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Agrivoltaic Systems for Aotearoa New Zealand

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Abstract

The uptake of solar photovoltaic (PV) systems has increased substantially in Aotearoa New Zealand, but the relative contribution to the overall energy mix is still small. Nevertheless, the potential of niche PV applications is receiving more attention. Specifically, for areas with a good solar resource and a productive agriculture sector, agrivoltaic, or agriPV, systems may be appropriate to utilise the high value land more productively for both food and energy production. This short communication subsequently investigates the potential opportunities to develop such systems. Global experience shows that various crop and pastoral production practices can be tailored for dual land usage and can, indeed, benefit from agrivoltaic systems. Also, advancements in PV technology now enable more suitable energy generation configurations. The optimisation of agrivoltaic systems, however, will require more information about the behaviours of crops, and animals, with different PV technology configurations in various climatic conditions across Aotearoa New Zealand. Apart from test and demonstration sites further research focus areas are highlighted.

Keywords: Solar energy; Photovoltaics; AgriPV; Agrivoltaics; Dual land-usage; Agricultural efficiency; New Zealand

Introduction

The uptake of solar photovoltaic (PV) systems in Aotearoa-New Zealand, as a significant technology for the transition to a net-zero carbon economy, has been argued [1]. Nevertheless, challenges remain for the installation of utility-scale systems, such as ground-mounted solar farms [2]. In regions with a productive agricultural sector the land value tends to be higher, or in some regions the land holds intrinsic cultural value [3]. This land value makes the development of ground-mounted solar farms more complicated, even when a good solar resource is available.

Agrivoltaic, or agriPV, systems are subsequently receiving much attention globally as a potentially viable alternative to conventional large-scale installations [4]. The concept is not new [5] and essentially means the combination of agricultural production with energy generation over the same area, with potential benefits for both economic activities. Specifically, the decreased land competition between solar PV electricity generation and agricultural production, through a symbiotic, coexistence relationship.

The efficient and effective use of land is especially appealing for Aotearoa New Zealand, since half of its land area serves agricultural purposes. From the nearly 47 million ha available, more than 4 million ha account for sheep. Beef and dairy together account for almost 5 million ha, while horticulture and grains account for less than 700 thousand ha [6]. Nevertheless, simply allowing some agricultural activity with the development of raised ground-mounted solar PV does not necessarily imply an efficient agrivoltaic system – such as the dual use 229 MW solar project that is underway in the upper North Island [7]. Indeed, Pascaris in [4] emphasises that a robust agrivoltaic system "*would actively accommodate farming activity and be designed for maximum dual output of both electricity and agriculture*". Several factors might constrain the implementation of agrivoltaic systems, such as crop height, crop resistance to shade, soil type, and soil slope, among others. Moreover, community acceptance is vital, and needs to account for different values and preferences within communities in specific contexts [8] – as a fundamental aspect for the growth and uptake of these systems [9].

This short communication investigates the potential opportunities to develop such systems by focussing on the mentioned, more technical factors and considering the aspects of the agrivoltaic technology together with agricultural production in Aotearoa New Zealand – to pave the way forward for the implementation of appropriate agrivoltaic systems in the country.

Aotearoa New Zealand Agricultural Produce Appropriate for Agrivoltaic Systems

An overlay of crop production on a previously reported GIS analysis [1], shows, as can be expected, that the solar resource is extremely good in areas with intensive agricultural activities (see Figure 1, and the Figures in the Appendix for the regions of Aotearoa New Zealand). The kind of crop production that may suit agrivoltaic systems, however, needs further consideration.

