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Agricultural Practices Appropriate for Agrivoltaics

Towards a Customized Guideline for Aotearoa New Zealand

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Abstract. In striving toward a target of 100% renewable electricity generation by 2030 as part of wider global concerns of climate change and the integral role that energy production plays within this, Aotearoa New Zealand will have to mitigate the increased strain on available land resources and look toward multi-use land initiatives in the uptake of utility-scale solar photovoltaic (PV) generation. Agrivoltaic systems, integrating PV arrays with agricultural production, have been defined and tested internationally and offer a solution to Aotearoa New Zealand in dealing with over-allocation of limited land resources, where 42% of the total land area, or over 11 million hectares, are already dedicated to agriculture. Owing to the relatively recent advancements in the technologies and prerequisites for agrivoltaic systems, as well as diverse agricultural practices and systems worldwide, agrivoltaics require customized guidelines for each specific location where they are introduced. The German DIN SPEC 91434 is an example of such a guideline. The goal of this research is to contribute to the development of a guideline for Aotearoa New Zealand. This guideline will look to understand key agrivoltaic technologies and configurations as they pertain to certain crop types and agricultural practices, aligning these with the key agricultural sectors and crop types within the country, then looking to how agrivoltaics can further integrate with the sector goals. The guideline definitions will flow into a matrix tool for the farming community wishing to implement agrivoltaic systems, streamlining the process in which such systems can be implemented in Aotearoa New Zealand.

Keywords: Agrivoltaics, AgriPV, Agricultural Practices, Aotearoa New Zealand.

1. Introduction

Agriculture, primarily pasture for livestock farming and cropping, and horticulture use around 42% of the land in Aotearoa New Zealand [1]. Although this sector contributes less to the economy in general, compared to the services and goods-producing sectors, it is the top export earner for the country.

The electricity market is seeing significant growth in utility-scale solar photovoltaics, with projects in various stages of development across both islands. Projections are that the current generation capacity (of 10 GW) can be doubled with solar farms by 2050 [2]. The installations would require approximately 25,000 hectares, and current developments have raised concerns [3] of converting highly productive land that has a good climate, suitable soil, and is flat or gently sloping [1] – suitable for solar farms if near the power grid. Agrivoltaics has subsequently been argued as the way forward for the country with the more effective utilization of agricultural land [4, 5]. Previous research has suggested that about 40%, or 5 million hectares, of the agricultural land is rated as 'Good' for agrivoltaics (see Figure 1) with grazable grassland suitable for larger-scale agrivoltaic systems and croplands being more suited to smaller-scale agrivoltaics [6]. Nevertheless, the current economic value of the primary production needs due consideration to ascertain which activities may warrant the best options for agrivoltaic systems. Table 1 provides an overview of the economic value (in 2023) of different agricultural and horticultural produce [7, 8]. This paper informs the development of a guideline for the Aotearoa New Zealand context by evaluating the appropriateness of the different agricultural practices for the uptake of agrivoltaics in the country.

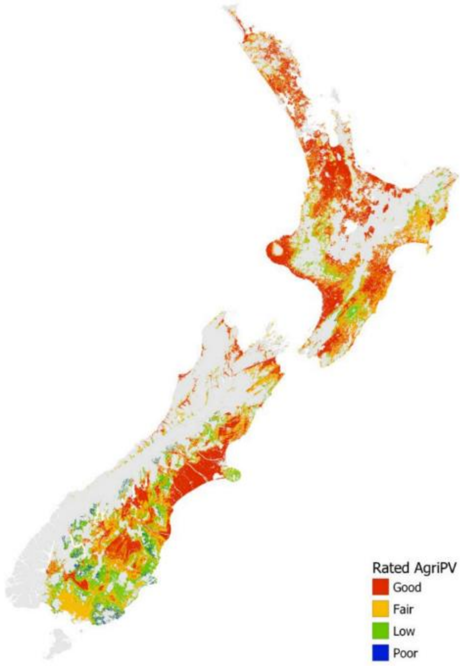

Figure 1. *Land suitable for agrivoltaic system in Aotearoa New Zealand [6].*

Table 1. *Estimated agriculture production and economic value in gross margin figures [7, 8].*

