A scientific approach to researching and promoting sustainable agro-ecosystems

By Conor Kendrew

Introduction by Martin Crawford

This article by Conor Kendrew summarises his research and results from work done on two of our sites (and a third on the Dartington Estate in Devon) in 2018. We expected him to find improvements in soil quality, carbon storage etc. in our 24-year-old forest garden but the extent of these improvements is truly impressive. Amongst other findings, the soil carbon has accumulated at a faster rate than almost any other temperate climate measurements.

The prerequisite to conducting this research

A large proportion of the audience reading this report are aware of the relatively short lifespan agrochemical and fossil fuel supported agriculture provides to society. The aim of this study was not to contribute to the set of literature outlining the damages of modern agricultural models. Instead we aimed to set up a method for tackling and finding a solution to the embedded issues that agriculture has expressed since its origins some 13,000 years ago.

The Sumerians, Maya, Rapa-Nui, Neolithic Europeans and to a lesser extent Roman Empire are all examples of civilisations which experienced collapse due to their miss-management of environmental resources. These damages were done without the aid of mechanised chemistry or fossil fuels as an energy source. Instead agricultures collapsed due to a lack of understanding in the ecological considerations required to upkeep some level of environmental stability over large tracts of managed land. It is not unreasonable to suggest that today's common agricultural methods disregard the basic rules of a viable ecosystem just as readily as those of previous civilisations, regardless of whether the process is done organically or not. I summarised this issue as *The farmer's problem*:

Any process involving the removal and suppression of ecosystem development, for replacement by a system managed to perform a comparatively narrow set of functions i.e. production of one crop, will inevitably feature less of the stabilising and re-enforcing features which secured the prosperity of the original ecosystem; increasing the potential for environmental overshoot

This issue is rarely discussed on a societal level; however, a few committed research scientists, theorists, applied scientists and farmers have been developing solutions and worldviews to tackle the task of designing and maintaining sustainable agro-ecosystems. My project aims to contribute to their work in analysing examples of such systems in a way that demonstrates ecosystem health.

Experimental design

Figure 1 depicts the ecological engineering research framework adopted in this study, this approach can be used broadly across climates and cultures to strengthen the evidence base of agro-ecological design (e.g. permaculture design, forest gardening, natural farming, biointensive agriculture and long-lasting indigenous techniques).

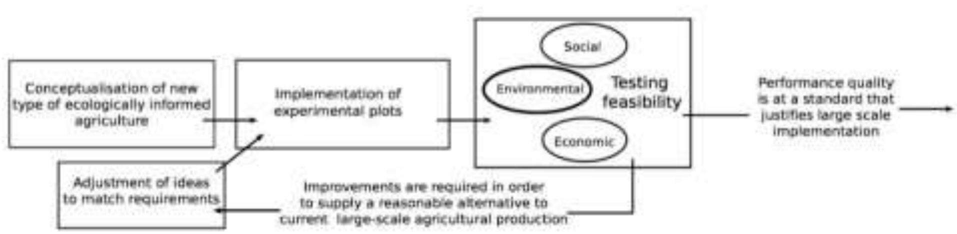


Figure 1: A general method for improving the impact and effectiveness of ecological principles applied in agriculture. Note that my analyses only tests the environmental performance of the implemented systems selected in this study, social and economic contexts are essential before techniques are deemed suitable for large scale implementation.

For the conceptualisation stage (background research) I drew from both the formal scientific publications and independent thinking that have formulated today's array of ecological design principles for agriculture. Reading starts as far back as Smith's 1929 *Tree-crops: A permanent agriculture.* From the formal scientific realm, I found particular use from reading the Odum brothers' publications; both E*nvironment Power and Society* 1971, and *The strategy of ecosystem development* 1969. Bergen, Bolton and Fridley's *design principles for ecological engineering* 2001 along with Kevan and Thomas' *Basic principles of agroecology and sustainable agriculture* 1993 offered excellent and concise demonstrations of sustainable best practice in agriculture .Some of the independent publications studied are Edward Goldsmith and Robert Allen's *A Blueprint For Survival* 1972, Fukuoka's *The One Straw Revolution* 1978, Mollison and Holmgren's *Permaculture One* 1978, Mollison's *Permaculture: A Designers Manual* 1988, Robert Hart's *Forest Gardening: Rediscovering Nature and Community in a Post-Industrial Age* 1991 and Martin Crawford's *Creating a Forest Garden: Working with Nature to Grow Edible Crops* 2010.

