV systems.
Although such approaches, to describe and categorize different crops according to underlying physiological mechanisms and their ability to adapt to shaded environments, seem reasonable, its applicability to identify potentially suited crops for the cultivation under AV and predict potential effects on crop productivity is very limited. Beside the fact, that the data base is often inadequate and certain information e.g. on light saturation points of specific crops or varieties is missing, climatic and regional effects still remain uncertain.

Identification of crops suitable for the cultivation under AV

Coming back to the findings of the present work discussed in the preceding section, most of the investigated crop species showed comparable responses to the altered environment, so that it can hardly be estimated which crop can be considered more or less suitable. Furthermore, this estimation also depends on the actual threshold being defined regarding acceptable yield losses (see also section 3.3). Assuming that yield losses of 20% can be tolerated, all of the here investigated crop species can be considered as suitable for the cultivation under AV (under given climatic conditions), with yield reductions ranging from 10.6% (grass-clover) to 14.4% (winter wheat) on a three-year-average (excluding losses through a reduced cultivation area) (section 3.1.1; Fig. 3). Apart from reductions in harvestable yields, crop monitoring revealed that vegetative growth and partly also biomass of the investigated crop species was enhanced by AV, potentially through shade-adaptive responses of the crops. Derived from this, it has been assumed, that in particular such crop species, in which yields are determined by above-ground biomass, are suitable for the cultivation under AV (see also section 2.1). In addition to leaf vegetables such as lettuce, spinach or different cabbage species, also biomass-based energy crops (e.g. silage maize or perennial crops like miscanthus) or crops for fiber production (e.g. hemp) therefore may be appropriate. The same applies for forage crops, though species-specific adaptions in particular in mixtures need to be considered as discussed in the preceding section. However, apart from findings in lettuce [25], most of these crops so far have not been cultivated under AV or shaded conditions. Furthermore, not only harvestable yields, but also quality characteristics need to be considered when evaluating the suitability of crops (see also section 2.2). With regard to the above-mentioned crops, e.g. the here found reductions in fiber content (see also section 2.2) or other yet unknow shading effects on chemical composition may become relevant, e.g. in terms of sensory or texture quality (e.g. of lettuce or leaf vegetables) [26], biogas yield as well as fiber yield and quality (energy/fiber crops) [27,28].
In section 2.1, the suitability of AV for crops, in which adverse environmental/climatic factors

are already a limiting factor, and/or cropping systems, which already apply protective structures such as nets or also polytunnel, has been discussed. In this context, different crops can be identified, which either can profit through direct positive effects of shading (e.g. in berries [29–31]) or through the protection of extreme climatic events, such as hailstorms, rainfalls or excessive radiation and temperatures, which are known to cause crop yield losses and negatively affect quality, e.g. in horticultural crops like tomatoes and pepper [32,33], orchards [34–37] or viticulture [38–40]. Here, AV may facilitate to reduce weather risks and in addition also the costs for more short-life protective materials like nets or foils which are being replaced. Consequently, this aspect has recently been taken up by several projects addressing the application of AV for example in fruit production [41,42], viticulture [42] and in the cultivation of different berries [43] (Fig. 5). As can be seen from Fig. 5, the technical design of such AV facilities is adapted to optimize such protective effects of the solar panels as well as to consider crop-specific needs.

Figure 5: Application of AV in Raspberry and apple production. (source: BayWa r.e. [43] (top); Fraunhofer ISE [41] (below)).

Although the application of AV in such cropping systems has not been investigated more in detail yet, it offers a certain potential to reduce potential trade-offs between food and energy production of AV by utilizing synergistic effects, also in more intensive cropping systems and in temperate climates.

The above made assumptions regarding the suitability of different crop species for the cultivation in shaded environments like AV or agroforestry, have recently been confirmed in a meta-analysis, assessing the impacts of shading on crop productivity [44]. For this, the findings of different shading studies, of which many also have been discussed within section 2.1, have been pooled and categorized into different types of crop species [44]. The evaluation indicated, that in particular fruit and berry crops, followed by fruity vegetables, are most suited for the cultivation in shaded conditions. In these crops, moderate shading with a reduction in solar radiation of up to 30%, was found to be negligible or even beneficial regarding crop productivity. In addition, forages and leaf vegetables were estimated to be suitable, too, with none or only little reductions in harvestable yields occurring in response to moderate shading [44]. By contrast, losses in harvestable yields of C3 cereals and tuber/roots crops increased with increasing shade [44]. However, as the reductions in yields were lower proportional to the actual reduction of incident light, the authors concluded, that these crops can be considered as suitable for the cultivation under shaded conditions, too [44]. In grain legumes and maize however, reductions in harvestable yields were found to be overproportionate to the reduction in solar radiation, so that these crops have been considered as less suitable [44]. The findings of the meta-analysis provide a valuable insight into crop-specific differences in response to shading intensity, also confirming the above made deliberations regarding the suitability of different crop species. However, the significance of the results is limited: As concluded by Laub et al. [44], studies and data on the effects of shading on different crops is generally scarce, so that the overall number of studies included in the meta-analysis is quite small. Therefore, the findings do not allow site-specific yield predictions.

In accordance with the conclusions in section 2.1 it thus can be reiterated, that a further development and improvement of (crop) modelling can be seen as most promising approach, to allow reliable, site- and design-precise predictions regarding the impacts of AV on crop productivity as well as its overall performance including aspects of power generation. Since first modelling approaches have been introduced, addressing different aspects like light distribution, microclimatic alterations as well as electrical and crop performance of AV systems (e.g. in [25,45–48]) (also see section 2.1), this approach has been readopted and further developed by several researchers [49–51]: Beside the integration of economic considerations [50], the combination of different modelling tools enables to simulate the overall performance of AV systems also with a high spatial resolution, as recently demonstrated by Campana et al. [49] or in a preliminary study by Willockx et al. [51]. But still, a reliable modelling of crop

performance is challenging as many different aspects like microclimatic alterations as well as responsive crop-specific physiological adaptions need to be incorporated, emphasizing the need to further develop and refine crop modelling tools.
Anyway, disregarding modelling approaches and site-specific effects, it can be summarized, that some crops and cropping systems as suggested above may be more suitable for the application of AV and thus, should be addressed in prospective research (see also section 3.2.1). In this context, 'suitable' always relies on its actual definition, which can range from a maximized utilization of synergistic effects to a minimization of crop yield reductions to a certain, defined extent. However, the data basis is still not adequate to allow solid conclusions. In addition, the identification of single crops may not be sufficient as these crops always have to be embedded in the context of a crop rotation (except plantations with permanent crops), so that the complete rotation including all crops needs to be regarded.

3.1.3. Practical cultivation underneath AV

Beside a scientific view on the crop production underneath an AV system, the present study also offered the opportunity to evaluate this technology from a farmers' point of view: Although this was not the main objective of the study, it has been conducted under practical conditions on a farm managed according to organic principles. Consequently, the entire study site has been processed with conventional farm machinery by the farmers themselves. Although on-farm field trials are always accompanied by a certain loss of accuracy in comparison to small-scaled precision experiments conducted with special machinery, they offer a valuable view on the prospective practicability of current research objectives. In case of AV, its practicability is an inevitable premise for its application as dual use technology in agricultural production. This accounts even more as AV is partly already implemented on a commercial scale (see also section 2.1). Consequently, several aspects regarding its repercussion on practical field management will be discussed in the following. The addressed aspects are only based on the experience gained from the field experiment and personal communication with the farmers involved in the APV-Resola project. These aspects have not been explicitly addressed within the field experiment, so that some aspects may need to be assessed more in detail in future research (see also section 3.2). Although the discussed aspects of uneven rain distribution and concomitant effects on soil erosion and crop production also affect the practical cultivation underneath AV, these will be addressed more in detail in section 3.2.

Management of the inaccessible strips between the mounting pillars

As already discussed in Section 2.3., the pillars of the AV plant lead to formation of strips, as most processing steps like sowing, weed control and harvest will be conducted parallel to the pillars, so that the area in-between probably will not be accessed with common farming machinery during the vegetation period. Accordingly, throughout the field experiment, these strips had to be mowed manually by using string trimmers approximately twice a year. As a consequence of missing tillage operations and a comparably extensive management of these strips, weed control could not be accomplished sufficiently, so that the propagation of weeds within these strips has been promoted as indicated by the field experiment. Here, an enhanced emergence of problematic weeds like broad-leaved dock (*Rumex obtusifolius*) has been observed in and next to these strips (Fig. 6).