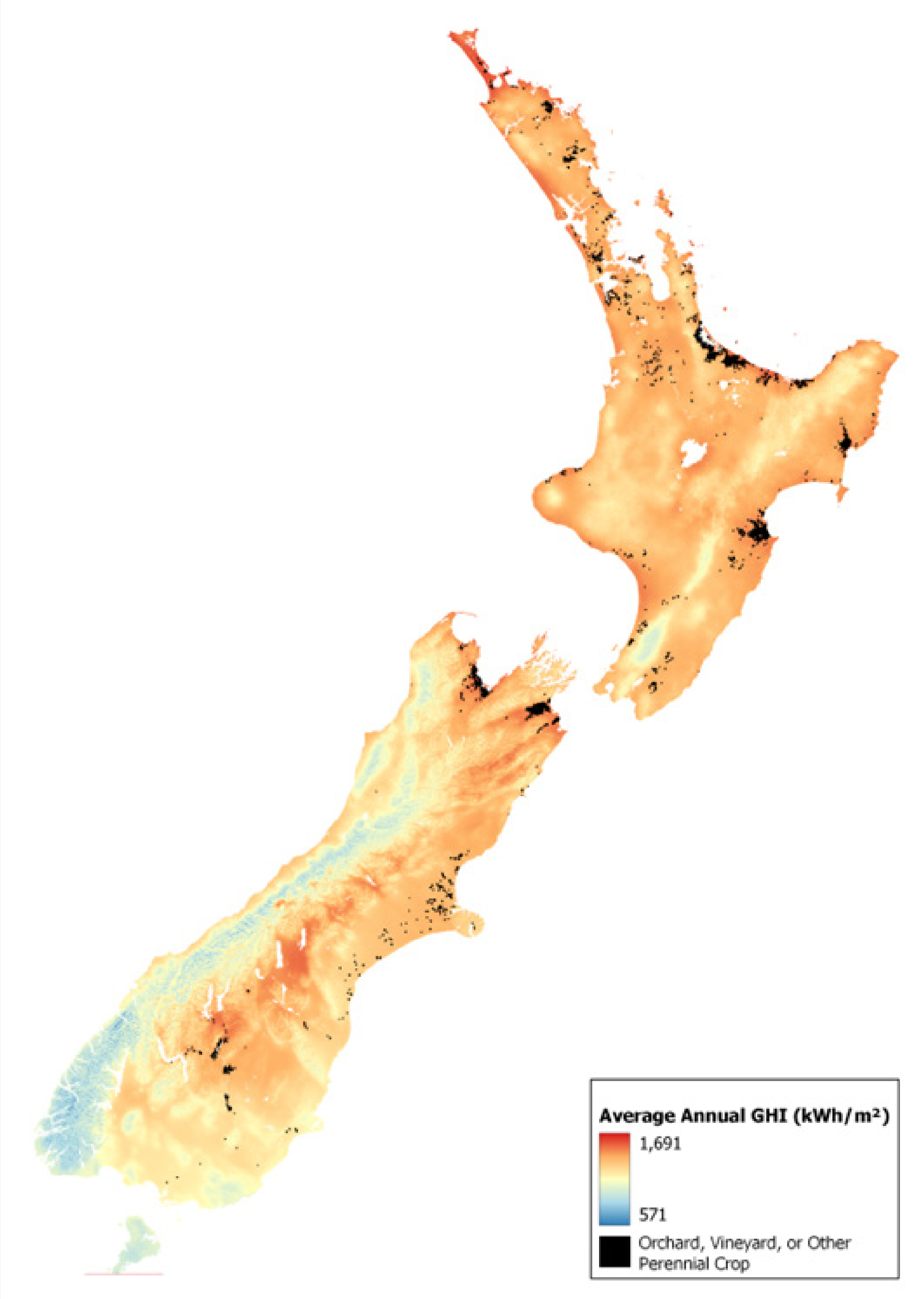

Figure 1: Long-term average of annual sum of Global Horizontal Irradiance (GHI), period 2007-2018 [kWh/m2], with current crop production.

Source: Adapted from [1] with metadata from [10].

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Aitken and Warrington [11] report that the main horticultural exports in Aotearoa New Zealand are kiwifruit, apples, and wine. The kiwifruit tree can grow as high as 10m or more, making this crop a weak candidate for agrivoltaics, since the maximum height of agrivoltaic systems is around 4 to 6m [12,13]. Apple trees are smaller – 5 to 8m standard size and 3 to 6m dwarf size – and can be suitable for agrivoltaic applications. Grapes, on the other hand, are considered good candidates for this application [14].

Aotearoa New Zealand also produces avocados, berries, stone fruit, and others. Berries, such as cranberries, are potentially suitable for agrivoltaic systems [15], but are not a major crop in Aotearoa New Zealand. Vegetables, on the other hand, are (usually) a feasible option for agrivoltaics [13]. According to Aitken and Warrington [11], New Zealanders prefer vegetables, such as potatoes, tomatoes, lettuce, carrots, broccoli, and others. These crops are usually moderate-to-high shade tolerant, and therefore suitable candidates for agrivoltaic systems [16].

For appropriate horticulture crop the potential benefits of agrivoltaics, for the Aotearoa New Zealand context, are the creation of cooler conditions during the day and warmer conditions at night, thereby reducing heat stress and frost damage, and increasing soil moisture levels in dry periods due to the microclimate under the panels [17].

For pastoral production the appropriateness of agrivoltaics is, globally, abundantly clear. Grazing has little risk to the installed solar infrastructure, with many benefits from a farming perspective; for example, increased health and wellbeing of the animals due to protection from the elements, less water consumption of the animals, and access to pasture during dry conditions [18].

A further consideration is the impact of climate change on the agriculture sector, and the required adaptation [19]. The impacts may accentuate the benefits of agrivoltaic systems going forward, and its appropriateness for different crop and pastoral production.

Ongoing Research Elsewhere

Several research initiatives are ongoing globally, and some are summarised in Table 1. The observations and findings highlight the importance of different technology considerations and context specificity on the overall performances of agrivoltaic systems.

