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ESMAX for spatial agroecology: A conceptual spatial model for the quantification and visualisation of ES performance from different configurations of landscape

Richard Morris[1] | **Shannon Davis**[2] | **Gwen-Aëlle Grelet**[3] | **Pablo Gregorini**[1]

[1]Department of Agricultural Science, Faculty of Agriculture and Life Sciences, Lincoln University, Lincoln, New Zealand

[2]School of Landscape Architecture, Faculty of Environment, Society and Design, Lincoln University, Lincoln, New Zealand

[3]Manaaki Whenua—Landcare Research, Lincoln, New Zealand

Correspondence
Richard Morris, Department of Agricultural Science, Faculty of Agriculture and Life Sciences, Lincoln University, PO Box 85005, Lincoln 7674, New Zealand.
Email: richard.morris@lincolnuni.ac.nz

Funding information
Lincoln University

Abstract

Introduction: Agriculture is confronted by the dual challenges of increasing global demand for food production while reducing negative impacts on the environment. One suggested solution is transitioning modern industrial agriculture to more agroecologically-informed practices, thus realigning increased food production with the carrying capacity of Earth Systems. The transition to multifunctional agroecological systems, that promote the production of multiple ecosystem services (ES) as well as food production, requires an adaptive management process that addresses climate-change, market complexity, practical implementation and knowledge transfer.

Materials & Methods: This work proposes a spatially explicit methodology to support this process. Spatial agroecology, in this context, combines a new Geographic Information Systems (GIS)-based model (ESMAX) with development of a 'solution space' to assist stakeholders identify configurations of agroecological components (in this case, trees on farm) at the scale of a 1 ha paddock to supply a targeted range of regulating ES (cooling effect, flood mitigation and habitat). ESMAX uses distance-decay characteristics specific to each type of regulating ES to quantify and visualise the influence of spatial configuration of ES-supplying tree clumps on overall ES performance.

Results: The results from this application of spatial agroecology suggest regulating ES production at farm and paddock scale is influenced by the arrangement of trees on farm. ESMAX's results show paddocks with large tree clumps return the best cooling effect, while small clumps deliver the best flood mitigation and most suitable habitat. Evenly dispersed arrangements of small tree clumps provide the best multifunctional performance across all three ES modelled in this work.

Conclusion: Designed spatial agroecological interventions can affect landscape multifunctionality at paddock scale, where practical decisions are made and implemented. This provides spatially explicit support of an adaptive management process. Utilising agroecological systems as spatial mechanisms for supplying critical regulating ES also highlights a new function for agriculture in the Anthropocene epoch.

KEYWORDS

adaptative management, ecosystem services, GIS

1 | INTRODUCTION

Agriculture is well documented as the world's single largest driver of global environmental change—playing a lead role in our present and projected transgression of all nine Earth System Boundaries (ESBs) (Campbell et al., 2017; Poore & Nemecek, 2018; Tilman et al., 2011). Critically, modern industrial agriculture—agricultural systems dependent on artificial inputs and singly focussed on food and/or fibre production (Franzluebbers & Hendrickson, 2024; Sumberg & Giller, 2022)—has reduced the potential for agroecosystems to sustain the myriad of essential ecosystem services (ES) to counter threats to ESBs (climate change, biodiversity loss, breakdown of nutrient cycles, freshwater depletion etc.) and to meet the accelerating rate of human demand on natural systems (Crist et al., 2017; Pörtner et al., 2022; Rockström et al., 2017). Of utmost importance are vital regulating ES—the invisible processes that regulate and maintain ecological balance, critical to mitigating threats to ESBs (Daily, 1997; Sutherland et al., 2018). Examples of regulating ES include the maintenance of water quality (for human consumption and for waterway biological health), microclimate regulation, provision of biodiverse habitat and flood protection (from both riverine flooding and sea level rise) (Bommarco et al., 2013; Dominati et al., 2016; Haines-Young & Potschin, 2010). While the negative feedback loops generated by modern industrial agriculture (soil health and water depletion, dependence on artificial inputs etc.) undermine the enhanced food production it was originally designed to promote (Balmford et al., 2018; Matson et al., 1997; Springmann et al., 2018), agriculture remains one human activity that can be harnessed to decelerate further transgression of ESBs, and even return us to existing within ESBs (Bennett, 2017). Returning modern industrial agriculture to sustainable production systems that equally valorise a range of ES, however, presents significant challenges. Discourse on agroecology [the application of ecological concepts and principles to the design and management of agricultural systems (Gliessman, 2007)] over the past three decades—whether as science, social movement or farming practice—illustrates the degree of transformation required (Wezel et al., 2009). Contemplating the magnitude of this challenge is helped however when we consider modern industrial agriculture as an experimentally simplified subset existing within the broader spectrum of agroecological farm systems (AFS); a subset that relies on the integration of chemicals, energy and irrigation into ecological systems to achieve its singular function of food production (Wojtkowski, 2016). Decelerating further transgression of ESBs, while still producing food, requires moving modern industrial agriculture towards agroecological multifunctionality (Frei et al., 2020; Garbach et al., 2017). This refers to AFS in which a suite of multiple ES are provided to match local ES demand (Hodbod et al., 2016; Yahdjian et al., 2015). Regulating ES play an essential leveraging role in such multifunctional systems, underpinning provisioning ES (the supply of food and fibre) and cultural ES (the cultural, emotional and recreational value arising from our perception of ecosystems) (Sutherland et al., 2018). Adaptive management approaches have been proposed as the most suitable process to achieve the transition from modern industrial agriculture to agroecological multifunctionality (Groot & Rossing, 2011; Hodbod et al., 2016). Such systems-based approaches integrate management and learning in an iterative process, considering multiple factors (economic, environmental, operational etc.) and updating farming practice as learning occurs (Allen & Garmestani, 2015; Holling & Sundstrom, 2015). Progress is hampered, however, by lack of spatial tools that (1) can be used to quantify and visualise the production of regulating ES by AFS, and (2) help farmers, given their practical spatial and operational constraints, to effectively design and implement multifunctional AFS. These two factors underline the importance of developing a spatial agroecological approach.