Figure 6: Transition from the celeriac to the winter wheat cropping area in 2017. In between, one of the inaccessible strips with wild, grass-accentuated vegetation can be seen. At its right edge, the occurrence of individual plants of broad-leaved dock (*Rumex obtusifolius*) can be observed. (source: Bauerle/University of Hohenheim)

The AV facility in Heggelbach was actually designed so that the distances between the supporting pillars in both long- and crosswise direction fit to the working widths of the farms' machinery. Accordingly, all working steps (e.g. tillage operations) can be carried out in both long- and crosswise direction, facilitating an effective weed control and diminishing the proliferation of problematic weeds within these strips. However, within our field trial, sensors and data loggers for microclimatic monitoring have permanently been installed on these strips, obstructing a mechanical processing in longwise direction throughout the entire experiment. It therefore can be assumed, that the observed proliferation of weeds within these strips will become less relevant, once the experimental set-up has been removed and the area underneath the AV facility can be cultivated with less restrictions. Notwithstanding, prospective AV arrays should be planned accordingly, so that the pillar distances in either direction fit to the working widths of the farm machinery to enable a management in both directions. If not so, either soil tillage may need to be performed more elaborate by driving around the supporting pillars and/or a more sufficient management of the strips is needed for an effective weed control. Anyway, even if the strips can be processed mechanically during the off-season, they still need to be somehow managed during vegetation period as expound above. While in organic farming these strips can only be managed quite labor- and consequently cost-intensive by manual mechanical weed control, conventional farming offers the opportunity to apply herbicides which can be considered to be less labor- and cost-intensive. Unless, more sophisticated approaches for the utilization of the strips are found. While the strips have been managed extensively in our trial without any particular concept for its utilization, various options are conceivable (see also section 2.1): In more intensive farming systems of vegetables and fruit production with a high share of manual labor, the area between the pillars may be utilized regularly for crop cultivation. As a consequence, also lower shares of area would be lost for agricultural production. On arable farms with a high level of mechanization, the strips between the pillars may be used more passively for measures to enhance biodiversity, like the sowing of annual or perennial flower strips (see also section 3.2.1). As such, these would offer the opportunity to reduce both labor efforts and weed pressure, while at the same attracting pollinators and enhancing biodiversity. However, considering recent innovations in robotics and robotic lawn mowers already being used in many private gardens, less labor- and cost-intensive possibilities for mechanical weed control are conceivable in near future. Apart from AV facilities in which the PV modules are lifted several meters above the cultivation area, also ground-mounted facilities are currently discussed for its application in combination with arable farming (see also section 3.3). Here, weed control underneath the solar panels may become even more challenging, as the area underneath the panels is less well accessible in comparison to pillar-mounted AV facilities like in Heggelbach. However, weed pressure can also be assumed to be lower due to unfavorable growing conditions in the dense shade of the ground-mounted panels in comparison with pillar-mounted panels.

Cultivation under AV: extra efforts and expenses?

Aside from the area between the pillars of the AV facility, the practical experience has shown that most common farming operations can be carried out without considerable constraints. This is in particular the case for all working steps which are generally carried out with more slow driving speeds, like sowing or harvest. In contrast, more-intensive measures like soil tillage or measures which can be carried out more rapidly (e.g. mechanical weed control with hoes or currycombs), have to be conducted more carefully to avoid any damage or physical contact with the AV construction. This requests an increased attention while driving, in particular during measures like hoeing, where slight deviations from the driving lane may also lead to a damage of the crops. According to the farmers participating in our field trial, such procedures can be handled quite good after some practice, especially if enough safety distance is left to the AV construction (which on the other hand will lead to higher losses in cultivation area). However, still some more time probably needs to be taken into account for such operations, when carried out in or under an AV installation. As the effectiveness of mechanical weed control procedures is often dependent on driving speeds, the right balance between caution and effective weed control and working speeds has to be found.

Figure 7: Potato (top) and wheat harvest (bottom) in 2017. Even with big machinery, harvesting of the different crops could be managed smoothly (source: Heggelbachhof (top), Bauerle/University of Hohenheim (bottom)).

When regarding extra efforts for the cultivation under AV, not only working hours, but also fuel consumption needs to be considered. Until now however, a more detailed assessment of additional expenses (e.g. for fuel or labor) for crop production under AV is outstanding and has also not been addressed in recent studies evaluating the profitability of AV [23,52,53] (see also section 3.2.1). However, given recent technology innovations in robotics and the increasing application of GPS supported machinery like controlled traffic farming and/or automatic steering systems, the mentioned aspects may become less important in future.

3.2. Experimental and technical improvements as indicated by the field trial

3.2.1. Optimization of the experimental set-up and the identification of prospective questions in AV research

Consideration of microclimatic heterogeneities – Rain distribution and soil moisture

As discussed, the results from rain distribution measurements indicated, that all monitoring and harvest plots within the field experiment were placed in the rain sheltered area between the panel rows receiving less rain (Fig. 8) (see also section 2.3). The question arising thereby is, whether the results discussed within this work can be regarded to be representative for the conditions underneath the whole AV facility or not. This applies in particular for the evaluation of crop performance and yields, as the monitoring plots presumably received less rainwater and thus may have been affected differently in comparison to other areas underneath the AV facility. The same applies for the monitoring of soil microclimate, as also soils sensors have been installed in an area receiving less rainfall, explaining the finding, that soil moisture was found to be lower underneath AV occasionally. However, as the facility has been placed on a field with a slope in southwest and northwest direction, surface and soil water redistribution is likely and may also differ between different crops, depending on row distances and crop density, as first measurements in 2019 indicated (see also section 3.1.1). Accordingly, it remains unclear, whether uneven soil moisture underneath the AV facility affected the experimental results, or can be neglected as they may have occurred only shortly after rainfalls until they adjusted over the whole area through a horizontal water redistribution. Regarding prospective research questions and the optimization of the experimental design however, two approaches can be derived from this: (1) For the placement of sensors and monitoring plots, representative areas should be selected or if not applicable, areas with differing microclimatic conditions need to be considered equally. In case of Heggelbach, the monitoring plots and sensors therefore should have been placed at least at two different positions in relation to the above-mounted panel rows: with plots equally placed in between (receiving lower amounts of rain) and directly underneath the panel run-off (receiving higher amounts of rain). Beside a better understanding of microclimatic heterogeneities, this would facilitate to further assess, if also crop development and yields differ dependent on the position underneath the AV array

(2). For a more in-depth evaluation of microclimatic heterogeneities underneath the AV facility, more precise and comprehensive measurements are needed. An approach which also has been pursued with the measurements with mobile TDR probes conducted in 2019, though further measurements and a more detailed analysis are needed (see also section 3.1.1). In this context, an experimental set-up on a plain field without slopes should be preferred to eliminate potential side effects and a distortion of the findings through enhanced soil or surface water redistribution.

Figure 8: Rainfall distribution underneath the AV array after a light drizzle. The rain shaded area behind the PV panel row is still dry. At the left and right side of the picture, the placement of sensors recording aerial climate and PAR can be seen (source: Weselek/University of Hohenheim).

Apart from a more accurate and comprehensive data acquisition, rain water distribution generally may be improved by adapting the technical design of AV facilities (see also section 3.2.2).

Light distribution underneath the AV array

In addition to uneven water distribution, also light distribution underneath the AV facility is likely to be altered depending on the position in relation to the PV panel rows. In our case, the facility has been constructed based on preceding studies and simulations, predicting that the technical design of the AV facility in Heggelbach facilitates a homogenous light conditions underneath the solar panels [54,55]. However, this has not been validated within the field trial as the sensors recording aerial climate and photosynthetic active radiation had to be placed in equal positions in relation to the above mounted modules, on the same level as the supporting pillars of the AV plant (Fig. 8). This placement was necessary due to practical reasons, to enable unrestricted movement of the agricultural machinery on the cropping area underneath the AV plant. Consequently, no measurements of PAR have been carried out on the area between the panel rows. Thus, in addition to microclimatic measurements, also heterogeneities of solar radiation underneath the AV facility should be addressed to verify, whether the predicted uniform light distribution underneath the AV plant can be confirmed in practice. This may be achieved either by establishing a field trial which is not cultivated with large agricultural machinery so that the sensors can be distributed more widely, or by performing measurements with mobile probes recording PAR comparable to the measurements of soil moisture as described above. An approach, which also has been carried out for testing purposes within the field trial in Heggelbach. However, the measurements have shown, that measuring PAR occasionally is insufficient as the values are strongly dependent on sky coverage (clear, cloudy, overcast, etc.), solar altitude and the position in relation to the solar panels as well as to the borders of the AV plant. Consequently, the collected data is not sufficient enough to allow clear inferences regarding heterogeneities of PAR underneath the AV array. Therefore, measurement series with high temporal and spatial resolution are needed to examine whether PAR is distributed homogenously, while at the same time excluding potential side effects (e.g. sky coverage). In this context, the fixed installation of sensors at different positions with a constant monitoring of PAR as suggested above, seems to be more appropriate than occasional measurements with mobile probes.

With regard to border effects, the data of the fixed installed sensors gathered within the present study has pointed out, that on early morning hours after sunrise as well as during wintertime, PAR sensors at the southeastern side under the AV plant received higher PAR levels compared to sensors on the northwestern side, while sensors on the southeastern side of the REF site received lower PAR levels compared to those on the northwestern side. These findings may be explained by the fact, that during these times, PAR sensors on the southeastern side of the AV plant were directly irradiated from the sides of the array without any shading effects. At the same time, sensors on the REF site – which was placed in northwest direction of the AV site – were shortly shaded by the AV facility. Although the found differences between the southeastern and northwestern sensors were not significant, such border effects could have been reduced by placing the reference site in a higher distance to the AV array, so that a shading of the REF site during early morning hours in can be avoided.