The result of reading these publications and many more was the statement of eight key ecological principles for conducting sustainable terrestrial agriculture; this is given in Table 1 and will most likely be second nature to the reader.

The three sites used for analysis were The Agroforestry Research Trust's Forest Garden Project (in development since 1994-5), Chestnut-Walnut-Hazel orchard (in development since 1995) and a local chemical free, mixed variety, but cultivated (mole board ploughed) wheat field. I predicted the environmental quality to increase from the wheat field to the nut orchard, and from the nut orchard to the forest garden, due to the obvious changes in ecological considerations (Table 1).

Principle	Explanation	Examples
1.Maximum power principle	The tendency for healthy ecosystems to maximise energy intake and reinforce future productivity is an essential quality for achieving sustainability. Agro-ecosystems should be either getting better or remaining productive. (4th thermodynamic law)	• High density planting • Niche maximisation • Selection of productive/ low maintenance varieties • Reluctance to export biomass
2.Species and genetic diversity	Ecosystems are composed of few common species and many rare species, they exhibit species diversity patterns that ensure temporal and spatial niches are realised, within a species there also exists considerable genetic diversity. Agro-ecosystems however have largely ignored the importance of diversity.	• Crop rotation • Intercropping • Multiple varieties • No use of general biocides

Principle	Explanation	Examples
4.Functional diversity	A late 20th century development from ecosystem stability-diversity discussions was that functional traits and combinations in ecosystems play a larger role than simply the number of species. Theoretically a stable agro-ecosystem could be created with relatively few species.	• Plants with nitrogen fixing root associates • Pest deterrent/predato r attracting plants
5.Succession	The development of ecological communities towards a state of greater stability and resource utilisation: often involving a 'climax community' and K type species. Early successional agro-ecosystems require energy to prevent this process. Linked with principle 1.	• Forest gardening, some orchards • Aquaculture • Semi-wild agriculture e.g. beekeeping
6.Soil health	The increases in soil organic carbon, nutrient balances and microbial biomass are key indicators of stability and health in ecosystems. Agriculture has often benefited from but degraded these soil properties. Linked with principles 1 & 6.	• Zero-till cropping • Perennial cropping • Mulching with crop residues
7.Energy throughput	The net energy yield from natural (autotrophic) ecosystems is high because only 'natural' energies are imported. Agro-ecosystems must aim for a high net energy production by minimising continual work requirements, this aids in minimising negative energy outputs (pollutants).	• Avoidance of annual machinery needs • Implementing renewable energy e.g. gravity irrigation • Work with succession (5.)

Principle	Explanation	Examples
8.Cycling & conserving	Developed ecosystems involve pathways for the cycling and conserving of nutrients and water through the system, preventing leaching of resources away from where they can be utilised. If agro-ecosystems are capable of cycling resources, required inputs will be minimised. A key component of principle 1.	• Bound residues in soil organics • Nutrients 'held' in vegetation • Water holding capacity • Aggregate stability

A testing approach had two requirements; first it needed to demonstrate the direct implementation of ecological principles and second it needed to quantify an indirect environmental component indicative of an ecosystem scale response. Figure 2 is a schematic demonstrating these research components and how they interact.

Basic community description of the vegetation was a logical element to study as a directly controlled factor; several analysis techniques including species distribution, diversity and functional diversity can quickly determine the levels of complexity and ecosystem structure. These datasets were collected over four months (March-June) using a 1.5m quadrat in a stratified-random sampling design. At each quadrat location I also took a 15cm deep by 8cm diameter soil sample for analysis in the laboratory; microbial biomass, organic matter (including organic carbon), bioavailable nitrogen and phosphate and aggregate stability (against rainfall) were all recorded for each soil sample. Soil analysis across its biological, chemical and physical properties was chosen for the tendency of soils to reflect and react to management changes over mixed timeframes (microbial biomass can change weekly, whereas carbon content will change notably over numbers of years).

The data collection was an eye-opening experience and an invaluable opportunity to work in agroecosystems which are unfortunately rare in our part of the world.