Spatial agroecology is the design of AFS through the configurational and compositional arrangement of agroecological components (Perley, 2021). The configuration of such components—trees, hedgerows, shelterbelts, watercourses, pasture, crops and so forth (Wojtkowski, 2006)—has been shown to have an influence on regulating ES supply, although this has not yet been explored or conveyed in a spatially explicit manner (Case et al., 2020; Duarte et al., 2018). Such explicit configurational considerations include the size and shape of components, and the degree of aggregation or dispersion with which they are arranged (Turner & Gardner, 2015; Verhagen et al., 2016). Furthermore, discourse on agricultural multifunctionality primarily focuses on broadscale (frequently regional) rural contexts (Bruley et al., 2021; Mastrangelo et al., 2014). Subsequently, limited attention has been given to the spatial efficiency with which AFS can produce multiple ES at the smaller scale of individual farms, or even smaller single paddock (we use the term ‘paddock’ (the common term for a farm field used in New Zealand) to avoid confusion with ‘field’ in an ecosystemic spatial sense as described in the Method section) scales. At this scale it is most feasible for farmers and land managers to implement changes in configuration and composition affecting ES supply, this being the scale they are used to modifying from year to year, and the smallest self-standing unit of land found on a farm (Hatt et al., 2018; Landis, 2017). Our recent work has developed ESMAX, a conceptual spatial model used to quantify and visualise the ES performance of different configurations of landscape components (Morris et al., 2024). This work applies ESMAX to spatial agroecology, in this instance to designing paddock-scale AFS to deliver multiple regulating ES. This is a novel consideration for the design of agroecological systems. We suggest that the spatially explicit configuration of agroecological components at paddock scale directly influences AFS multifunctionality. Our first objective is to create a range of 1 ha paddock configurations and use ESMAX to test these for the supply of three regulating ES—cooling effect, habitat suitability and flood mitigation—with contemporary relevance to agricultural contexts in New Zealand (Maseyk et al., 2019; Nguyen et al., 2023; Paulik et al., 2021). The AFS configurations comprise simplified woody vegetation components of different sizes and spacings. These are arranged on a neutral matrix background (hypothetically comprising open pasture or cropping) that for the purposes of this study produces zero ES. Similarly, the soils supporting all Service Providing Units (SPUs) and the pasture/cropping matrix are also assumed to be homogenous throughout the 1 ha AFS paddock and to produce zero ES for the purpose of this conceptual study. The second objective of this research is to demonstrate a spatial agroecology methodology that supports the iterative design process required by an adaptive management approach. We translate the trade-off/synergy characteristics seen in the results of ESMAX simulations as a graphical ‘solution space’. This enables farmers and designers to choose solutions from alternative paddock-scale configurations that both meet local ES demands and specific contextual operational and spatial limitations. These objectives combine to describe a novel spatial perspective of AFS design and indicate an emerging role for agriculture as a mechanism to mitigate and counter threats to ESBs.

2 | MATERIALS AND METHODS

2.1 | The ESMAX model and the virtual experiment

ESMAX is based on a Geographic Information Systems (GIS) platform, developed in ESRI ArcGIS Pro (Version 3.0.1; Esri). The model converts the distance-decay idiosyncrasies of each type of regulating ES into characteristic ‘ES fields’. ES fields are first-order effects—the intensity of ES radiating from a source agroecological component (termed ‘Service Providing Units’ or SPUs in this work). Based on literature review, a characteristic ‘kernel’ is assigned to each type of ES, representing the distance-decay of ES intensity from the SPU. ESMAX also calculates the response of ES performance where ES fields of the same ES type overlap. This overlap response (or second-order effect) is also idiosyncratic to each type of ES and is seminal to calculating the effect of SPU configuration on overall ES production. Outputs of ESMAX consist of a heat map of the research area, graphically illustrating the ES fields being produced by each configuration and a normalised ‘ES Score’ that represents the overall quantity of the ES produced. The outputs of the model are plotted on a radar diagram to communicate the performance of each configuration across multiple ES as a ‘solution space’. The first four steps are set out in more detail below.

2.1.1 | AFS paddock configuration

In this work, the woody vegetation components arranged within the 1 ha AFS paddock are the SPUs supplying the three regulating ES (Kremen, 2005; Sutherland et al., 2018). As there is no data on typical paddock size in New Zealand, 1 ha is selected as a reasonable base module for the purposes of this research based on personal observations and anecdotal data on local paddock sizes. The SPUs within the paddock are the focus of spatial intervention, with ES fields generated by individual SPUs overlapping and interacting to generate the total ES performance across the paddock. To focus on the effect of spatial configuration on ES supply, circular SPUs are arranged in various configurations across the AFS paddock (Figure 1). The configurations are designed to test the effect of SPU size and spacing, with many mimicking well-studied spatial typologies of agroecological systems (Dixon, 2007; Nair, 1985; Wojtkowski, 2019). Four sizes of individual SPUs are used (0.1, 0.02, 0.01 and 0.0005 ha—named L, M, S and XS, respectively), with the total area of the SPUs being kept constant at 0.15 ha, or 15% of the 1 ha paddock, for all configurations. This corresponds to the middle to upper range of tree cover on typical farmland in New Zealand (Welsch et al., 2014). Composition of the woody vegetation within SPUs is not considered; it is assumed the species included provide the maximum level of each respective ES and that the community of trees within each SPU is at a climax stage of succession. As noted earlier, the pasture or cropping matrix within which the SPUs are arranged, and the soils beneath all SPUs and the interstitial matrix, contributes no ES to the calculation.

2.1.2 | The ESMAX model

ESMAX uses the distance-decay properties specific to regulating ES to visualise and quantify the overall performance of each individual regulating ES across the entire 1 ha AFS paddock (Figure 2).

An overview of how the woody vegetation SPUs influence ES production, including the basis for characterising ES field kernels and overlap response, is provided below.

- Cooling effect: Global warming has effects specific to agriculture, including reduced availability of water, reduced pasture/crop growth and thermal stress in livestock (Altieri et al., 2015; Pörtner et al., 2022). The cooling effect of tree clumps in a rural context has not been as widely studied as the established cooling phenomenon provided by green ‘cooling islands’ (such as parks and gardens) in urban areas (Blachowski & Hajnrych, 2021). The three variables by which vegetation regulates urban temperatures apply also to tree clumps in rural environments: by shading solar radiation, through the process of evapotranspiration and by altering air movement and heat exchange (Ryszkowski, 1995; Zardo et al., 2017). For example, cooling is provided by inducing vegetation breezes, where comparatively warm air over pasture rises, reducing local air pressure and drawing the cooler subcanopy air from within the tree clump into the pasture zone (Cochrane