Adjustment of the crop rotation

As mentioned in section 3.1.1, potato yields have not been evaluated in 2019 due to high weed pressure. As shown in Fig 9, the potato cropping area was strongly infested with different weeds like white goosefoot (*Chenopodium album*), common amaranth (*Amaranthus retroflexus*) and orchard grass (*Dactylis glomerata*).

Figure 9: Potato cropping area completely covered with weeds on the 22th August 2019, a few days before harvest. (source: Weselek/University of Hohenheim)

As can be seen from Fig. 10, potato has been cultivated twice on the same strip within three experimental years with an intermediate cultivation of celeriac in 2018. In other words, the same strip has been cultivated with summer crops in three consecutive years, explaining the high incidence of typical summer weeds as described above. As consequence of high weed pressure, also direct measures like hoeing and ridging, which are usually quite effective for weed control in potatoes, were insufficient.

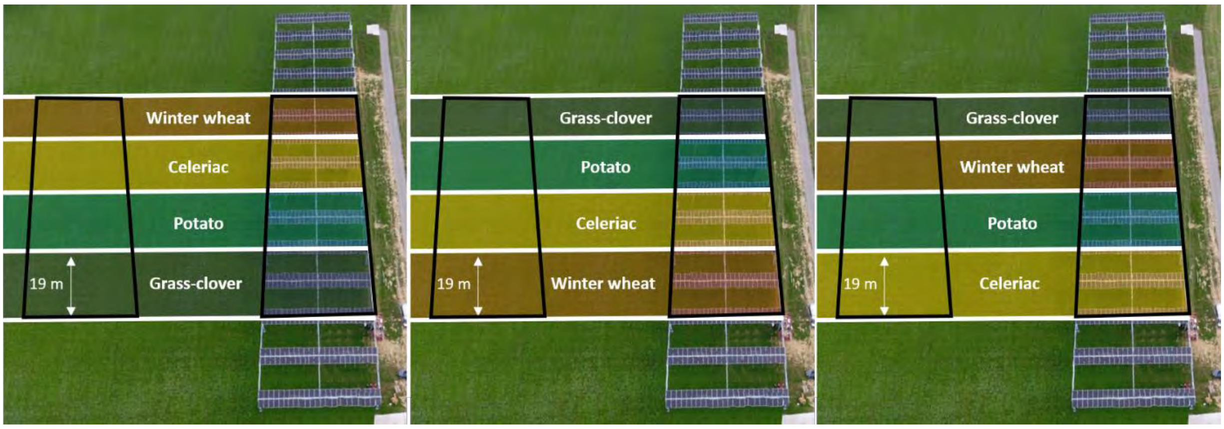

Figure 10: Schematic illustration of the crop-rotation within the field trial underneath the AV facility and on the REF site in the years 2017-2019. (modified after BayWa r.e.)

In general, appropriate crop rotations play a key role in arable farming to maintain soil fertility, control weeds and prevent the propagation of pests and diseases. This applies even more in organic farming, where the input of external resources (e.g. synthetic pesticides and mineral N-fertilizers) is quite restricted. For the proper planning of (organic) crop rotations, some basic rules have to be considered. Among others, these include the alternation of spring and winter crops, cereal and foliage plants, the adherence of cultivation breaks of respective crops to prevent the proliferation of pests, the cultivation of catch crops and (perennial) grass-clover [56]. Although these principles are generally considered in the farm's standard crop rotation, they could not be fully implemented within the field trial due to the limited experimental area. Consequently, only four different crops of the farms' common crop rotation have been selected for the field trial. In addition, the experiment initially has only been planned for the years 2017 and 2018, while a further funding for another experimental year in 2019 has just been confirmed by a time (end of October 2018) when it was already too late to sow grass-clover. As a consequence, grass-clover was cultivated biannual (which is not uncommon, but divergent to the preceding experimental years) in 2019, while the remaining crops had to be placed in the remaining cropping strips. Apart from weed pressure, the resulting suboptimal crop sequencing may have promoted pest incidence, too. For example in potatoes, an infestation with Colorado beetle has been observed in all three years. Beside crop rotational effects however, pest incidence may also have been promoted by the very-limited cultivation area. In case of Colorado beetle for example, it cannot be excluded, that also an immigration of the beetles from the neighboring strip, where potato has been cultivated in the preceding year, took place after overwintering [57]. However, as the infestation with pests and diseases has not been monitored in detail, it cannot be validated, whether an increased incidence occurred within the years as a consequence of a limited crop sequencing and cultivation area. Nevertheless, the example of potatoes illustrates the challenge of finding an appropriate experimental design. This applies in particular in case of the present AV field trial, where the aspiration was to investigate multiple crops, while at the same time the experimental area is strictly limited and also non-relocatable due to the fixed AV installation. Apart from feasible adverse effects like increased pest and weed infestation, crop rotational effects also have to be considered when comparing yearly crop yields (see also section 2.3). To minimize crop rotational effects, the experimental design of the field trial may have been improved by using the same sequence staggered on each strip, while at the same time incorporating an optimized alternation of spring and winter crops (Fig. 11). As a result, weed pressure may be reduced, while at the same time, potential side effects through differing preceding crops can be excluded. Potential disadvantages would be, that grass-clover is only cultivated for one year, leading to lower nitrogen fixation and weed suppression. In addition, the cultivation of grass-clover may be problematic after celeriac due to late harvest dates.

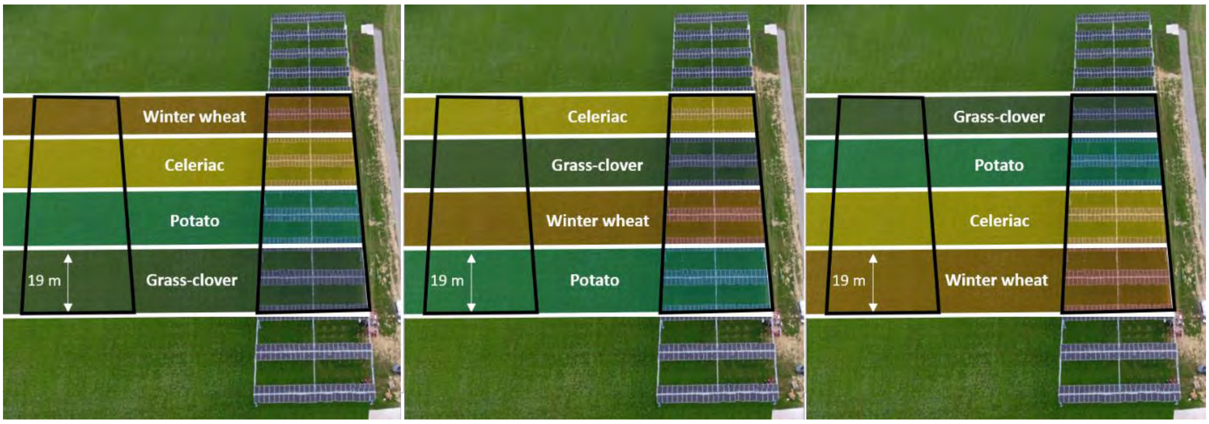

Figure 11: Schematic illustration of an alternative optimized crop rotation with a consistent alteration of summer and winter crops to reduced crop rotational effects. (modified after Baywa r.e.)

Another alternative would have been to reduce the number of crops investigated at once, so that for example only two crops are cultivated at once each year (Fig. 12). Beside the reduction of crop rotational effects, this would also facilitate to improve the general quality of the experimental design, enabling true replicates to be established. As again, potato and celeriac as summer crops would be cultivated in two consecutive years, weed pressure may be reduced by cultivating a winter catch crop with mowing one or twice. However, in this scenario, the acquisition of multi-annual data for each crop would have taken considerably more time, so that first in the year 2020, two-year data for each crop would have been available. Considering limited project resources and duration, the rotation with four crops each year thus can be seen as compromise, maximizing the number of investigated crop species in a limited time period, though at the cost of statistical quality.

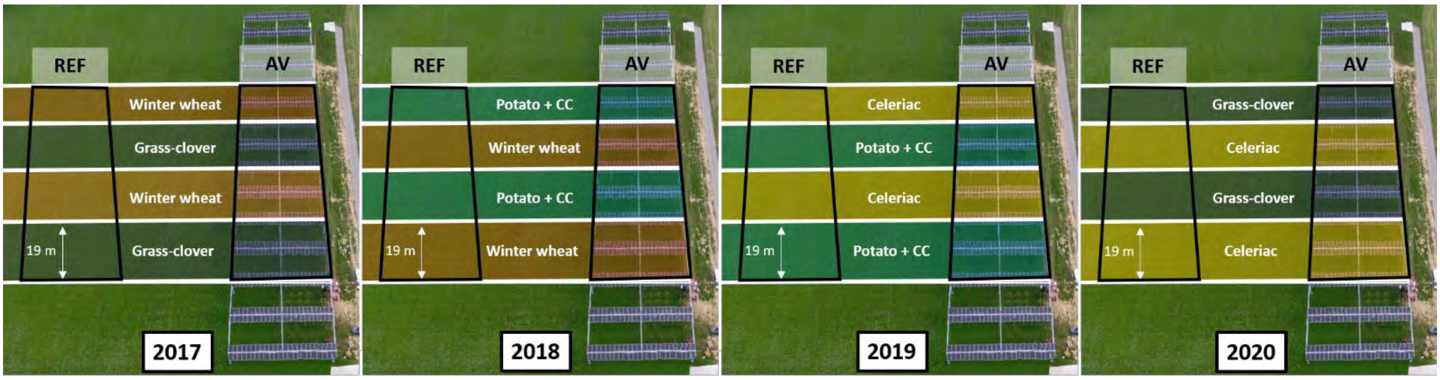

Figure 12: Schematic illustration of an alternative optimized crop rotation with less crops cultivated each year. In addition to a reduction of crop rotational effects, true replicates may be established to improve statistical analysis. CC= catch crop. (modified after Baywa r.e.)