Technology Considerations and Advancements

Schindele and de Vries, in [21], note that light is a key factor for PV power generation, which is, of course, also crucial for agricultural production. An equal sharing of light is technically possible, but may not be suitable for all kinds of crops and climates. They emphasise that "*so far, very little research has been done in this regard*". Apart from understanding the requirements of specific agricultural production, different technology components and configurations are being investigated, or have been implemented (see Table 1).

Table 1: Selected agrivoltaic research initiatives underway globally.

<table>
<tr><td rowspan="2">USA</td><td>National Renewable Energy Laboratory (NREL)</td><td>The Innovative Site Preparation and Impact Reductions on the Environment (InSPIRE)

project, funded by the US Department of Energy, "seeks to improve the environmental compatibility and mutual benefits of solar development with agriculture and native landscapes".</td><td>https://openei.org/wiki/InSPIRE</td></tr>
<tr><td colspan="3">The InSPIRE initiative is a collective effort that brings together researchers from national laboratories (NREL, Argonne National Laboratory), universities, local governments, environmental groups, and industry partners. The goal is to create guidelines for cost-and-environmental effective solar practices through low environmental impact designs and approaches, including the co-location of solar arrays on agricultural lands. InSPIRE combines computational models with field-based data to assess: "Native vegetation growth underneath and around ground-mounted solar installations; agricultural crop performance under innovative solar configurations; impacts of low-impact solar development approaches on soil quality, carbon storage, stormwater management, microclimate conditions, and solar efficiencies; and benefits of pollinator-friendly solar on local agricultural yields".

The project consists of nearly 30 sites across the US and includes research on native vegetation, pollinator habitats, and livestock grazing, among others.</td></tr>
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France	Sun'Agri (a subsidiary of Sun'R) in partnership with the Vaucluse Chamber of Agriculture	Test site in the region of Piolenc, in Hérault, consisting of a single axis tracking PV system, mounted 4.2m above ground, and with 2.25 row spacing, over 600m^2 of black grenache grapes, and a control site of 340m^2.	https://sunagri.fr/en/project/piolencs-experimental-plot/
	The PV modules are controlled electronically by a system based on artificial intelligence algorithms, which can determine the "*ideal tilt of the panels according to the sunshine and water requirements of viticulture, growth model of the crop, soil quality and weather conditions*", thus favouring plant growth. The system can detect and protect the plants against extreme events such as drought, heatwaves, hail, frost, heavy rain, and others. Initial results show a reduction in water demand of around 10% due to the decrease in evapotranspiration. "*It has also been claimed the aromatic profile of the grape was improved in the agrivoltaic set-up, with 13% more anthocyanins – red pigments – and 9-14% more acidity*".		
Chile	Fraunhofer Chile Research	One of three agriPV plants, consisting of a fixed-tilted PV system, mounted 3.5m above ground, and with 1.65m row spacing, over 256m^2 of cauliflower.	[20]
	The test system has delivered half of the energy expected of a conventional PV system of the same size. The result is likely due to the row spacing and the chosen azimuth of the system. On the other hand, the researchers found that the minimum average temperature increased slightly (+0.6ºC), while the maximum average temperature showed a minor reduction. The average relative humidity under the system increased by 3%.		

One route is not to rely on standard PV modules, as such commercial products are considered unsuitable for an efficient agrivoltaic system – especially for conventional raised, tilted ground-mounted configurations [21]. To this end special monocrystalline solar panels, with different levels of transparency, may be suitable – again, depending on the targeted crop. Using organic semiconducting materials allows for the customisation of the wave lengths absorbed by the PV modules, passing the appropriate light through to the crops. This can be advantageous in the case where certain crops see an efficiency increase under certain light wavelengths [22]. Efficiency rates of such specially designed panels are reported to be in line with standard modules, and offer additional benefits, such as less irrigation requirements. Cost is currently an issue, but for larger projects, and with wider adoption, prices are expected to reduce drastically.

Research efforts have also focused on bifacial PV panels, which are PV modules that can produce power from both the front and back of the module. Bifacial PV modules have a greater power density per unit when compared to monofacial PV modules and also have the advantage of reduced sensitivity to temperature change [23]. In the literature, the concept of vertically mounting the bifacial PV modules for agrivoltaic applications has been compared to traditional fixed tilt monofacial PV modules with comparable energy output (in low density PV arrays). This has the advantage of minimum land coverage and the potential to mount panels closer to the ground [24].

Another route is to use tracking more effectively. By tracking the movement of the sun the efficiency of electricity generation can be improved. The required increase in spacing between PV modules, to minimise shading of the modules, also means light penetration for crop production below the panels. Also, tracking results in the movement of the shade across the ground. Specialised trackers have been developed that are tailored for agrivoltaic systems [25].

One practical implication of having agrivoltaics elevated high enough to ensure agricultural activities can be performed beneath them is the additional difficulty of cleaning the PV panels [24]. While a seemingly trivial implication, the accumulation of dirt, such as sand, dust and moss can reduce a panel's output by up to 85% [26], which highlights the importance of cleaning the PV modules regularly. Additional operational and maintenance cost may be involved in cleaning elevated panels, which will need to be considered in the agrivoltaic business case, or new technologies will need to be designed to account for the additional height.