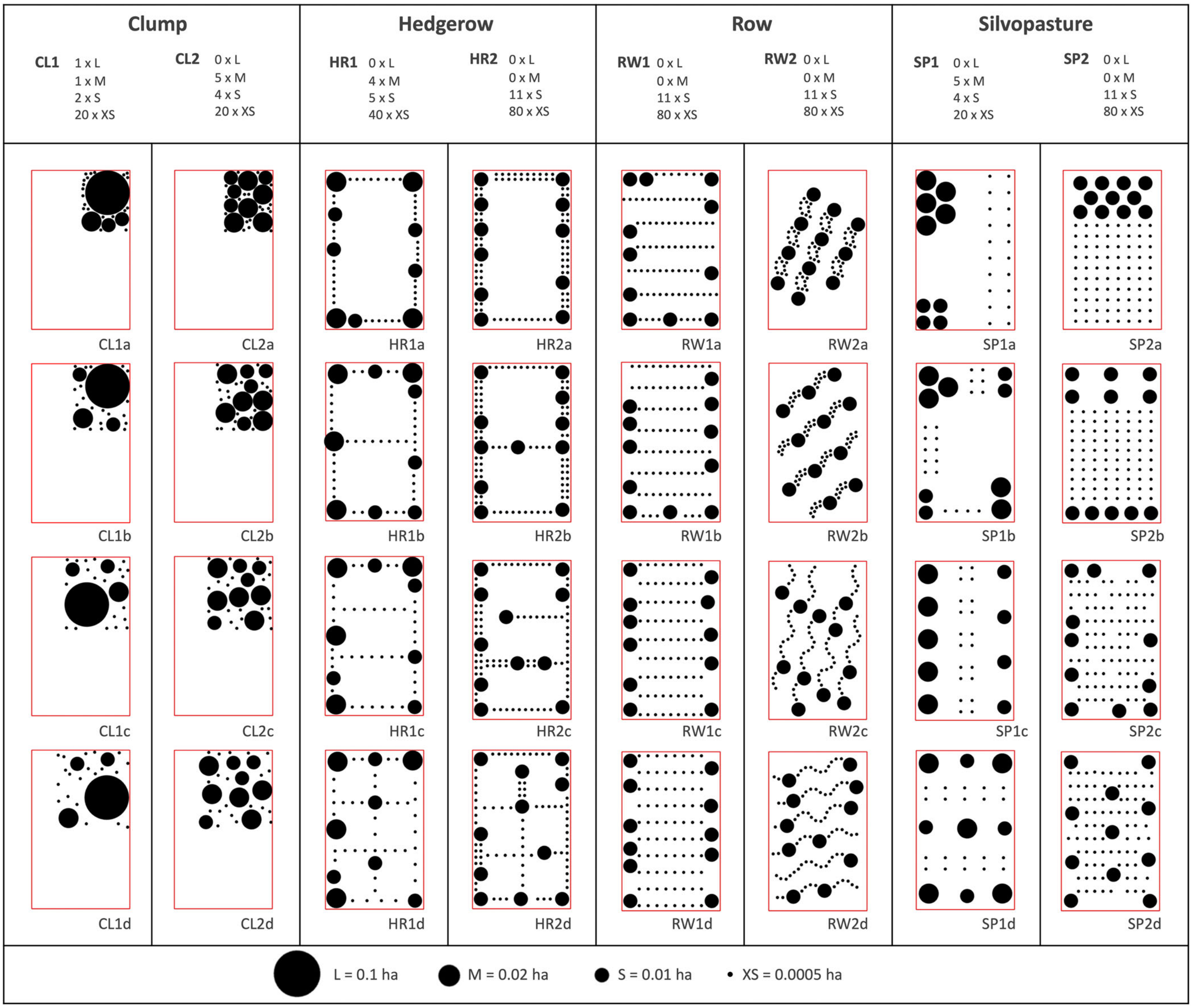


FIGURE 1 AFS paddock configurations. Four sizes of individual service providing units (SPUs) comprising circular clumps of woody vegetation are arranged in 32 configurations on the 1 ha AFS paddock (measuring 127 m × 78 m). The total area of woody vegetation in each configuration is kept constant at 0.15 ha, or 15% of the paddock area. The background matrix is assumed to be pasture or cropping and doesn't contribute to the calculation of ES by ESMAX. There are four broad groups of configurations, each group representing a different level of SPU dispersion. Within each level, eight different configurations are tested, based on the numbers of L-, M-, S- and XS-sized SPUs present in the paddock. Groups 1 and 2 represent clumpy arrangements, mimicking woodlots on-farm, remnants of larger forest or afforestation of non-productive areas. Groups 3 and 4 represent the enclosure of paddocks by hedgerows or shelterbelts, 3a and 4a mimicking the configurations of typical tall pine or macrocarpa shelterbelts surrounding paddocks in many parts of New Zealand. Groups 5–8 can be considered silvopasture configurations, with pasture and woody vegetation components more or less equally interspersed. The ribbons in Group 6 are based on concurrent research into multifunctional woody vegetation components in intensive pasture-based dairy operations. The densest arrangements of XS-sized SPUs are spaced to still allow for ploughing, sowing and harvesting (Wojtkowski, 2006). AFS, agroecological farm systems; ES, ecosystem services.

& Laurance, 2008; Laurance, 2008). Drawing from literature on micrometeorological phenomena occurring at forest edge settings, ESMAX employs clump size as a parameter for cooling intensity, proposing the cooling extent as equivalent to the diameter of the SPU (Eder et al., 2013; Huang et al., 2011). The negative exponential kernel form is used in the InVEST (Integrated Valuation of Ecosystem Services and Trade-offs) Urban Cooling model (Sharp et al., 2020) and is also supported by empirical measurement of cooling effect decay from parks in urban environments (Honjo & Takakura, 1990; Yin et al., 2022). Literature on urban cooling effect generally correlates cooling effect with the size of the parks and other urban green spaces (Blachowski & Hajnrych, 2021; Zardo et al., 2017), suggesting that green areas of all sizes, including individual trees, contribute