AV effects on biodiversity

To investigate the effects of AV on biodiversity, measurements were carried out within the AV field trial, including a monitoring of entomological fauna (using ground-based traps) and the occurrence of wild herbs (based on [58]) on the experimental site in both treatments. Both, the entomological assessment and the vegetation survey of wild herbs showed, that number and composition of species was only slightly affected by treatment and more dependent on the cultivated crop species (not published). It therefore can be assumed, that the altered microclimate under AV did not affect species abundance, though an alteration of species composition is possible. However, due to a very limited area of about 450 m² each crop and treatment, the monitoring area can be considered too small for a comprehensive and representative screening. In addition, a certain effect of the strips between the mounting pillars of the AV facility can be assumed: As discussed in section 3.1.3, these strips have been managed extensively within the field trial, so that they can be regarded as quite unimpeded habitat for insects or wild herbs and thus, being quite valuable for biodiversity. However, as also the REF site has been equipped with microclimatic stations within the experiment, these strips had to be extended over the entire experimental area and thus were present on both, the REF and AV site. Thus, it cannot be verified, whether these extensively managed strips and consequently the cultivation under AV did affect biodiversity or not. In order to assess this, another reference site without such strips would be necessary.

Furthermore, future research could also address the question, how biodiversity enhancing effects of these strips may be further improved by an active integration of biodiversity promoting measures like the sowing of annual or perennial flower strips or the establishment of small structured habitats like stone and deadwood heaps. An approach, which is also being pursued in conventional PV installations [59,60] and may facilitate to mitigate land losses and environmental impacts through AV (and also PV) installations by utilizing the area underneath the panel rows or in-between (in case of conventional ground-mounted systems) for integrated biodiversity measures, further enhancing reported biodiversity effects [61]. An aspect which has recently also been discussed for AV systems [62]. However, apart from potential effects on biodiversity, such strips may also promote the proliferation of problematic weeds if not managed adequately as discussed in section 3.1.3.

Transferability of the findings

With regard to the fact, that the field trial within the present work has been conducted under organic management, the question arises, whether the results are transferable also to conventional cultivation conditions. In recent studies investigating the effects of AV on crop production, the here found reductions in harvestable yields have been confirmed: In sesame and different types of beans (soy, mung and red bean) shading at rates between 21-32% led to decreasing grain yield by -7 to -53% with increasing shading rate [52]. Corn was shown to be the most suitable crop with increased grain yields at 21% shading. At shading rates higher than that however, grain yield was reduced by -22 to -30% [52]. With a shading rate of at 32% – which is comparable to the shading conditions in the present work as shown [11] – grain yield reductions ranged from -30% (for corn and soy) to -53% (sesame) [52] and thus were slightly higher than found yield reductions in the present work. In a case study in Japan performed on different farms in the years 2014-2019, rice yield reductions were also shown to be linearly correlated with shading density [15]. Although the climatic conditions in the regions these studies have been performed (South Korea and Japan) can be assumed to be slightly different compared to Germany with a higher solar irradiation, the results show, that found crop yield reductions by AV under conventional cultivation conditions are at a range of the reductions found in the present work. A finding which has also been confirmed in terms of fertilization as shown by Gonocruz et al. [15], who found comparable crop yield reductions under AV, independent of if the farm used organic or synthetic N-fertilizers. Although different fertilization rates were shown to affect grain yields, an interaction effect between shading and N-fertilization (which can also be assumed to be lower under organic conditions) has not been confirmed [15]. According to the current knowledge, it therefore can be assumed, that crop yield reductions under AV are comparable, independent of the actual cropping system (conventional/organic). Beyond that however, potential interaction effects between AV yield reductions and production system so far have not been addressed. With regard to a potentially increased risk for fungal diseases under AV (e.g. through found increases in humidity), the restricted usage of pesticides in organic farming may also become relevant regarding crop yields, so that both the infestation with fungal diseases as well as potential differences between the conventional/organic cropping systems may be addressed more in detail in prospective research.

Profitability of crop production under AV

In this context, also aspects of marketability and profitability need to be regarded more in detail. Schindele et al. [23] concluded that, due to higher producer prices achieved with organically grown potatoes, crop production under AV can be regarded more profitable when managed organically, in spite of generally lower yield levels of most crops in comparison to conventional farming. However, this deduction is somehow lacking, as for an analysis of profitability, the complete crop rotation has to be regarded, including less profitable crops grown in organic arable farming like grass-clover. In addition, yield reductions under AV can actually be considered to cause higher losses in revenues per hectare in organic farming due to the quoted higher producer prices. Apart from differences between the cropping systems, the profitability of crop production under AV undoubtedly should be evaluated more in detail, but has not been subject of the present work. In general, it has been shown, that overall income can be increased by combined revenues from food and energy production in AV systems [62]. While revenues from crop production decrease under AV through decreasing crop yields, these losses are overcompensated by additional revenues from solar power production [52,62].

However, depending on the actual business model, farmers not necessarily have to benefit from increased revenues from energy production, so that profitability of crop production should be regarded separately, disregarding potential payments to the farmer for leasing costs or services (e.g. for managing the land underneath the AV array) from the operator of the AV facility. Although crop revenues under AV have been discussed in recent studies [52,53], to date only Moreda et al. [53] addressed potential differences in crop production costs between AV and under conventional growing conditions, showing that in particular savings for irrigation and crop protection devices are conceivable. However, further matters of expense like potentially higher costs for labor or fuel under AV need to be included (see also section 3.1.3). As discussed in section 2.3, in this context also the effects of AV on crop quality, as one of the key drivers regarding marketability and consequently also profitability, should be addressed more in detail. The analysis of chemical composition of celeriac revealed, that quality characteristics were barely affected by AV, albeit potential repercussions on C metabolism and fiber content have been supposed (see also section 2.2). Although comparable analyses have not been conducted in any of the other investigated crops, the findings in wheat and potato prompt, that chemical composition and quality may be altered by AV: As discussed, size distribution of both wheat grains and potato tubers was shifted, with smaller grains/tubers found under AV, which inevitably will also affect chemical composition (see also section 2.2). Consequently, a full cost analysis of crop production under AV, also including an evaluation of marketability and determining quality characteristics should be carried out in prospective research.

Summary: Prospective research questions

Derived from the deliberations above as well as in the preceding sections, in summary the following aspects have been identified as feasible objectives for prospective AV research projects:

- Execution of further and long-term field trials investigating various crop species. In this context, in particular the application of AV in specialty crop cultivation, as well as in orcharding and viticulture should be addressed.
- Correlation between harvest dates and yields, in particular in root crops.
- Effects of spatial heterogeneities of microclimate and PAR on crop development and harvestable yields.
- Potential of mobile PV systems to improve crop productivity by adapted tracking modes, considering crop specific yield-determining development stages.
- Impacts of AV on quality and marketability of the harvested crops.
- Infestation with pests and diseases as affected by AV.
- Approaches for the utilization of the impassable strips between the supporting pillars

like the integration of biodiversity measures.

- Profitability analysis of crop production under AV including a full cost accounting also assessing additional efforts (time, fuel) for the cultivation under AV.
- Further development of modelling and simulation tools to allow a reliable prediction of photovoltaic and crops yields, considering given local climatic conditions and the technical design of the AV facility.

3.2.2. Technical improvements of the AV facility

Apart from considerations regarding the optimization of the experimental set-up and the identification of prospective research questions, the implementation of the three-year field experiment also revealed certain improvements for the technical design of the AV systems.

Enhancement of rain distribution underneath the AV array

An aspect which has not only to be addressed in the experimental (see also section 3.2.1) but also the technical design of the AV facility, is the heterogeneous rain distribution under AV found in the present study. As discussed, uneven rain distribution can lead to imbalanced water supply underneath the solar panels, so that also crops stand may develop non-uniformly with differing yield levels. Furthermore, the risk of soil erosion increases in the direct runoff of the solar panels, through a concentration-effect of rain water by the panels (see also section 2.1 and 2.3). An observation, which has also been made within the field experiment: In particular in row-crops like celeriac or potato, a siltation of the soil surface occurred in the direct run-off of the panels after heavy rainfalls (Fig. 13).

Figure 13: Silted soil surface in the potato plant stand in the direct runoff of the panel rows in 2019 (left) and 2017 (right). (source: Weselek (left) and Bauerle (right), University of Hohenheim).