Regardless of the chosen PV technology configuration, optimisation techniques are required to maximise yields – of energy and, especially, agriculture production.

Optimising the Design of Agrivoltaic Systems

Formulating the economic agrivoltaic optimisation problem, such that it is amenable to exact mathematical solution algorithms, substantially increases the risk of sub-optimality – or, in other words, it can result in a loss of solution fidelity [27]. Especially to solve complex problems, pertaining to system investment planning, and operational management, which are classified as analytically intractable without several (often strong) simplifying assumptions [28]. Associated developed simplified solution approaches, based on mathematical optimisation methods, have included various decomposition techniques, such as linear programming (LP), mixed-integer programming (MIP), mixed-integer linear programming (MILP), mixed-integer nonlinear programming (MINLP), and dynamic programming, of which the MILP is the most popular approach.

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However, an efficient agrivoltaic system is a complex combinational optimisation problem with a non-smooth, nonlinear, non-convex, non-differentiable, mixed-discrete-continuous, high-dimensional objective function subject to a variety of interconnected constraints. Accordingly, it can be classified as a non-deterministic polynomial-time hardness, or NP-hard, problem [29].

A recent, emerging strand of the long-term investment planning optimisation literature has proposed using meta-heuristic optimisation algorithms, based on artificial intelligence (AI), as an alternative to classical mathematical optimisation methods [28], which can be either adapted or utilised directly to optimise an efficient solution to the agrivoltaic infrastructure problem. Nature-inspired meta-heuristic optimisation is a sub-discipline of AI that seeks to determine the globally optimum solutions for NP-hard problems, in terms of identifying the least-cost combination of the sizes of the components of the system subject to a set of operational and planning constraints [30].

Another optimisation technique explored in the literature is “fuzzy mathematics”, a technique used to interpret vague or uncertain information [31]. This technique evaluates the crop’s “fitness” for agrivoltaic farming by comparing the ideal solar radiation, temperature and precipitation for a crop, with the expected environmental conditions at the location of an agrivoltaic system.

Way forward for Aotearoa New Zealand

More information about the behaviours of crops, and animals, with different PV technology configurations in various climatic conditions across Aotearoa New Zealand is required to inform the optimisation of agrivoltaic systems. To this end, test and demonstration sites are currently being explored.

Observational research campaigns are envisaged of selected systems of between 0.1 and 0.2 hectares per configuration, which, based on the experience of NREL (Table 1), are the minimum areas required for such observations. Techno-economic modelling of the potential energy yields, associated with different PV and energy storage configurations, can then be undertaken for different farming contexts.

The research campaigns will also observe the biogeophysical interactions between living-agricultural-systems (e.g., crops or livestock), hydrology, atmosphere, and PV infrastructure. Accordingly, it is envisaged to develop a PV-agricultural-biogeophysical model that will be capable of predicting how different agrivoltaic configurations would impact factors such as agricultural yield, plant/animal health, electricity production, and surface hydrology; to answer how regional patterns of climate variability might impact agrivoltaic systems (air temp, wind, humidity, rainfall, solar radiation), and what design/management practices would make agrivoltaic systems more climate resilient.

The development of AI-based multi-criteria optimisation approaches are then required that enable determining the optimal trade-offs (best compromise solutions) when dealing with several conflicting objectives, such as total discounted cost minimisation, total greenhouse gas emissions minimisation, water use minimisation, land use minimisation (including the minimisation of the impacts on highly productive agricultural land), maximisation of the net agricultural return from the irrigated area, maximisation of electricity generation, and so forth.

The formulation of probabilistic scenario generation and reduction techniques are also required to address the complexity of multivariate, variable systems with intertwined, inter-temporal parametric relationships, as well as dynamic uncertainties associated with, for example, meteorological and electricity market forecasts, and hybridizing the proposed coordinated, data-driven stochastic uncertainty quantification methods with the above-mentioned AI-based multi-criteria optimisation approaches (which are solved using specifically developed multi-objective meta-heuristic-based solution algorithms) – to systematically make the associated decision-making processes aware of the model-inherent parametric uncertainties.

Finally, research is underway to better understand the macro-economic implications of a large uptake of agrivoltaics, as well as the (social) impacts, and community acceptance, of agrivoltaic systems, by using augmented and virtual reality techniques.