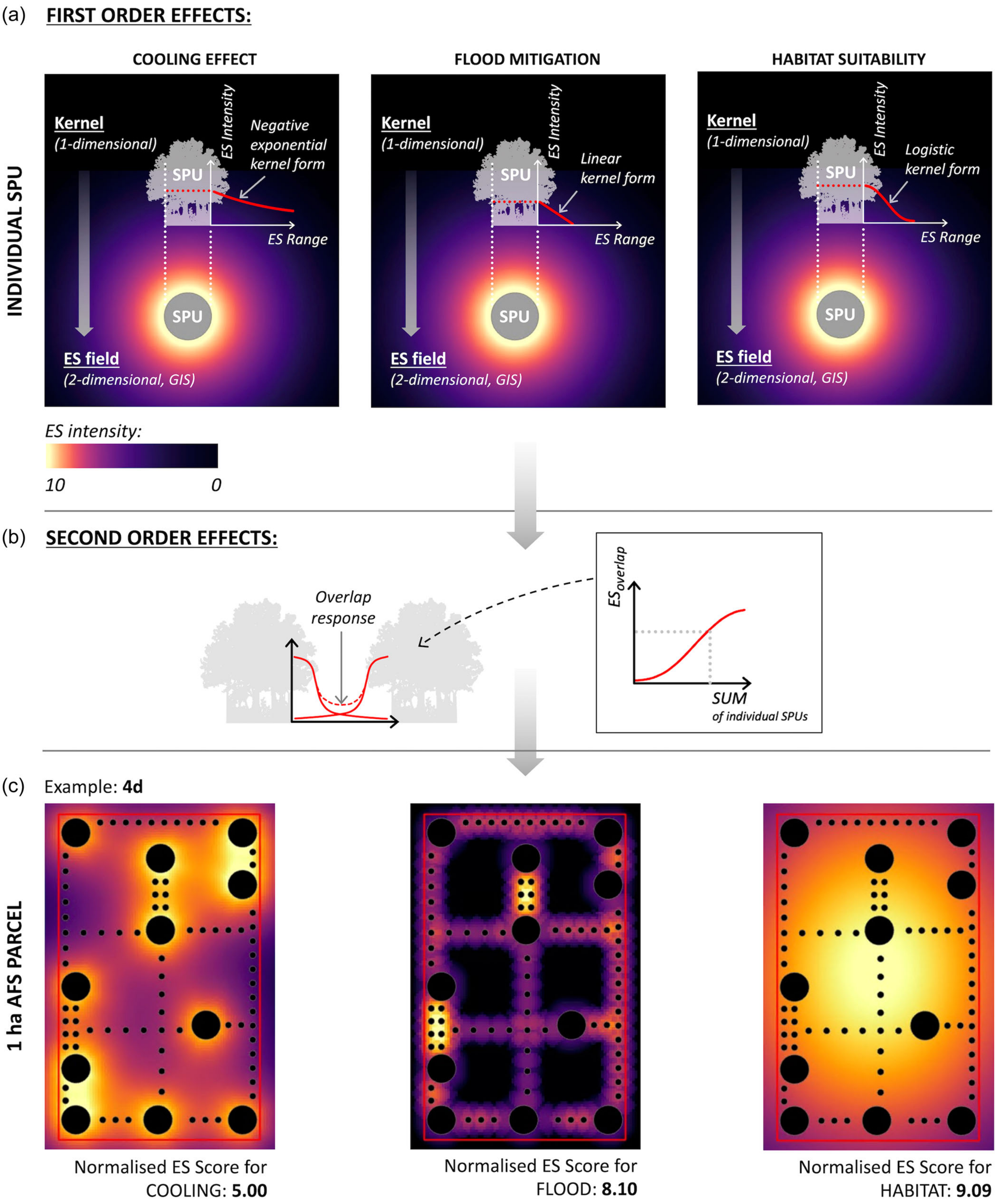


FIGURE 2 (See caption on next page).

to this cooling phenomenon (Martini et al., 2018). For the purposes of this work, we assume the second-order effect of overlapping fields to be additive (Morris et al., 2024).

- Flood mitigation: Among the secondary effects of agricultural intensification and simplification is increasing vulnerability to flooding, resulting from increased soil compaction, elimination of natural flood paths and reduction of ground surface texture (Rogger et al., 2017; Ryszkowski, 1995). Woody vegetation clumps provide protection against flooding by obstructing and storing above- and belowground water flow, as well as by promoting soil infiltration (Keesstra et al., 2018; Maes et al., 2009). For example, farming landscapes with shelterbelts can store 20–60 mm more water than an area of open and uniform cultivated fields (Ryszkowski, 1995). To predict ES performance in terms of flood mitigation, ESMAX focuses on obstructing belowground water flow and promoting soil infiltration and is therefore set up to model the spatial extent of root biomass provided by the woody vegetation SPUs in the AFS paddock. The ES field is estimated by reducing the root architecture to a linear approximation, with root biomass (including both coarse and fine roots) concentrated towards the trunk and the lateral extent of roots extending some distance beyond the perimeter of the SPU (Marden et al., 2018; Saint Cast et al., 2019). The ES field represents the spatial distribution of roots for the outermost trees only, extending beyond the edge of the SPU. For the purposes of this conceptual model, all trees are assumed to be the same height and therefore have same lateral root spread. Overlap response characteristics reflect how roots of SPUs interact, which differs depending on tree species. For the purposes of this work, we assume that where root zones of adjacent plants overlap, roots of adjacent plants interweave (i.e., root exclusion from one tree by another does not occur), and therefore the second-order effect is considered additive. Where the clumps are spaced more closely than the extent of the lateral root system, a proportion of root interweaving occurs beneath the SPU, which ESMAX recognises as saturated space. For flood mitigation modelling, the roots of all tree clumps, irrespective of size, extend beyond the above-ground extent of the SPU and, therefore, all sizes of SPU are included in flood mitigation calculations.
- Habitat suitability: The connection between biodiversity and the resilience of ES—regulating, cultural and provisioning—is well established (Hooper et al., 2005). The widespread loss of landscape spatial heterogeneity associated with agricultural intensification is often viewed as a key driver of biodiversity loss in rural landscapes (Butler et al., 2007; Haddaway et al., 2018). New Zealand's history of deforestation, agricultural intensification and importation of predators has had a ruinous impact on indigenous biodiversity (Meurk & Buxton, 1990; MFE, 2019; Norton, 2013). ESMAX is set up to model the habitat suitability for an indigenous bird species, the piwakawaka (fantail, *Rhipidura fugilinosa*), considered an indicator species of indigenous ecosystem resilience in Aotearoa New Zealand rural landscapes (Coleman, 2008; Powlesland, 2022). The ES field corresponding to habitat suitability is initialised using piwakawaka nesting habitat size requirements, feeding ranges and territorial characteristics. Kernel form is based on the triweight kernel used by Laca (2021), considered a reasonable representation of population distribution from a nesting site (Laca, 2021). Its single parameter λ is the reciprocal of the range. Conspecific attraction of external individuals for breeding is demonstrated even in highly territorial species such as piwakawaka (Valente et al., 2021), so the overlapping fields are considered additive. ESMAX is parametrised such as all sizes of SPUs provide fine-grained feeding 'stepping stones' for piwakawaka, as long as the distance to a neighbouring clump is no greater than this bird's maximum feeding range of 100 m (Coleman, 2008).