Horticulture	$/ha	Cropping	$/ha	Livestock	$/ha
Kiwifruit	$ 47,241.00	Carrot	$ 5,364.99	Sheep dairy	$ 7,773.43
Tomatoes	$ 32,125.00	Maize	$ 4,253.13	Cow dairy	$ 3,348.00
Vineyard	$ 27,863.00	Wheat	$ 3,632.74	Beef	$ 2,024.10
Cherries	$ 23,688.00	Barley	$ 2,793.48	Lamb	$ 1,562.00
Hops	$ 14,255.00	Beet	$ 1,620.69		
Pipfruit	$ 14,151.00	White clover	$ 1,506.07		
Potatoes	$ 10,828.00	Kale	$ 1,404.00		
Onions	$ 6,058.00	Peas	$ 1,298.66		
Avocado	$ 2,463.63	Rape seed	$ 827.49		
		Ryegrass	$ 386.63		

1.1 Livestock farming

Livestock farming in Aotearoa New Zealand is broken down into the categories of lamb and beef farming and dairy production, with the grazing of animals in pastural-based systems. Of key importance to the feasibility of agrivoltaic systems is the impact on livestock and forage productivity. Worldwide, and in Aotearoa New Zealand, the deployment of solar farms alongside sheep grazing has already begun [9].

A recent study [10] investigated multiple configurations in the Canterbury region of the South Island deemed suitable for large-scale agrivoltaic systems [6]. Two farms were specifically considered as case studies.

For a sheep and cattle farm, fixed tilt and tracking configurations with bifacial panels were considered. The fixed tilt was set at 25° from horizontal to face north, and north-south rows for the tracking system. Racking for the panels was designed to exceed the height of cattle at 2.5 m ground clearance. The financial analysis shows that the agrivoltaic system greatly improves the profitability of the farm with the net profit increasing nearly threefold [10, 11], which is significant considering the relatively low margins of lamb and beef farming (see Table 1).

For a dairy farm the designs for the agrivoltaic systems were similar, although integration with the current irrigation infrastructure was also considered, i.e. wet and dry lands. Although the capital cost is greater, there is a better opportunity to use generated electricity in the dairy business due to the large electricity demands, especially in the summer months; to run the dairy shed, irrigation and potentially in the future any electric vehicles [10]. However, the additional revenue from the electricity generation does not have a significant effect on the profitability of the farm [11] with dairy production already having relatively high margins (see Table 1).

1.2 Horticulture and cropland farming

Horticulture in Aotearoa New Zealand utilizes only 133,549 hectares of land but is a major contributor to the economy with an annual value of NZ$6.87 billion[1] (total exports of $4.6bn and total domestic consumption of $2.27bn) [12]. These numbers do not include viticulture, which accounts for a further 41,860 hectares and total exports of $2.4bn. Over thirty different types of crops fall under the horticulture and cropland farming banner, including many different farming techniques and land types across Aotearoa New Zealand. Four main crop-types allow for a good overview of the industry and its standard practices, and how these align with different agrivoltaic configurations.

1.2.1 Kiwifruit

With the largest amount of land consumption of all horticultural produce, as well as being noted as a shade-loving species with high humidity requirements, kiwifruit is commonly grown outdoors [13]. A study in China tested fixed tilt, overhead systems with multiple panel configurations [14]. The study determined that utilizing translucent panels arranged in a checkerboard configuration (PVc) ensuring shading at 19.0% in a southward direction and at a 16-degree tilt, created a balanced compromise between fruit production and growth with energy generation and "*may not cause a significant reduction in kiwifruit yield or adverse effects on kiwifruit growth*" [14]. This is important given the high margins of kiwifruit farming (see Table 1).