Acknowledgement

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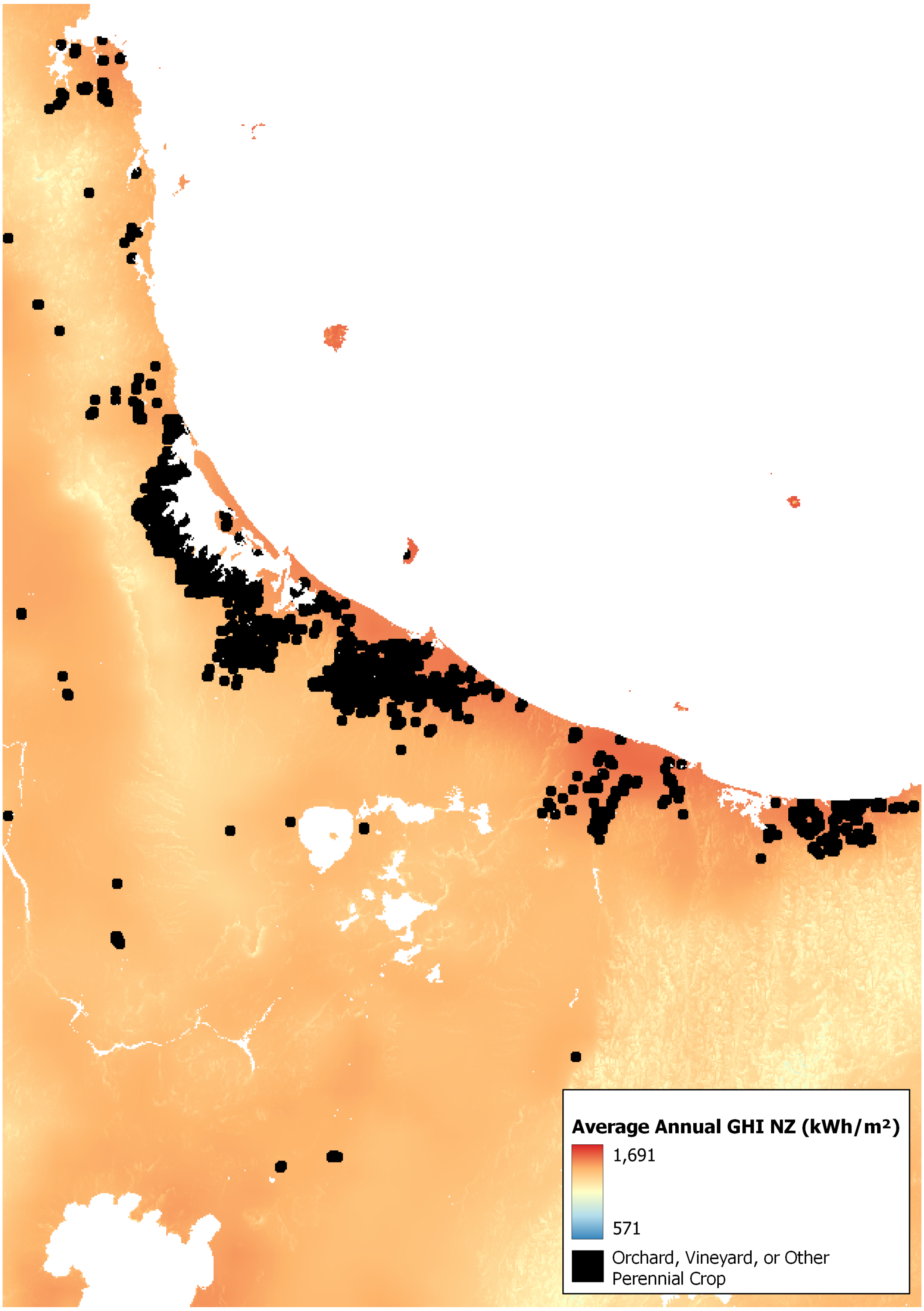
Appendix



Solar resource and crop production in the Bay of Plenty region of Aotearoa New Zealand.