2.1.3 | Solution space

The output from ESMAX enables the examination of possible trade-offs and/or synergies (Bennett et al., 2009; Rodríguez et al., 2006) between different ES in space (and time). We use a radar graph to examine which configurations lead to which trade-offs/synergies, interpreting these characteristics as a multidimensional 'solution space'. The solution space is comprised of numerous 'solution polygons', the number of polygon sides determined by the number of ES being compared (hence the solution polygon is triangular in this work). The vertices of the solution

FIGURE 2 The ESMAX model. ESMAX determines the individual ES (cooling effect, flood mitigation or habitat suitability) intensity provided by a given 1 ha AFS paddock configuration. (a) The outer edge of the outermost trees in the clump defines the SPU perimeter. ES performance is assumed to be constant and at a maximum value inside SPUs, with distance decay commencing at the perimeter of the SPU, in an outwards direction only. Note that the ES intensity colour scheme applies only to areas outside the SPU. Based on literature review, a characteristic 'kernel' is assigned for each type of ES, representing the distance-decay of ES intensity from the SPU. Developed using a GIS platform, ESMAX uses this kernel to calculate an 'ES field' radiating from each SPU, also termed the first-order effect of the SPU (top panels). (b) How these ES fields respond where they overlap is germane to the influence of spatial configuration on ES supply. The overlap response used in this research is assumed to be a logistic function (conceptually illustrated in the box). As further research into the characteristics of ES fields emerges, the model can be updated with ES-specific equations. The results of these interactions between SPUs are termed second-order effects. (c) ESMAX sums the total value of all points (or pixels, in GIS terminology) within the AFS paddock's boundary; this value is then normalised to provide an 'ES Score' for each arrangement (configuration 4d is shown for illustrative purposes). Normalisation is carried out by subtracting the lowest ES total of all the configurations, then dividing this by the overall range of values. Detailed explanation of the development and testing of ESMAX development of ES fields for these ES are provided in Morris et al. (2024). AFS, agroecological farm systems; ES, ecosystem services.

polygon are located on axes representing the ES Scores for each of the three individual ES. This solution space therefore provides a graphic depiction of:

1. The range of possible spatial solutions from which configurations can be selected to supply specifically required levels of each ES (Groot & Rossing, 2011). This approach avoids premature commitment to suboptimal solutions that undermine opportunities for multifunctionality (Rossing et al., 2007; Wiek & Binder, 2005).
2. The multifunctional performance of each configuration. The area of each solution polygon indicates the total quantity of ES provided across the three ES.

3 | RESULTS AND ILLUSTRATION

Summarised below are the ESMAX results in terms of individual ES and multifunctional performance. The simulations result in a range of ES Scores across the AFS paddock configurations for individual ES. Closely clumped arrangements, especially those containing L-size SPUs, produce the greatest cooling effect. Smaller SPUs (S-size and XS-size), at specific spacings depending on the ES, provide best habitat suitability and flood mitigation. Evenly dispersed configurations, with a heterogenous assortment of SPU sizes, provide the best multifunctional landscape configurations. These results are set out in further detail below.

3.1 | Individual ES performance

Cooling effect: there is a very small spread between the highest and lowest raw ES values (2.6%), indicating cooling effect is provided equally by all arrangements (Figure 3a). ESMAX results suggest that cooling effect is strongest in configurations that comprise L SPUs, with the four arrangements (configurations 1a–d) featuring the largest 0.1 ha woody vegetation clumps occupying the top rankings (1b ranks highest). The lowest performing cooling configurations comprise the smallest S and XS SPUs in dispersed arrangements exhibiting the largest expanses of interstitial clear pasture (configuration 4b ranking lowest).

Flood mitigation: The spread of ESMAX results for flood mitigation is larger than cooling, with a 60.0% difference between the highest and lowest pre-normalised values (Figure 3b). The best performing configurations feature the largest numbers of XS SPUs arranged in double rows (configuration 4a performing best). The lowest performing flood mitigating configurations comprise three of the four configurations featuring the largest 0.1 ha woody vegetation clumps, the most dispersed arrangement 1d providing the least mitigation. There is a distinct decrease in mitigation (35.7%) between configurations comprising only S and XS SPUs and those including M and L SPUs, coinciding with a change in total SPU perimeter length from 1025 to 708 m.

3.2 | Habitat suitability

As the 1 ha research site measures 127 m × 78 m, all SPUs located within these extents fall within the piwakawaka's feeding range of 100 m. As there is no lower limit on the size of SPU in which piwakawaka will breed, this means all SPUs qualify as suitable habitat. The spread of habitat suitability results (58.2%) resembles that of flood mitigation (Figure 3c). As with flood mitigation, configuration 4a is the highest ranking arrangement. The lowest performing habitat suitability configurations comprise three configurations (1a–c) featuring the largest 0.1 ha woody vegetation clumps.

3.2.1 | Multifunctional performance

For the three regulating ES, ESMAX suggests that the best multifunctionality is provided by arrangements of S and XS SPUs, evenly dispersed across the AFS paddock. Configuration 5a returns the solution polygon with the greatest area, and therefore highest average ES Score across all three ES (please see Figure 4).

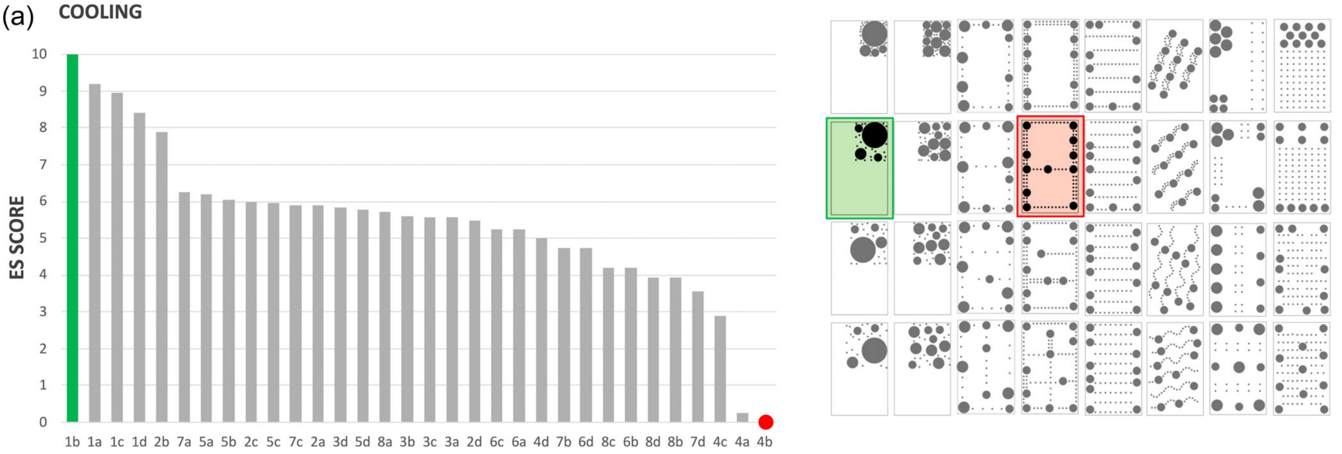
4 | DISCUSSION

The results from ESMAX suggest that a 1 ha AFS paddock with 15% woody vegetation cover delivers markedly different levels of ES performance depending on how the woody vegetation is subdivided and arranged. The solution space allows selection of AFS configurations to match regulating ES supply to local ES demand and to address spatial constraints specific to a particular landscape. This supports the main question of our research, that the configuration of in-paddock SPUs directly influences the multifunctionality of AFS paddocks. We discuss these results and their implications in two parts: (1) what spatial agroecology reveals about the physical implementation and appearance of agricultural multifunctionality at paddock scale and (2) how spatial agroecology can be developed to further support the transition from conventional agriculture to multifunctionality.