It therefore can be strongly recommended to consider technical solutions for an enhanced distribution of rainfalls in the design of prospective AV facilities. In this context, different possibilities are conceivable, depending on the general set-up of the AV facility: In AV constructions with fixed PV modules like the AV facility investigated in the present work, rain collection may be achieved by simple constructions based on gutters mounted underneath the panel edges. The run offs could be either forwarded directly into irrigation systems or collected in cisterns, which suits in particular for more arid regions, where cisterns for water collection and connected distribution systems with drip or sprinkler irrigation are already quite common. In subtropical and tropical regions, a combination of AV with such collection systems may also provide a protection of the soils from heavy rains during monsoon periods, will at the same time collecting the water for subsequent dry periods. As discussed in section 2.1, further synergistic effects like the utilization of the collected water for the cleaning of the PV panels [63] to avoid decreasing PV energy yields through dust deposition in dry periods, are conceivable [63,64]. However, in AV constructions with mobile, mono- or dual-axis PV modules, more flexible approaches for rainwater collection or distribution are needed. As shown by Elamri et al. [46] and discussed more in detail in section 2.1, one approach could be to adapt the adjustment of the PV panel tilt angels, depending on wind speed and direction, so that virtually uniform rain distribution can be achieved underneath the panels.

Application of mobile and vertical tilted PV modules

Apart from improved rain distribution, the application of solar tracking systems in AV installations may also improve both electrical and crop performance, depending on the module orientation and adjustment [47] (see also section 2.1). Although such approaches seem promising, aspects like costs for the building, operation and maintenance need to be regarded, in particular as operating and maintenance cost of single- or dual-axis tracking PV systems are considered to be higher compared to systems with fixed PV modules [65]. A more recent approach is the application of bifacial vertical tilted, east-west oriented PV modules which are currently investigated for the application in AV systems [66]. Such systems are already applied in first commercial projects (Fig 14). Beside an improved distribution of rainfalls and availability of sunlight between the panel rows [66], such systems provide further advantages regarding photovoltaic performance, like increased electrical yields (kWh/kWp) and profitability by achieving higher revenues through a power production especially during morning and evening hours [67]. In addition, less area is lost for its construction. Notwithstanding, its practicability in particular for arable farming remains questionable and so far, has not been investigated.

Figure 14: PV facility with vertically, ground-mounted bifacial PV modules, located in South Germany. The grassland between the panel rows is being mowed with conventional agricultural machinery (source: Tobias Kellner (left) and Next2Sun GmbH (right) [68])

These examples show, that various technical approaches for the implementation and optimization of AV systems to date already exist, with each having specific advantages and disadvantages for crop and power production. For a conclusive assessment of its economic feasibility as well as its applicability in particular in arable farming however, further research is needed.

Summary: Feasible improvements and technical innovations to enhance performance and practicability of AV systems

Derived from the deliberations above and from the aspects discussed in section 2.1, the following technical improvements of AV facilities, as well as technical innovations and adaptions could be considered to improve overall performance and suitability of AV systems for crop production:

- Technical solutions for rain water collection and/or distribution, including approaches for an intelligent water management and the combination with irrigation systems dependent on respective local climatic conditions.
- Application of mono- or dual-axis mobile PV modules and opportunities for controlled tracking to improve energy and/or crop yields as well as rainwater distribution (including a cost-benefit analysis). In this context, also the identification of less or more light-sensitive crop development stages (see section 3.1.1) might be considered.
- Innovations in photovoltaic technology like semi-transparent and wavelength selective PV modules.
- Integration and utilization of the produced energy within the farms' including

opportunities for improving electrical self-consumption (see also section 3.3).

- Integration of modern satellite-tracked and/or renewable energy driven farming machinery as well as current innovations in farm robotic, including an utilization of arising synergies between energy production by AV and consumption by the machinery.

3.3. Outlook: Implementation of agrivoltaics

Regarding the implementation of agrivoltaics, it can be concluded, that its impacts on crop productivity and consequently its suitability are dependent on different factors like the technical design of the AV installation, which crops are cultivated underneath and where the system is being implemented geographically. In this context, locations with more hot and dry climatic conditions have been discussed to be more suited for the application of AV, as here, synergistic effects within energy and food production are feasible and may even facilitate the expansions of agricultural production into areas with less favorable conditions for crop production. In addition to diminishing the adverse effects of heat and drought on crop development by engendering more favorable microclimatic conditions in the partial shade of the PV panels [11,69,70], also PV performance can benefit from the vegetation underneath, mitigating declining PV yields due to panel heat stress by cooling effects [69]. In addition to climatic conditions, furthermore also regional and local circumstances, like the availability of land and/or the infrastructural conditions, need to be considered: As discussed, in more rural and less developed regions, AV may operate as independent and decentralized energy source, contributing to improve local power supply. Regarding the AV facility in Heggelbach, it has been shown, that a capacity of about 194 kWp installed on a third hectare is sufficient to supply 62 households with an assumed power consumption of 4000 kWh a year [71]. As alternative or in addition, the energy might also be utilized directly on the farm for high energy consuming processes. This was also the case in Heggelbach, where an energy utilization concept has been developed and optimized, so that more than half of the generated power can be consumed directly on the farm, e.g. for storage or processing of the vegetables. As discussed, further opportunities for the utilization of the generated power like the operation of water pumps or irrigation systems (also see section 2.1.) are conceivable, further emphasizing the potential for the integration of AV in farming systems of more dry climates as well as in the field of specialty crops cultivation (e.g. horticulture, orcharding or viticulture). In this context, also more holistic approaches for the application of AV, addressing and utilizing several of the above-mentioned, synergistic effects, are conceivable. An aspect, which has recently been taken up by an AV research project located in West Africa, investigating how AV can be adapted and integrated according to regional needs by utilizing different co-synergistic effects like off-grid electrification, enhanced water supply, its integration in agricultural practice (e.g. by improving microclimate or by serving as power source for water pumps or irrigation systems) as well as its utilization for downstream processing [72] (Fig. 15). It therefore can be concluded, that such climates seem to be most suited for the application of AV, as here, the potential benefits of AV through the utilization of additional synergistic effects prevail. In addition, potential trade-offs between food and energy can be assumed to be less relevant, at least in regions with less limited land resources.

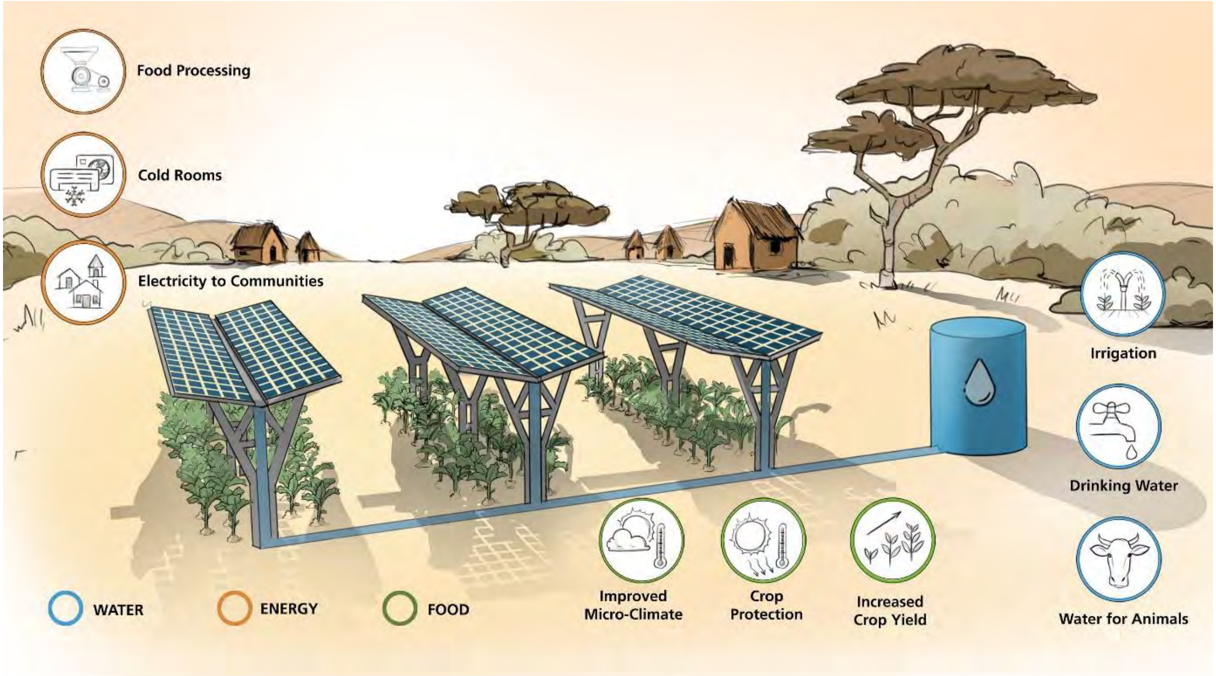

Figure 15: Visualization of an AV system adapted to West African conditions, enabling the utilization of various synergistic effects (source: ©Fraunhofer ISE [72])

Finding the right balance in a co-productive system

However, apart from potential synergies in regions and climates where high temperatures and intensities of solar radiation can become unfavorable for both crop and PV production, an actual competition between these two production systems can be assumed in areas with more limited land resources as well as in more moderate climates, where crop productivity is likely to be impaired by AV. Here, the preservation of agricultural land and productivity becomes more crucial. Consequently, the design of AV facilities in such regions requests to find a certain compromise between PV and crop production. The question, how this balance can be achieved and which indicators can be applied for its evaluation, will be debated in the following.