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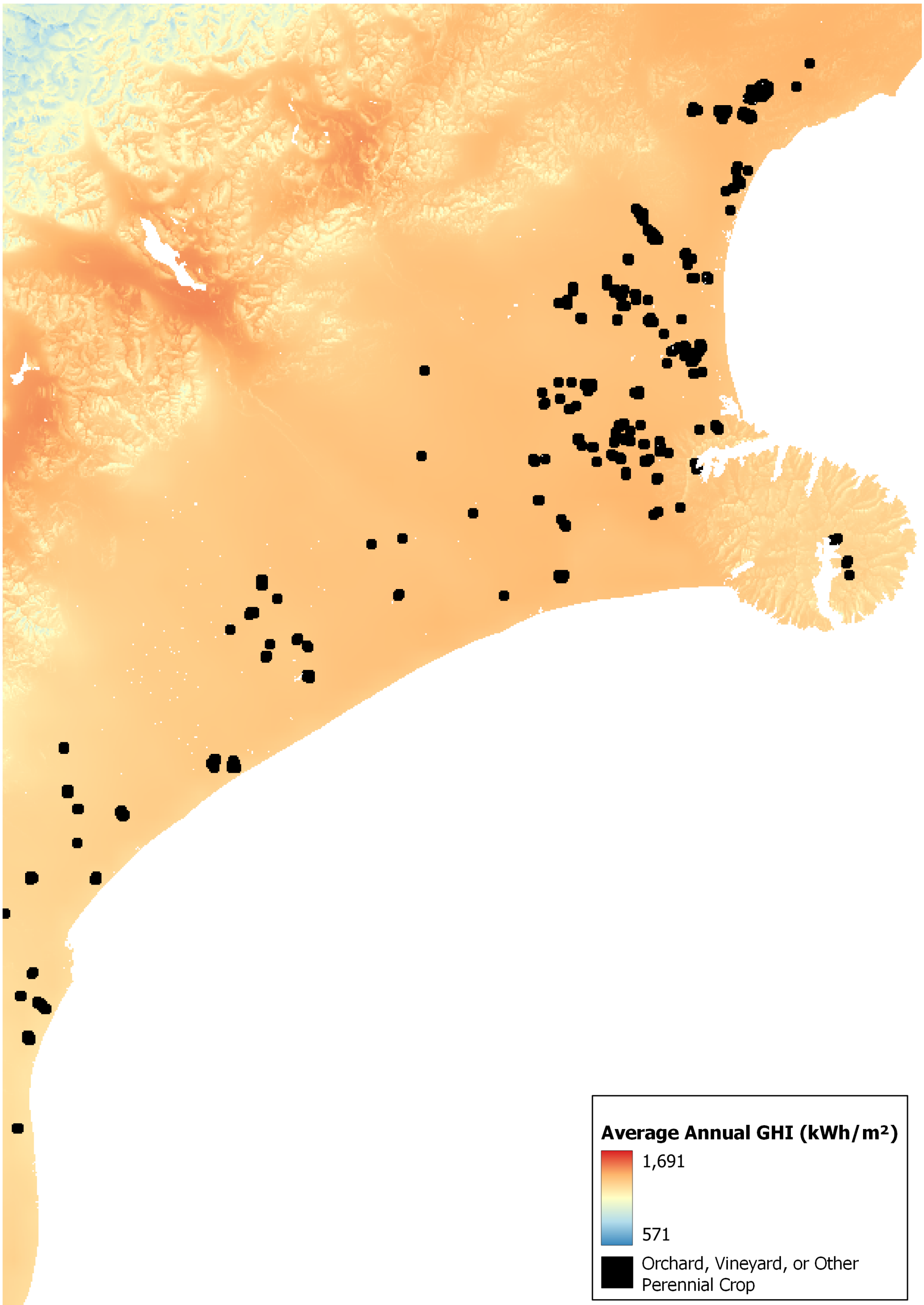

Solar resource and crop production in the Canterbury region of Aotearoa New Zealand.

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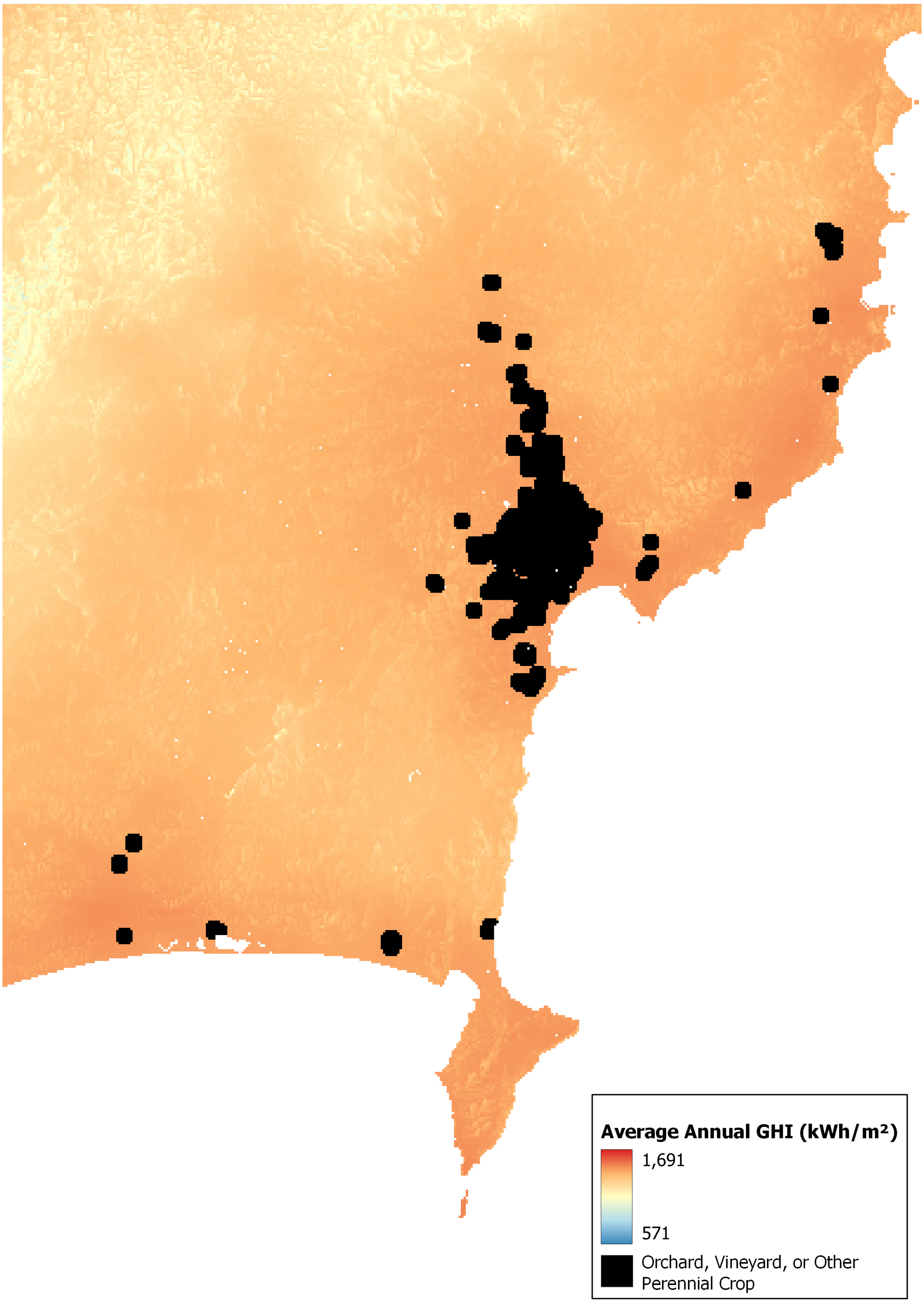