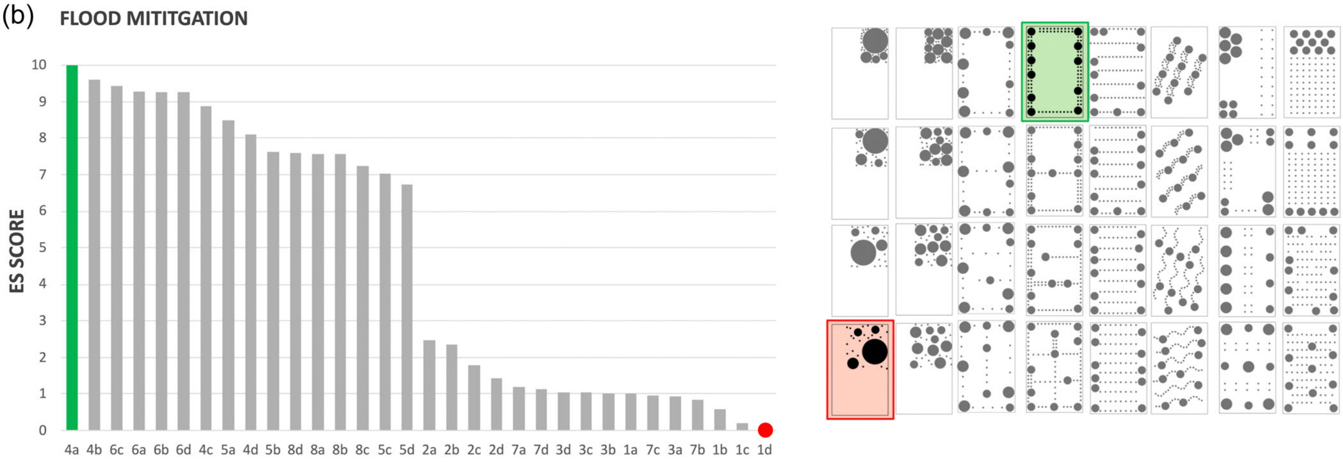
4.1 | Spatial agroecology: visualising a new role for agriculture

Deliberately controlling the provision of multiple regulating ES through the spatial design of agroecological systems is a novel consideration at any scale (Rieb & Bennett, 2020; Wu, 2021). The methodology applied at paddock scale in this research demonstrates the utility of spatial agroecology in (1) assisting the practical design and implementation of multifunctional agriculture and (2) visualising what multifunctional solutions will look like. By focussing on the manageable scale of paddock level interventions, this work affords farmers an entry point to providing multiple regulating ES. This supports the context-specific targeting of individual ES supply, both

(a) COOLING



(b) FLOOD MITITGATION



(c) HABITAT SUITABILITY

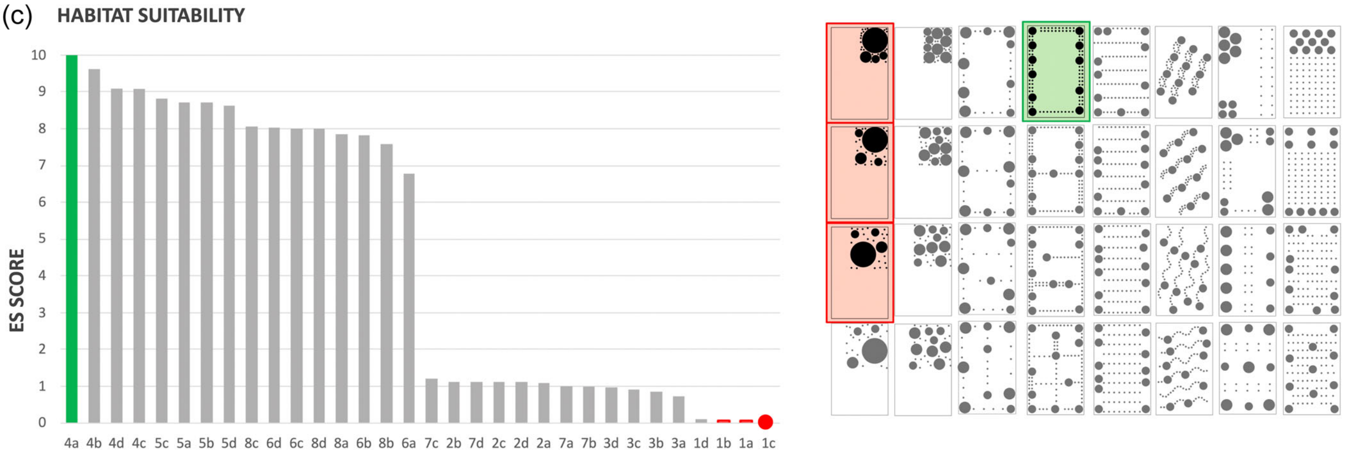


FIGURE 3 Individual ES performance. The histograms on the left show the performance of each configuration for each ES; (a) Cooling effect, (b) flood mitigation, and (c) habitat suitability. The best and worst performing configurations are shown on the right (the configurations are shown in the same order as Figure 1, with labels removed for clarity). The best performing configuration is filled-in green, corresponding to the green bar of the histograms. The worst performing configuration is filled-in red, corresponding to the red dot on the histograms. In the case of habitat suitability, three configurations rank equally as the lowest performers. ES, ecosystem services.

for the landowner and for adjacent areas. For example, cooling islands can be designed to provide refuge for livestock when daily temperatures are high and may also be positioned so that their ES fields infiltrate neighbouring residential areas. Similarly, deployment of flood mitigating spatial configurations can address specific flood-prone or flood path areas both on farm as well as contributing to larger catchment-based strategies. In the same vein, configurations informed by specific habitat spatial requirements may be aligned with larger scale local or regional ecological corridors and biodiversity enhancement strategies.