It has been discussed, that the intended benefit of AV systems is the utilization of a combined production of renewable energy and agricultural products on the same land. To assess this benefit, the application of land equivalent ratio (LER) has been introduced (see also section 2.1.). As shown, increases in land productivity through AV can vary over a wide range, depending on the technical implementation of the AV system as well as the cultivated crop species [45,73]. In the present study, variances in agricultural yields within the crops and years, combined with about 17% reduced PV yields (in comparison to sole PV production with a conventional ground-mounted PV installation) led to 56 up to 87% increased land productivity through AV [73] (Fig. 16). Even in less optimal scenarios, increases of at least 35% could be achieved [45]. It therefore can be concluded, that – regarding the sparing of land resources and the improvement of land use efficiency – AV undoubtedly can contribute to fulfill these objectives. Regarding the intended mitigation of the land-use conflict between food and energy production however, the potential of AV is still worthy of discussion: Despite positive effects on land productivity, the actual trade-off between agricultural and energy production remains to some degree, as – apart from above-mentioned scenarios, in which synergistic effects are conceivable – increases in both electrical and land productivity (to some extent) are always accompanied by a certain loss in agricultural productivity. As discussed in section 2.1, AV systems are specifically designed to enable as much light as possible, preferably evenly distributed, to be available for the crops grown underneath. Among others, such technical adaptions include an increased distance between the PV panel rows [45,54,74], an altered orientation of the PV modules [54], the usage of solar panels with higher translucency (e.g. bifacial or semitransparent) [73,74] and/or the application solar tracking systems, optional with adapted tracking modes [47] (see also section 2.1). However, while the latter has been shown and discussed as opportunity to improve both agricultural and photovoltaic yields [47], most of these factors are accompanied by a certain loss in crop productivity, when optimized for electrical performance. Correspondingly, Dupraz et al. [45] found that a higher density of solar panels mounted above the crops leads to higher electrical yields and land productivity. At the same time, relative crop yields were 27% lower in comparison to the unshaded control and also 10% lower in comparison to the treatment with reduced panel density [45].

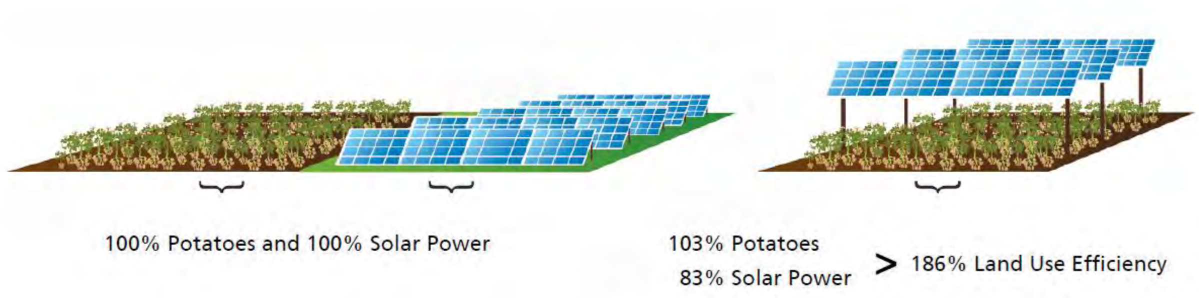

Figure 16: Increased land productivity through AV by reference to the field trial of the present thesis. The calculations are based on the results of the year 2018, in which potato tuber yield was increased by about 12% (deducting 8% cultivation area losses), while electrical yield decreased by about 17% [73] (source: [41] © HappyPictures/ shutterstock.com)

Given the "food or fuel" discussion, therefore the question arises, to what extent potential losses in agricultural productivity can be tolerated and outweighed by benefits in land productivity and renewable energy production. This applies all the more, since also from an economic perspective, a maximization of energy production may be more profitable than a combined food and energy production through AV: As shown by Cuppari et al. [62], net revenues from sole energy production with conventional PV systems can outperform the net revenues from a combined production in AV systems. However, whilst this is the case for more shade-sensitive crops and crops with lower producer prices, higher net revenues may be achieved when combined with more suited and/or high-margin crops [23,62]. Nevertheless, this emphasizes that, regarded from an economic perspective, a maximization of PV energy yields can be considered more desirable for now, due to expectable higher revenues from renewable energy production in comparison to food production, in particular in farming systems with less profitable crops. As a consequence, agricultural productivity may become subsidiary and de facto end up in a conventional PV installation with lower capital expenditures [23] and higher economic benefits through maximized photovoltaic yields in comparison to AV installations.

Quality assurance of AV installations

Consequently, suitable instruments have to be found to preserve agricultural productivity in AV systems. Although governmental funding of AV installations can be helpful to facilitate the propagation of AV on agricultural land as alternative to conventional ground-mounted PV installations, the above described conflict remains present. Therefore, a distinct definition of AV has to be found, with clear requirements for the construction of AV facilities (e.g. availability of crop available radiation, adapted water management, etc.) and a downstream quality assurance to validate if a sufficient crop production is being maintained. By this, any kind of mock farming in AV systems, which are actually adjusted to optimize PV performance, while crop production is only subordinate, may be prevented. This becomes even more important once AV systems are explicitly promoted by funding instruments. Schindele et al. [23] defined agrivoltaic as "integrated food-energy system, utilizing its dual functionality by maintaining or even improving agricultural production." In this definition, Schindele et al. [23] further exclude the implementation of AV on grasslands, as practices of livestock grazing can also be found in conventional ground-mounted PV systems, and thus, would inevitably lead to difficulties regarding the demarcation of AV from conventional ground-mounted PV systems. Vice versa, this does not mean that grazing underneath AV has to be excepted. Especially in organic livestock farms, perennial forage production and occasional grazing within arable crop rotations is quite common.

Coming back to the definition of AV, the question that arises is how a maintenance of a sufficient crop production can be specified or even quantified. As shown in a recent study, farmers stated that maintenance of long term land viability and productivity would be a personal premise for the implementation of AV [75]. According to the farmers involved in the field trial that has been presented within this thesis, obtaining a minimum of 80% of the yields achieved at the reference site for them personally can be considered as adequate. Regarding the results of the field trial with an average reduction of harvestable crop yields of 11.1% in the three experimental years 2017-2019 plus an estimated loss of cultivation area of about 8.3%, this aim was concisely fulfilled with an average loss of 19.4% (i.e. 80.6% of reference yields were achieved). However, it is disputable whether the results can be considered as representative for a long-term average. Furthermore, they do only pertain specifically for the technical design of the AV facility, the location and the crops investigated within our field trial. A comparable approach is being pursued in Japan, where the construction of AV is subject to the condition, that for the crops cultivated underneath, 80% of the agricultural yields attained under normal conditions have to be achieved [15,23]. Although maintaining 80% of agricultural yields under AV seems to be desirable, the implementation may be problematic: farmers are obliged to report annually and remove the AV installation in case of insufficient crop yields [76]. A requirement, which may be obstructive due to relative high investment risks for investors or farmers who are planning to install an AV facility. This applies even more, since modelling approaches as well as the practical experience is still insufficient to allow reliable predictions of estimated crop yields in dependence of environmental and technical factors beforehand. Therefore, more universal criteria may be needed to assess the suitability of AV arrays for crop production, preferentially already during the planning stage to avoid potential risks of a removal in future like shown for Japan. As described by Schindele et al. [23], the "Solar Massachusetts Renewable Target Program" set a maximum reduction of 50% of crop available radiation as premise for AV systems. As shown by Laub et al. [44], a reduction of crop available radiation by about 40 – 60% is expected to cause declining crop yields for most crop species, with yield reductions of up to 75% for some species. Thus, a targeted maximum reduction of 50% of crop available radiation can be assumed to be inadequate in order to achieve acceptable agricultural yields. Given the results from the present study, it can be roughly estimated, that a reduction of about 30% of crop available radiation can be reasonable in Central Europe, if crop yield losses of up to 25% are tolerated. It can be further assumed, that with decreasing latitude, potential adverse effects of heat and intensive solar radiation will increase and thus shading intensity may be increased. Disregarding the definition of appropriate thresholds, the approach of defining a minimum of solar irradiation kept available for the crops grown underneath may be more simple and predictable than defining attainable crop yield levels. Trommsdorff et al. [73] demonstrated, that radiation modelling tools can be effectively used to simulate photosynthetic active radiation available at ground level in different AV design scenarios, integrating variables like the orientation of the facility and PV module row distance. Correspondingly, such tools may facilitate to predict reductions in crop available radiation of projected AV facilities already during early stages of the planning, so that the facility can be specifically modified in order to achieve the defined minimum benchmarks. It therefore can be concluded, that crop available radiation can be one suitable criterion for the evaluation and standardization of AV installations. However, it can be questioned, whether defining maximum shading rates is sufficient as only criterion determining the suitability of an AV facility for crop production, as not only light availability but also homogeneity has to be considered in order to achieve a uniform plant population. This also applies with regard to the demarcation from conventional PV facilities, as it is conceivable that also ground-mounted PV installations with larger distances between the panel rows may facilitate to achieve average reductions of only 50% of crop available radiation, whereas repercussions on light homogeneity and land total land productivity are disregarded (see also below).