Agrivoltaic systems may also address environmental concerns in the kiwifruit industry. These include increased impacts of water use "*due to fully or over-allocated local water resources*" [15]. Agrivoltaics have been noted to contribute a 63.4 ± 1.0 mm reduction in soil evaporation in mature vines and a further improvement in water productivity of 8.2 ± 5.7% [14]. Typically, variations of soil types in an orchard require precision irrigation so that water is not

[1] NZ$ 1.00 = US$ 0.58; https://www.xe.com

wasted, and vines are not stressed [14]. The generated electricity can then be utilized to provide the constant power required by the industry standard ‘dripper’ irrigation systems [15].

The system tested in China grew the kiwifruit on trellis’ with the vines running horizontally and the overhead translucent PV panels fixed to a clear ‘ceiling.’ In Aotearoa New Zealand the most common structure for kiwifruit farming is a pergola system for support [15] due to their ‘greater yields’ compared to the less-expensive T-Bar system. Therefore, further investigations are needed as to how overhead agrivoltaics can be implemented with pergola structures of kiwifruit orchards in Aotearoa New Zealand.

1.2.2 Apples/Pipfruit

As a crop, most apple varieties thrive in temperate climates with mild summers and high humidity and have been noted as susceptible to climate change [16], with direct sunburn effects, as well as hail, wind, and cold damage, which decrease marketable fruit.

Internationally, several studies have investigated applying agrivoltaic systems to apple orcharding. For example, Sun’Agri has tested an overhead PV system at an orchard in Mallemort in Southern France [17]. The system has dynamic tracking panels installed at a 5m height, 1.5m above the treetops, in a horizontal position to stop thermal radiation from escaping the orchard, with the trees spaced at 1.25m oriented in a norther-south direction. With maximal shading a decrease in cumulative incident radiation over the season of up to 47% was recorded, as well as a reduction of temperatures of about 1–2°C. The latter is attributed to the microclimate created at ground level, or a ‘thermal blanketing‘, with an increase in humidity, which decreases irrigation requirements, as well as protection against temperature fluctuations and frost. Importantly, fruit maturity and harvest dates were not altered and all the fruit were marketable [17].

Another study conducted in Gelsdorf in Rhineland-Palatinate implemented overhead PV systems with transparent panels to further investigate the protective aspects of overhead systems, where shading is kept to 30% [18]. The information from this study has yet to be released and will be relevant to Aotearoa New Zealand applications.

The pipfruit sector in Aotearoa New Zealand is currently undergoing widespread changes due to the impact of Cyclone Gabriel in February 2023, which caused “*significant damage in the Hawke’s Bay and Gisborne apple-growing region*” [8]. Therefore, dynamic overhead systems would be the most appropriate configurations, due to their protective aspects, and simultaneously assist in the re-development of the producing areas of Hawkes Bay and Gisborne through sustainable energy generation, secondary income generation as well as developing further climate resilience for orchards. However, further research is needed to draw conclusions on the ideal ratio of shading to maintain the current economic value of the agricultural activity (see Table 1). Developing a tracking system appropriate for Aotearoa New Zealand, building on Fraunhofer’s Simtool [18], would also be advantageous.

1.2.3 Potatoes and other vegetables

Potatoes have been a central crop tested in many agrivoltaics studies. A ‘shade-tolerant crop’ [19], potatoes require moderate irradiance conditions [20] and has been demonstrated to grow successfully in agroforestry systems in Nigeria, Kenya and South Asia. Shading up to 50% has minimal effects on yields, although a 26% reduction in total irradiance is the maximum to maintain economic productions [19].