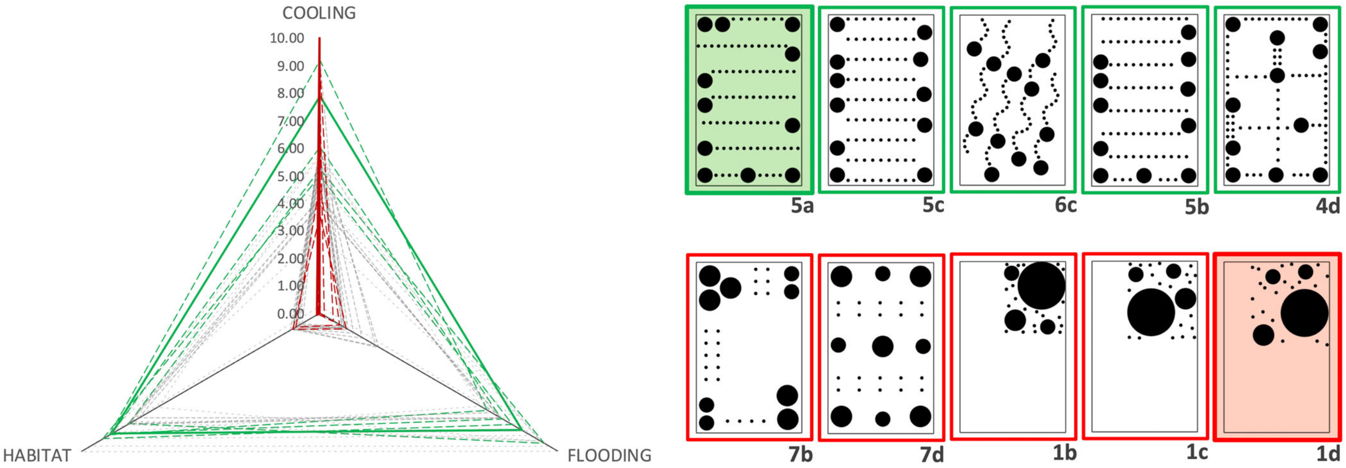


FIGURE 4 Multifunctional solution space. The radar charts on the left show the solution polygons for all configurations. The best and worst performing configurations are shown on the right, ordered according to the total multiple ES supplied based on an area calculation of the solution polygon. ES, ecosystem services.

For example, in terms of individual ES, the range of ESMAX results for flood mitigation show a 60% difference between the highest and lowest ES Scores. This suggests that changes in configuration have a significant influence on this ES. The predominance of configurations featuring large numbers of XS clumps arranged in double rows (Figure 3b) reflects flood mitigation being related to amount of lateral root biomass. Therefore, the greater the total SPU perimeter, the greater the root biomass. With piwakawaka habitat, there is a similar preference for greater total SPU perimeter—that is, as many smaller sized clumps as possible, as long as they fall within the 100 m feeding range. This reflects this species' propensity for forest edge habitat (Berry, 2001). What is noticeable in comparing flooding mitigation to piwakawaka habitat is that flood protection is more sensitive to the spacing between clumps, owing to the shorter ES field range (7 m) compared to the 100 m range of the habitat ES field. With cooling effect, the effect of configuration is predictable—size matters. The largest clumps provide the greatest cooling effect, as ESMAX bases both cooling intensity and ES field range on clump size. The largest clumps (0.1 ha) clearly provide the best cooling performance, whereas there is relatively little difference between paddocks featuring the next largest sized 0.02 and 0.01 ha clumps. This may seem contrary to experienced effect, such as the cooling effect inside an orchard. In this case, the shading effect alone likely imparts cooling; however, ESMAX calculates cooling capacity based on extensive research into the urban cooling phenomenon, in which analysis of different green urban typologies shows that the most important consideration is component size, followed by tree canopy coverage and soil cover (Zardo et al., 2017). Our suppositions when basing rural cooling effect on urban cooling phenomena recognise limitations arising from the obvious differences in context. The reason for the emphasis on size for urban cooling islands is possibly due to the stronger contrast of those green areas with their urban, relatively homogenous context, and the presumably non-cooling (and likely heating) properties of that context. Therefore we need to exercise caution transferring this cooling phenomena directly to rural contexts, where the landscape context is heterogenous, with some non-wooded areas displaying heating and others cooling properties, depending on soil type, bare ground cover and vegetation. Our work emphasises the relevance and importance of conducting further research in rural contexts to better characterise the cooling effect of trees growing in such heterogenous non-woody vegetated environs.

What ESMAX provides, and in doing so conceptually develops the research field of spatial agroecology, is the provision of explicit sizing of SPUs and the spacing between them to achieve a specific multifunctionality. Being able to physically map these configurations provides two important benefits for farmers (and a basis for future development of spatial agroecology). First, precise quantities of tree clumps enable precise estimation of costs associated with implementation and reduces valuable resources apportioned to potentially valueless planting. To further assist this, future development of ESMAX should incorporate the composition of agroecological species as well as their configuration, identifying per-species contribution to the ES being targeted. Referring to Figure 2, this would involve further refinement of the first-order effects/kernels specific to individual species, achieved by literature review and expert opinion—the same way the generic kernels were developed for individual ES in this initial development of ESMAX (Morris et al., 2024). Second, the precise establishment of distances between SPUs to produce a specific ES effect enables integration of these interventions with the practical operational requirements of residual pasture/crop spaces. This mainly relates to the offset distances between SPUs, which is critical to the degree of overlap of ES fields and therefore seminal to overall ES performance. These offsets will need to be managed against practical operational dimensions—such as practical subdivisions of the 1 ha paddock for rotational grazing and access/manoeuvring requirements for agricultural machinery. Fine tuning the paddock layout to accommodate these operational requirements, then retesting the ES performance of revised configuration with ESMAX, exemplifies an iterative systems-based process, as well as the integration of system functions (operational, ecological, economic etc.), management and learning, espoused by an adaptive management approach (Hodbod et al., 2016). This supports the applicability of ESMAX and the solution space as part of a spatial agroecology methodology, suited to assisting these agroecological transitions. Furthermore, the results of exploring the solution space offer an initial glimpse into what designed multifunctional AFS paddocks might look like. For this specific suite of three regulating ES and, noting the imposition of a constant 15% tree cover for the purposes of this work, ESMAX suggests that the best multifunctionality is provided by a heterogenous arrangement of S and XS SPUs, evenly dispersed across the AFS paddock. The result, in this particular case, reflects the widespread occurrence of spatial heterogeneity within ecosystems and the fundamental idea that it both mirrors and influences ecosystem functions (Laca, 1999; Pickett & Cadenasso, 1995). We recognise that for another specified multifunctionality, comprised of combinations of different ES, that these results will be different (assuming that the first- and second-order effects of these ES are also different). Nevertheless, our results make plain the need for reconsideration of on-farm tree distribution, should multifunctional ES supply become a core driver of agroecological systems (Boeraeve et al., 2020; Power, 2010). This implies a radical aesthetic shift—at least for most industrial, monocultural agriculture contexts. As stakeholders increasingly recognise farming's responsibility to provide multiple regulating ES for areas beyond the farm boundary, the present-day default to trees located at the perimeter of the paddock or field of crops will need to be reconsidered. Multifunctional agriculture, based on a spatial agroecology approach, anticipates exacting designs comprising various tree species, of heterogeneous clump size, distributed across the paddock according to science-based criteria.