Solar resource and crop production in the Gisborne region of Aotearoa New Zealand.

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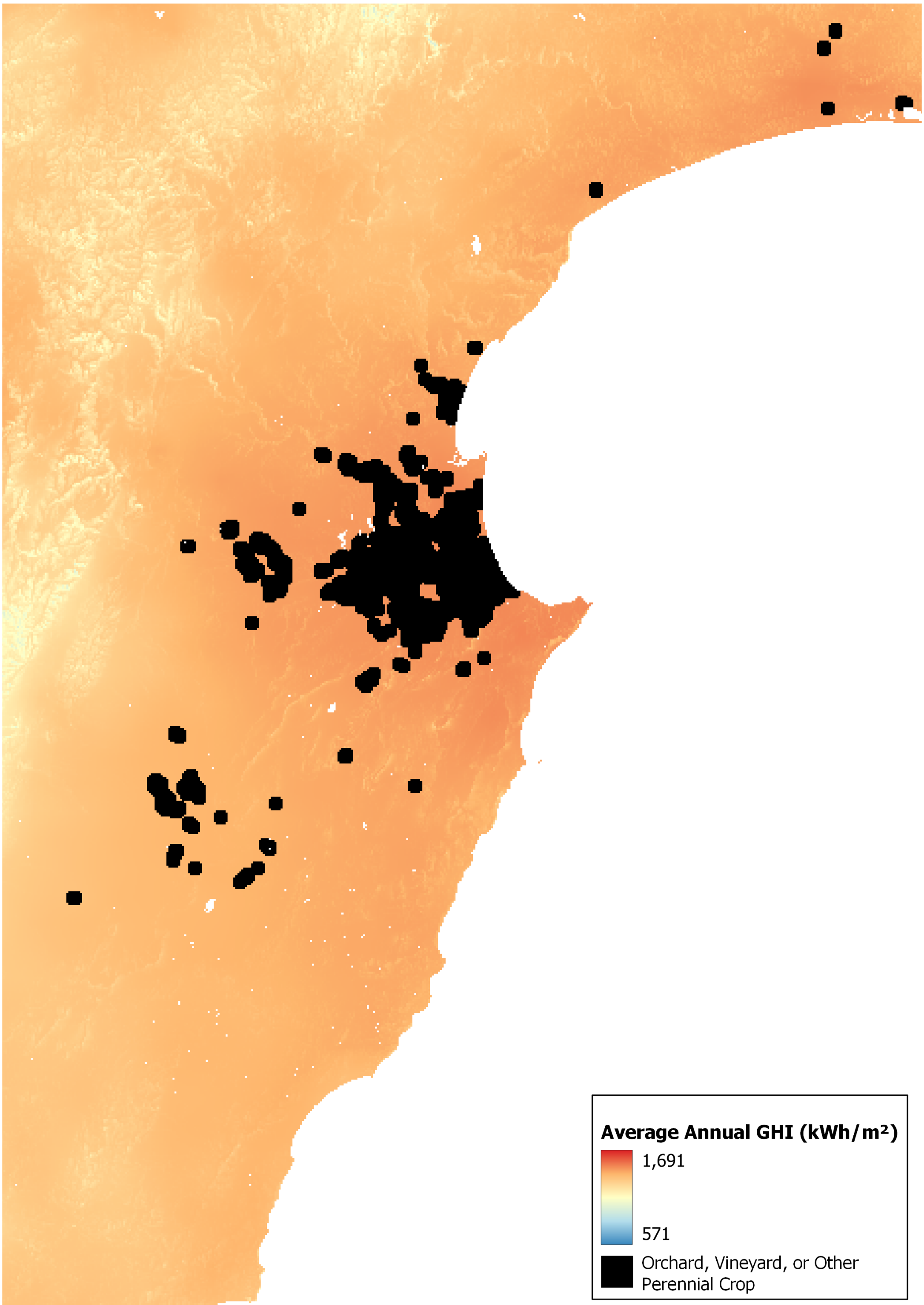