Potatoes in amongst several crops, such as lettuce, were simultaneously grown by Weihenstephan-Triesdorf University of Applied Sciences with the company TubeSolar under tube shaped PV-modules with a capacity of 14kWp [21]. Bi-facial PV modules were installed in 15 rows. An overhead system of fixed-tilt panels, with a clearance height of 5m, and an 11.75m space between row supports, allows room for machinery such as combine harvesters, thereby maintaining farming productivity. Researchers determined that yields were no more than 15% lower than those grown without the PV system above, giving credence to utilizing agrivoltaics for shade-sensitive crops.

In Aotearoa New Zealand the planted area has decreased between 2018 and 2023 by 18.6%, or 1920 hectares, with a total annual production decrease of 20% or by 107,990 tonnes. However, numerous other crop types are produced with potatoes. A mutually beneficial increase in land productivity can be expected with the implementation of overhead agrivoltaic systems, where potatoes are combined with other crop types. In Germany, for example, a 186% increase in land productivity is reported where potatoes and other crops are cultivated under agrivoltaics [21].

1.2.4 Tomatoes

Much of the literature on tomatoes focus on different PV panel layouts and shading ratios in greenhouses. Overall, the literature has determined that a PVc layout has an improved distribution of sunlight received within the greenhouse [22], leading to an increased crop growth. Niche technologies have also been investigated. For example, semi-transparent PV panels that allow light wavelengths relevant for crop growth through while generating sufficient electricity is showing promise [23] but is not yet commercially viable.

Open systems have also been studied. For example, an experimental PV and tomato growing site in the Apulia region of southern Italy [24], with two distinct lighting exposures: one under full sunlight, and the other in the shadow of the PV panels. They demonstrate a significant (>17%) increase in fruit weight under the panels, although the quantity of fruit produced in the control area is more. Therefore, the overall production was not affected much, and is in line with the findings reported by other studies [24].

The overwhelming application of agrivoltaic systems to tomatoes in PV greenhouses is also of relevance to Aotearoa New Zealand where undercover production accounts for 80 hectares of the total 309 hectares of high-value production (see Table 1) [8]. 18% of production is occupied by small-sized greenhouses (<1 ha), 45% occupied by medium sized greenhouses (>1 to <5 ha), and 37% occupied by large greenhouse complexes (>5 ha). Greenhouses are electricity intensive, and the integration of solar PV has been suggested for the Aotearoa New Zealand industry [25].

1.2.5 Viticulture

Agrivoltaics have been tested extensively in the viticulture sector [26]. For example, the French company Sun'Agri has multiple test sites with overhead dynamic agrivoltaic systems at heights of 4 m [27]. An experimental vineyard plot at the Technical University of Cartagena in Spain has investigated interspace agrivoltaics to minimize initial costs and incorporate PV panels into already existing vineyard structures and utilize inter-row space [28]. They determined that a ratio equal or greater than 1.5 between row distance and trellis height allows for PV integration without significant shading between consecutive lines. By orienting the panels vertically allows complete irradiation to the vines below [28]. Research in India has also utilized a fixed-tilt interspace system on existing vineyard structures to integrate the PV modules. They examined shading and evaluated the economic feasibility of the project [29]. In general, it is found that under low to moderate shading (30% or less), the productivity, or yields, is maintained or slightly affected (5%), with good marketable production [26]. In some instances, the postponement of harvesting and improvement of wine quality has been reported [30].

Viticulture in Aotearoa New Zealand currently occupies 41,860 hectares of land, managed by 681 growers across the country [31]. Akin to the pipfruit sector, viticulture was also heavily impacted by cyclone Gabriel in 2023, leading to approximately 800 hectares of vineyards losing some to all their fruit, with a further 300 hectares experiencing significant infrastructural damage on top of the loss of crop [31]. Therefore, in the re-build efforts, agrivoltaics could provide a crucial role.