Hence, in addition to maintaining crop available radiation to a certain extent, further criteria like homogenous light distribution as well as a limitation of losses of agricultural land for the sub-construction of the PV installation would be appropriate when evaluating the suitability of AV systems. The former has also been addressed within simulations during the planning of the AV installation in the present study, so that the facility could be specifically designed to enable a homogenous light distribution underneath the panels [73]. By contrast, theoretical losses in agricultural land of 5% due to the mounting structure of the AV facility were slightly underestimated, as only losses for the construction were consulted, whereas losses, e.g. for safety distances for farm machinery, have not been considered. However, with 8.3%, the actual losses found in the present study are in accordance with Dupraz et al. [45], who assumed that 90% of the agricultural area can be preserved for crop production. Nevertheless, this further shows, that the technical suitability of projected AV facilities can already be addressed through solid simulations during an early stage of planning, which makes it a more reliable approach than predicting prospective agricultural yields. As such, simulation tools may be used for the standardization of AV facilities, whereby different criteria like a sufficient and homogenous light availability as well as agricultural land losses must be considered and certain thresholds defined to ensure, that the AV installations are suited for crop production to the extent required.

Development of a standard for the characterization and categorization of AV facilities

An approach, which has recently been taken up in Germany. As a follow-up study of the APV Resola project, several of the above described challenges in the characterization of AV facilities have been addressed within the development of a pre-standard for the classification of AV systems. The pre-standard has been published in cooperation with the German Institute for Standardization (DIN) as DIN SPEC 91434:2021-05 [77]. In this section, this pre-standard will be described and discussed as an example of how AV facilities may be characterized and standardized.

The intention of this pre-standard is to classify for the first time, which requirements AV facilities have to fulfill, to allow a clear demarcation from conventional ground-mounted PV systems with a primary use for energy production. For this, the standard distinguishes between two different categories of AV facilities: (1) AV facilities which are mounted on pillars with a clear height and (2) near-ground mounted AV installations. The pre-standard further defines, that farm activity has to be maintained under AV, whereby different kinds of agricultural usages are conceivable: The production of (A) permanent and perennial crops (e.g. orchards, wine and berry crops), (B) annual crops (e.g. field or vegetable crops) as well as its utilization as permanent grassland used for (C) hay production and/or (D) grazing [77]. For the planning of AV installations, the targeted agricultural activity has to be specified within a utilization concept, compromising the first three years after the construction of the AV facility or within a crop rotation cycle. In addition, this concept has to address different aspects like the distribution of water and light, the construction (including mounting and resulting losses in cultivation area) and land use efficiency [77]. Accordingly, the projected installation must ensure agricultural usage through an adequate water and light supply, with a preferably homogenous distribution. The risk of soil erosion must be minimized through appropriate solutions for rainwater collection or the like [77]. It can be summarized, that many critical aspects regarding the suitability of AV installations for crop production, that have been discussed in the preceding sections, have been addressed by the pre-standard.

However, a more detailed description of how these criteria need to be fulfilled is missing in most cases. By contrast, maximum acceptable losses of cultivation area and agricultural yields are clearly defined. According to that, the loss of cultivation area through the AV installation should not exceed 10% for facilities of category 1 (pillar-mounted), or 15% for facilities of category 2 (ground-mounted; see also above) [77]. Agricultural yields (including losses through lost cultivation area) must at least achieve two thirds (66%) of the reference yields under normal cropping conditions. The reference yields either can be calculated from the farms' mean yields of the last three years (in case of permanent crops or grassland) or the mean yields of the crops intended for cultivation under AV averaged over three crop rotation cycles (in case of field and vegetable crops). If a crop has not been cultivated so far, the reference yields can be obtained by averaging the yields of the preceding three years as stated in literature [77]. According to the pre-standard, prospective reductions of agricultural yields through the cultivation under AV can be estimated by qualified personnel.

Transferred to the AV facility in Heggelbach and the results from the field trial, it can be noted, that both maximum losses in cultivation area as well as crop yields were within the range stated in the pre-standard. In general, the AV facility in Heggelbach can be classified as category 1 facility (pillar-mounted), which can be managed either in longitudinal or crosswise direction. According to the pre-stand, then losses in cultivation area of up to 10% can be tolerated. As shown, losses in cultivation area in the trial were estimated at -8.3% when managed in crosswise direction to the facility. Losses through a management in longitudinal direction could not be ascertained practically, but have been calculated to range around -7.3%. It can be presumed that actual losses would have been higher as in this calculation, the width of the non-processable strips was assumed to be only as wide as the mounting pillars with its skirting protection, while practical losses for keeping safety distances with farm machinery have not been considered (see also above). Nevertheless, assuming losses of -7.3% in longitudinal and -8.3% in crosswise direction, losses in cultivation area consequently ranged around -8% averaged over both processing direction. Consequently, the losses would have been within the range of the defined maximum acceptable losses of 10% stated in the DIN SPEC. Regarding crop yields, the pre-standard stipulates that a minimum of 66% of reference yields has to be achieved, whereby crop yield reductions are specified as the sum of direct losses, through altered microclimatic conditions and impaired crop growth, and losses of cropping area for the foundation of the AV facility [77]. In our trial, crop yield reductions through AV were 13.3% for celeriac, 10.6% for grass-clover and 14.4% for winter wheat on a three-year average (Fig. 3). Including the estimated losses of cultivation area of -8%, over all yield reductions accordingly would have been 21.3% for celeriac, 18.6% for grass-clover and 22.4% for winter wheat and thus, were within the range of the DIN-SPEC, too.

However, in some parts, the pre-standard may need to be defined more precisely: Regarding category 2 AV installations (ground-mounted) with an agricultural use for fodder production through haying (C) and pasture (D), a clear distinction from classical ground-mounted PV arrays (with energy production as primary purpose) may be problematic as such PV installations can also be used for fodder production through haying or pasture (see also above). Here the most important distinguishing factor between category 2 AV facilities and conventional PV installations will be the defined maximum tolerable loss of cultivation area through the mounting structure (15%), which leads to higher distances between the PV panel rows and/or lower panel density as in regular PV systems. A reason why facilities of category 2 are included in the pre-standard might be, that capital expenditures can be considered to be lower in comparison to pillar-mounted systems, due to lower costs for the mounting structure [23]. However, in pillar-mounted AV installations (category 1), higher shares of area can be preserved for agricultural production, so that these systems can be regarded to be more effective in order to preserve crop productivity and agricultural land. According to the pre-standard, systems with high accessibility between the mounting columns for agricultural machinery, like for example pole-mounted solar tracking panels, are considered to demand least space for the mounting structure, as also the area between the pillars is considered to be available for crop production. Hence, when calculating land losses through the mounting structure of the AV array, only the area which is actually lost for the pillars (and if applicable for the skirting protection) must be incorporated according to the DIN SPEC (Fig. 17). When applied on the AV array in Heggelbach (which can also be managed in both directions), losses then just would have been -0.3% (instead of -8% stated above) and consequently would have been far below the defined maximum tolerable losses of 10% defined in the pre-standard.

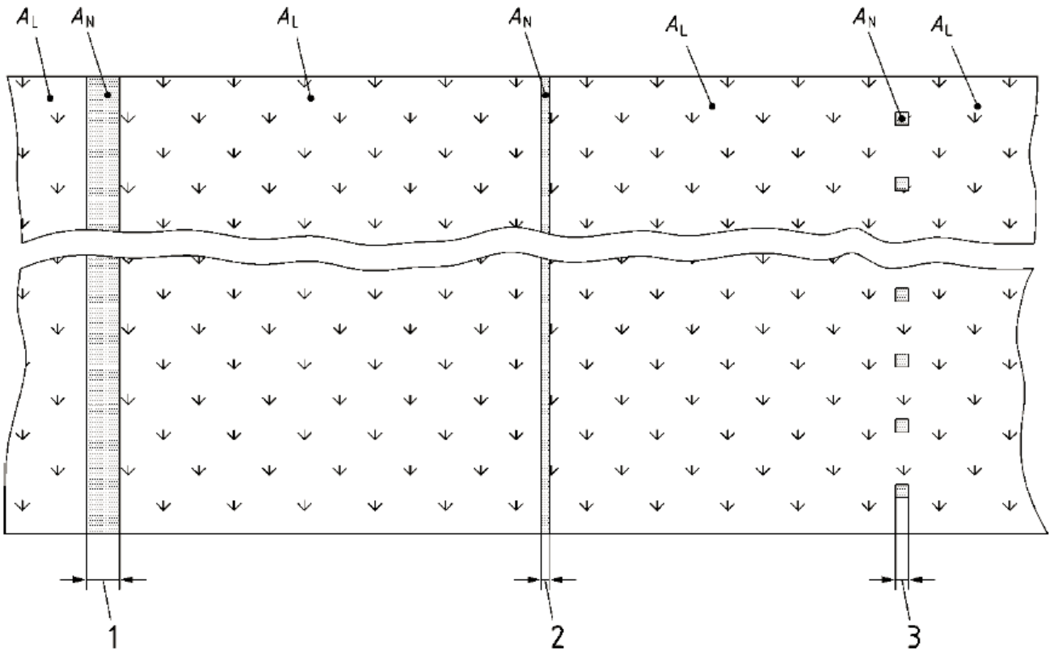

Figure 17: Topview on different categories of AV installations according to DIN SPEC 91434:2021-05. 1 and 2 can be either ground- or pillar-mounted facilities with only one processing direction, whereas 3 are pillar-mounted facilities that can be managed in either direction. The area is differentiated into parts that can be utilized for agricultural production (A_L) and not (A_N) (© Beuth [77])