4.2 | Future development of spatial agroecology to support the transition from conventional agriculture to multifunctionality

Spatial agroecology brings with it a notion of clarity—it enables a categorical visualisation of agricultural multifunctionality, and it enables the ideation and implementation of operationally and ecologically functional AFS paddocks. It can also support the transition from modern industrial agriculture to multifunctionality in more nuanced ways. First, the solution space's ability to identify next-best solutions enables multifunctionality adapted to context-specific spatial constraints. Second, future development of ESMAX could support the spatially explicit design of synergetic tree/crop systems. Third, by visualising and quantifying specific ES, ESMAX provides a valuable tool for the development and implementation of schemes remunerating farmers for the production of specific ES.

Arguably, the greatest value of the solution space is not the identification of the best performing multifunctional configurations, but the presentation of a set of alternative next-best solutions that reveal synergies or trade-offs among the objectives (Groot & Rossing, 2011; Rossing et al., 2007). Rarely, if ever, will designers be engaged to design spatial interventions into a landscape with the tabula rasa, isotropic qualities demonstrated in this introductory work. The ability of the solution space to identify next-best alternatives presents opportunities to enhance multifunctionality even when presented with intractable spatial and operational constraints. For example, there may be no possibility of planting 80 specifically located XS tree clumps or integrating them with an existing system resembling this. However, the incorporation of another option with 20 XS SPUs into existing farming operations is feasible, accepting the trade-off in terms of ES performance. Another example is an established carbon-sequestering woodlot resembling a 1000 m^2 L-sized SPU. The solution space can then be used to identify configurations featuring L-sized SPUs that match the local ES demand. Even if configurations don't exactly match the precise woodlot dimensions, a starting point is provided for an iterative design process.

The supply of ES explored in this work so far only accounts for the woody vegetation components of the AFS paddock. In reality, agroecological systems are built on synergies between trees, interstitial crop/pasture components, soil types and the community of organisms they host, as well as various operational practices, which function as integrated systems in time and space (Altieri & Nicholls, 2012; Gliessman, 2007; Martin et al., 2019). Essentially it is the configuration of the entire AFS paddock, comprised of SPUs, interstitial spaces, the soils that sustain them and how these natural components are managed, that influences the production of regulating ES (Kremen et al., 2007; Tscharntke et al., 2005). For example, the delivery of ES by tree clumps is impacted by activities in the interstitial field areas, such as the use of agrichemicals that can negatively impact on soil organisms upon which tree growth depends (Edlinger et al., 2022). Some agrichemicals are known poisons to nontarget organisms such as birds and might consequently negatively impact on the habitat suitability of tree clumps for native bird species (Brzozowski & Mazourek, 2018; Power, 2010). Conversely, by reducing the use of pesticides, insect abundance increases, leading to a proliferation of insectivorous fauna, such as piwakawaka (Brzozowski & Mazourek, 2018). As a forest-edge dwelling species, the reduction in synthetic biocides applied to adjacent open spaces also benefits piwakawaka health generally, including reproduction rates (Fry, 1995). Reciprocally, the health of the piwakawaka population, as well as other beneficial predators, establishes an environment that handicaps an establishment of overwhelming pest populations (Altieri, 2004). Hence, agricultural landscapes with a high proportion of woody vegetation favour biological pest control by natural enemies (Salliou et al., 2019). In this way, the integration of tree and crop components represents a synergy between two regulating ES—the provision of suitable habitat and the provision of natural biological control services (Bennett et al., 2009). In its initial development, the visualisation of first-order ES fields from the tree components using ESMAX could indicate how configurational changes might influence the efficacy of these synergies. For example, SPU arrangements that do not provide adequate habitat could impact the pest management capacity of the overall system. This could be compensated for by adjusting crop/pasture mixes to include specific companion species to support appropriate predator species. Future development of ESMAX should allow testing of configurations and composition of SPUs; this includes SPUs comprised of pasture or crops, with properties also reflecting the soil status underneath them. Referring to Figure 2, incorporating the tree/crop/soil interactions that are central to agroecological systems could be facilitated with further parameterisation of the second-order effects. Using the ES examined in this work, these second-order effect parameters would reflect the root interactions and combined surface texture of two species, and how these influence flood mitigation, provide mutualistic (or antagonistic) feeding and nesting habitat or effect the vegetative breezes induced by different evapotranspiration, albedo and shading characteristics (Arroyo-Rodríguez et al., 2020; Ryszkowski et al., 1996).

Spatial agroecology paradoxically suggests that solving food problems may mean relegating food production to a cobeneficiary or by-product status, while the production of multiple ES to regenerate and protect productive ecosystems assume equal or even greater priority (Hodbod et al., 2016). Inevitably, this transition to multifunctional agricultural systems will require that society appropriately rewards farmers and other agriculturalists to produce both provisioning and regulating ES (Hill, 1998; Tilman et al., 2002). Methodologies that enable clear visualisation and quantification of the ES being supplied at both single farm scale and when aggregated at multifarm/catchment/regional scales will be essential to developing these discussions (Dominati et al., 2019). Further, such applications will be invaluable for educating farmers and other stakeholders of the ES generating potential of AFS, in both their extant condition and as a result of scientifically-designed spatial interventions (Bagstad et al., 2013; Burkhard et al., 2014). The development of the spatial agroecology method presented in this work, combining the explicit information provided by ESMAX and the capacity for adaptive management provided by the solution space, makes a potentially significant contribution to this process.

5 | CONCLUSION

As pressure mounts on ES and the spaces that produce them, agriculture in the Anthropocene may come to be seen as the preeminent means to effectively procure, maintain and deliver critical regulating ES. Regulating ES represent the health of underlying ecosystem function; dependent on this health are cultural ES and provisioning ES (i.e., the production of food). This work has presented ESMAX, a conceptual model which allows clear visualisation and quantification of regulating ES generated by agroecological components and identifies how ES performance changes depending on how these components are configured at paddock scale. Translating the results of ESMAX to a trade-off/synergy matrix (or 'solution space') enables assessment of multiple solutions and iterative tailoring to meet spatial and operational constraints of that paddock. This spatial agroecological method is suited to support an adaptative management approach to transitioning industrialised, monocultural farm systems to multifunctional ES-providing agrosystems. While this work has focussed on paddock level manipulations, the approach is presently being adapted for the modular application of spatial agroecology at a larger farm and regional scales. This potentially expands the spatial window of spatial agroecology design focus from paddock scale to the landscape scales that are relevant to critical Anthropocene land management and spatial planning decision-making.

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The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

All data is available upon request.

ORCID

Richard Morris https://orcid.org/0000-0003-0208-8440

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