2. Agrivoltaic systems appropriate for farming practices

The common agrivoltaic system structures and how the above agricultural sectors/crop types align with these technologies are summarized in Table 2 – as a guide for farmers and industry. In Aotearoa New Zealand agrivoltaic systems are not well defined and the requirements are yet to be stipulated. The German standard is taken as a further guide [32]. It stipulates a clear height of at least 2.1 m, which is defined "*as the free vertical area between the base of the agricultural land and the lower edge of the lowest structural element under self-weight deformation. In the case of movable structural elements, the lowest bottom edge shall be measured where the clear height is at a maximum.*" For high-mounted systems the area that is not usable for agriculture should be less than 10%, and for ground-level systems less than 15%. From the review of the literature a ground cover ratio, or shading, of 30% or less is sufficient to maintain crop and/or livestock production in most cases.

Table 2. *Summary of agrivoltaic system configurations for different agricultural activities.*

System	Open	Open	Closed
Structure	Interspace PV	Overhead PV	PV greenhouse
PV configuration	Fixed-tilt, single-axis tracking	Fixed-tilt, single-axis and dual-axis tracking	Fixed
Livestock	Cattle, Sheep	Cattle, Sheep	
Horticulture	Kiwifruit Apples / Pipfruit Potatoes Viticulture Others	Kiwifruit Apples / Pipfruit Potatoes Viticulture Others	Tomatoes

3. Conclusions

Integrating solar PV panels with agricultural production offers a sustainable solution to the challenge of limited land resources in Aotearoa New Zealand, where a substantial portion is already dedicated to agriculture. By leveraging agrivoltaic systems, Aotearoa New Zealand can simultaneously address energy needs and agricultural productivity, optimizing land use without compromising on either front.

The study delves into various agricultural sectors—livestock farming, horticulture, cropland farming, and fruit—demonstrating how tailored agrivoltaic configurations can be effectively implemented. Livestock farming, especially sheep and cattle production, shows considerable potential for large-scale agrivoltaic systems due to the extensive (flat) grazing areas available. Similarly, the horticulture and cropland sectors may benefit from smaller scale agrivoltaic systems, particularly for crops like kiwifruit, apples, potatoes, and tomatoes, which have been shown to thrive under agrivoltaic systems.

Additionally, viticulture presents unique opportunities for agrivoltaic integration, providing benefits such as protection from environmental hazards and enhancing climate resilience. The dynamic overhead systems offer promising results in maintaining crop yields while generating solar power.

The development of a customized guideline for agrivoltaic implementation is needed for streamlining the adoption of these systems by the farming community. Such a guideline will help farmers identify the most suitable agrivoltaic configurations for their specific crop types and agricultural practices, ensuring optimal performance and economic viability.

Many research efforts are ongoing in Aotearoa New Zealand that will inform the development of guideline:

1. **Conduct long-term field studies**: Implement and monitor various agrivoltaic configurations across different regions and agricultural sectors in Aotearoa New Zealand to gather comprehensive data on their performance and impact.
2. **Develop advanced agrivoltaic technologies**: Explore innovative agrivoltaic technologies, such as dynamic tracking systems and transparent photovoltaic panels, and tailoring these to Aotearoa New Zealand to enhance efficiency and adaptability for different crop types.
3. **Economic analysis**: Perform detailed economic analyses to evaluate the cost and benefits of agrivoltaic systems, including potential financial incentives or support mechanisms for farmers.
4. **Stakeholder engagement**: Foster collaboration between researchers, planners, policymakers, industry, and the agricultural community to ensure the successful implementation and scaling of agrivoltaic systems nationwide.

By addressing these topics, Aotearoa New Zealand can further optimize the integration of renewable energy into its agricultural sector, making significant strides towards a sustainable and resilient future.

Data availability statement

No data was used for the review paper.

Underlying and related material

The review paper does not have underlying and related material.

Author contributions

Juan Cabrera Pirela undertook the literature review and drafted the paper. Alan Brent provided guidance with the literature review and edited the final paper.

Competing interests

The authors declare that they have no competing interests.

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