From a practical point of view, this definition leads to an underestimation of the actual losses of cultivation area, that are practically not available for agricultural production: In practice, the field will only be managed into the same direction during the same cropping period or principally (e.g. on slope sites) and thus, the area between the stilts will factually not be used for crop production (see also section 3.1.3). Therefore, it seems to be more appropriate to either use the mean percental losses of area (including non-processable strips) in either way of processing (e.g. -8% in case of Heggelbach), or losses through the major direction of field management (e.g. -8.3%). As shown for the AV installation in Heggelbach, actual loss of cultivation area was higher than calculated, as it depends on how the working widths of the machinery fits the distance between the mounting pillars of the AV facility and how close these can be passed. As a consequence, estimated land losses should not only comprise theoretical losses through the pillars and the resulting strips, but also a certain safety distance that inevitably will be kept when driving with agricultural machinery in an AV installation (see also section 3.1.3). As mentioned, to assess the suitability of a projected AV installation for crop production, the pre-standard demands prospective agricultural yield (reductions) of projected AV installations to be estimated upfront by qualified personal, whereas it is not further specified, which qualifications such surveyors need to have. As the findings of the present work have shown, a reliable prediction of microclimatic and crop yield alterations through AV yet can be considered as unfeasible, as various factors (technical, climatic, agronomic) have to be regarded. As discussed above, as well as in consideration of the circumstance, that the empirical value and consequently also the availability of personal experienced enough is still inadequate, it therefore can be concluded, that crop yield predictions should not should be included within the standardization of AV facility. Instead, rather technical aspects and requirements of AV installations (e.g. regarding light availability and distribution, rain water collection and distribution, soil protection) should be defined more precisely, including certain minimum criteria and thresholds which need to be fulfilled. Combined with modern simulation tools assessing such criteria, a more uniform, location- and personal-independent but design-dependent standardization of AV facilities may be achieved. Nevertheless, as first pre-standard, the DIN SPEC 91434:2021-05 can be considered as an important step towards the quality assurance of AV installations, providing some basic criteria for its standardization and the distinction from conventional ground-mounted PV arrays. As such it can support policy- and lawmakers for creating a legal framework with appropriate funding measures to promote the implementation of AV on the market, while at the same time ensuring the preservation of agricultural land.

3.3.1. The implementation of agrivoltaics in Germany

The question, how AV can be promoted and integrated into the existing legislation, has also arisen in Germany in the last years [23]. Here, the task is not only to create financial incentives but also to adapt given legal regulations, to facilitate the implementation of AV in practice. In the year 2000, the Renewable Energies Act (EEG) was introduced in Germany with the aim to propagate renewable energy production by supporting the different renewable energy sources with price-based Feed-in-Tariffs (FiT). Apart from first upscaled PV facilities that have been implemented subsidy-free [23], the granting of FiT support still can be seen as premise for an economic realization of projected PV installations. However, since the awarding of FiT support is regulated in a tendering process, the funding of less competitive PV technologies and installations with comparably higher investment costs (like for example AV) is aggravated [23]. To overcome this, the amendment of the EEG in 2021 for the first time included a regulation (ger. *Innovationsausschreibungsverordnung* or short *InnAusV)*, declaring a separate tendering for innovative PV technologies like rooftop-PV, floating-PV and AV, with an overall volume of 150 MW a year [78]. For its execution, a more clear definition of the PV technologies encompassed within the *InnAusV* has been delivered subsequently in October 2021 by the German Federal Network Agency (ger. *Bundesnetzagentur*) [79]. In its definition of AV, as well as regarding some basic requirements defined (e.g. the adherence of maximum crop yield losses of 34%), the *Bundesnetzagentur* refers to the DIN SPEC 91434:2021-05. While the implementation of FiT-supported PV installations on agricultural land yet was only possible to a very limited extent (e.g. on areas next to transportation infrastructure or in areas being less suitable for agricultural production; see also section 1), AV installations now can also be implemented on agricultural land without such restrictions. In contrast to the DIN SPEC however, the implementation of AV facilities is restricted to agricultural areas with arable farming or permanent crop production, whereas permanent grassland is explicitly excluded [79]. In addition to the *InnAusV*, another instrument for the funding of more small-scaled AV facilities was also introduced in 2021 by German Federal Office for Agriculture and Food (ger. *Bundesanstalt für Landwirtschaft und Ernährung*; BLE): To facilitate a reduction of agricultural CO_2 emissions, the so-called "Guideline for the promotion of energy efficiency and CO_2 savings in agriculture" (ger. *Richtlinie zur Förderung von Energieeffizienz und CO_2-Einsparung in Landwirtschaft*) promotes different measures. Among others, these include the installation of PV installations like rooftop-PV as well as AV facilities [78]. However, as discussed above, a more distinct definition regarding the quality assurance of AV installations and the preservation of agricultural productivity beyond the standards defined in the DIN SPEC is still missing and not required within these funding instruments.

Apart from funding measures, the consideration of AV in building law remains uncertain. As discussed by Schindele [78], local building authorities to date do not differentiate between conventional and AV installations, so that the projected area has to be redesignated to a special zone, comparable to an industrial area. As a consequence, compensatory measures for nature conservancy have to be realized, while at the same time the eligibility for agricultural subsidies is lost [80]. As suggested by Schindele [78,80], an approach may be to explicitly incorporate AV systems as an option in land development plans, so that agricultural activity can not only be maintained in practice, but also on paper. Another advantage would be, that the preservation of agricultural activity can be ensured by retaining the documentation obligation which is required to receive agricultural subsidies within the European Common Agricultural Policy (CAP) [78]. However, it can be questioned, whether the resulting double funding of the produced energy (e.g. through FiT support according to the EEG) on the one hand, and of the agricultural activity (through CAP payments) on the other hand is expedient or may further aggravate the pressure on agricultural land: In Germany, about 60% of agricultural land is leased [81]. Since 2010, the leasing prices for agricultural land increased by about 62% and 64% for arable land [81]. A trend which may be further promoted, once the installations of AV facilities becomes more profitable (e.g. through funding instruments), while at the same time legal obstacles have been removed. In this context, the aforementioned potential of AV to mitigate the land-use conflict between food and energy production undoubtedly would become debatable, arising the question, who will be the actual profiteers or rather how farmers can be involved or protected from increasing costs for agricultural land.

Coming back to the implementation of AV in Germany, also regional differences like agricultural productivity (depending on factors like soil quality, climatic conditions, etc.), the type of crops cultivated, as well as given agricultural structures have to be regarded to evaluate its potential. While the south of Germany is characterized by comparably small structured fields and farms with a mean size of about 30 to 45 hectares per farm (federal states Baden-Wuerttemberg, Bavaria, Rhineland-Palatinate and Hesse) and a high share of specialty crops cultivation (e.g. fruits, vegetables and viticulture), the fields and farms in the north-east are markedly bigger with an average farm size of about 210 to 290 hectares (federal states Brandenburg, Mecklenburg-Western Pomerania, Saxony-Anhalt and Thuringia) [81]. In case of the former, more small-scaled and farm-owned AV facilities with a focus on its integration into specialty crops cultivation are conceivable and may be funded within the above-mentioned Guideline. By contrast, the farm and field sizes in the north-east may provide themselves for bigger, potentially investor-sponsored AV installations, funded within the *InnAusV* of the EEG [23].

However, to attenuate its impact agricultural productivity, AV systems still should be implemented preferably on less-favored areas with low agricultural productiveness (e.g. due to low soil quality and precipitation) as well as in production systems (e.g. specialty crop production), in which synergistic effects on crop productivity are feasible. Regions with a high agricultural productivity instead should be completely preserved for agricultural production. On the other hand, also conventional ground-mounted PV installation, even when installed on agricultural land, should not be generally precluded: As the previous years have shown, the risk of agricultural yield losses as a consequence of the impacts of climate change and concomitant extreme weather events like drought or heavy rains increased and likely will become more frequent in the near future. As a consequence, agricultural productivity on the long term may not be maintained in some regions (e.g. locations with low-quality soils, low precipitation amounts as well as limited irrigation possibilities). Here, the realization of conventional ground-mounted PV installations instead of AV may be conceivable and may reduce the overall impact on agricultural area by renewable energy production through maximizing energy yields, while at the same time repercussions on agricultural productivity are negligible in such regions. It therefore can be concluded, that regarding the implementation of AV in Germany, regional differences and specifics should be considered to find appropriate solutions and application fields for AV technology. Although first steps towards the promotion of AV recently have been made by adapting the legal framework and providing funding instruments, further adjustments are demanded to facilitate the introduction of AV. At the same time, the quality assurance of AV installations needs to be ensured to minimize its impacts on agricultural productivity.

3.4. References

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