Solar resource and crop production in the Hawkes Bay region of Aotearoa New Zealand.

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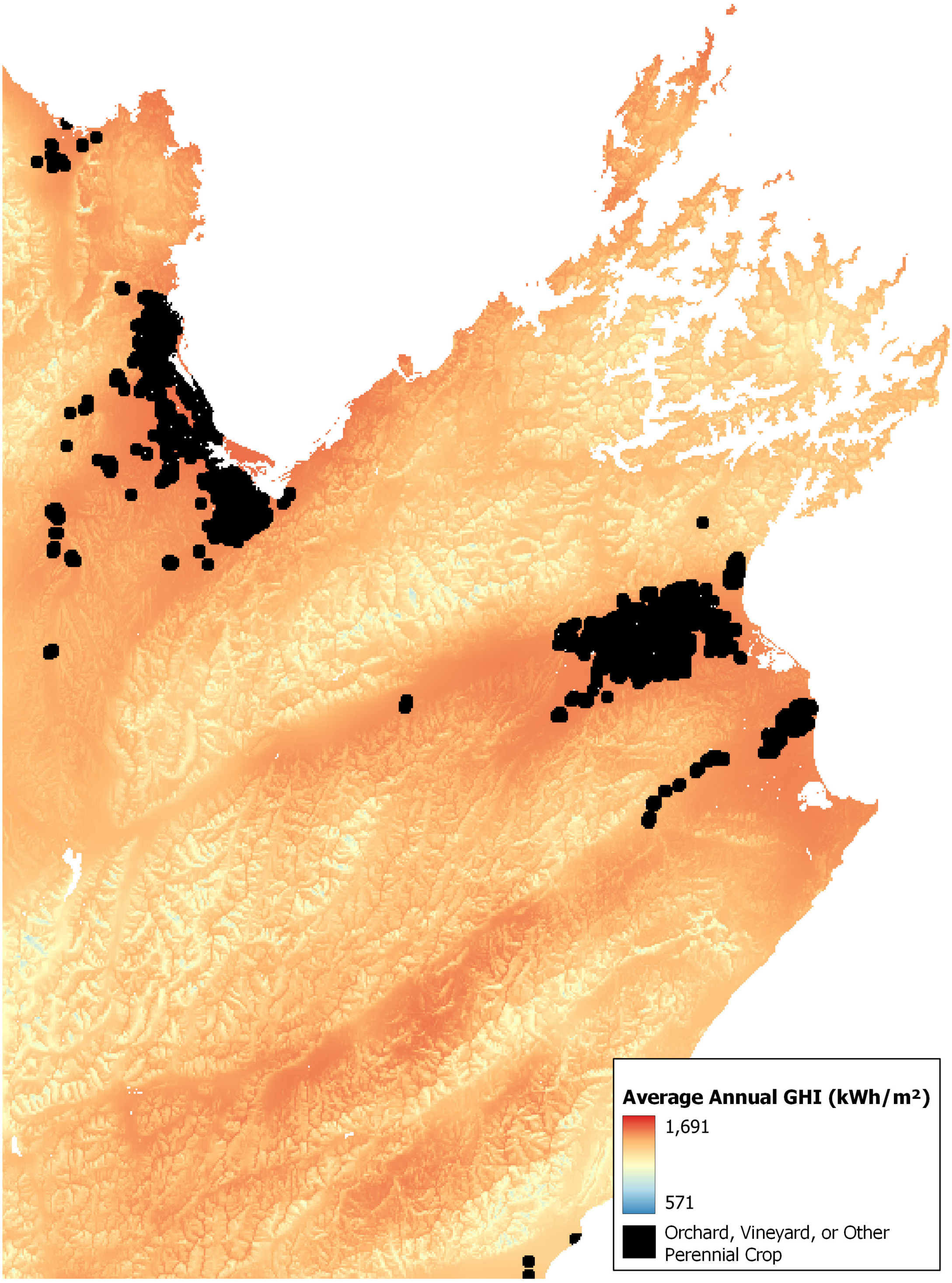

Solar resource and crop production in the Marlborough region of Aotearoa New Zealand.

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