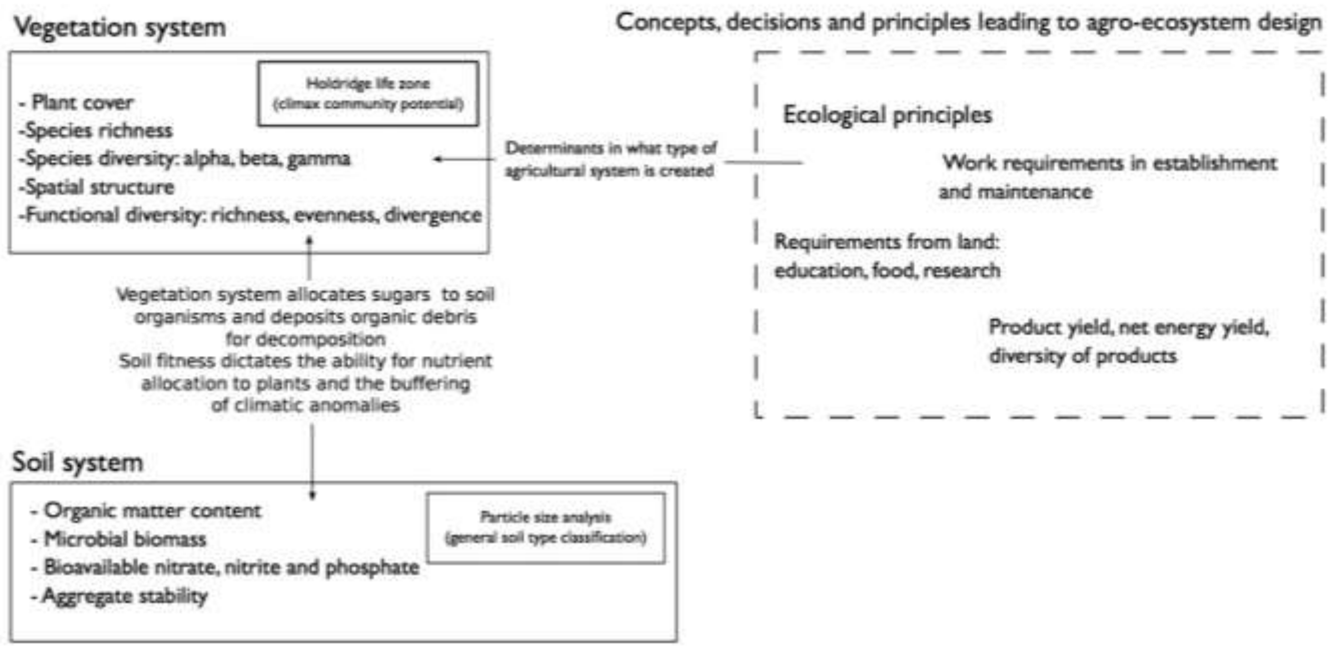


Figure 2: The dashed box represents the main tangibles that constitute how agro-ecosystems relate to ecological principles; these factors were considered in site selection. The solid squares are the two data-fields selected for analysis and the variables selected to represent them, selection of data-fields and variables has been done with consideration of their connections and individual importance for agro-ecosystems. Inner boxes represent site-specific considerations, which are made in order to enhance the context of the study.




Results and implications for agroforestry, society and ecological design

Vegetation analysis

Despite the obvious visual differences across the sites, the statistical results for the vegetation analysis are complicated.

Species diversity (not to be confused with species richness) accounts for both the number and relative abundance of species in a community; it was obviously much higher in both the forest garden and nut orchard than in the wheat field. On a whole site basis, the forest garden expressed a much higher species diversity than the nut orchard, but when looking at individual quadrats, the nut orchard and forest garden were quite similar (nut orchard slightly higher). Above anything else, this demonstrates the spreading and competitive nature of the species selected in the forest garden opposed to the patchwork structure of the nut orchard grasses and herbs. While the wheat field stands out as a system purposefully selected to minimise diversity.

Functional diversity works in much the same way, but we use functional traits rather than species as the unit of measurement, this is a more appropriate way of indicating ecosystem function and particularly resilience, it is also a consideration that many ecological designers make when selecting species for use. The result for functional diversity was an exaggeration of the trends found in species diversity. The forest garden had more than twice the functional plant groups than the nut orchard, while the nut orchard had almost double the functional groups than the wheat field. This is a profound result because it demonstrates a clear consideration of the previously stated farmer's problem, ecological design in this case had tried to account for as many functions as is required to create a sustainable system.

The best (and most intuitive) visual demonstration of the continuum between sites came from plotting rank-abundance graphs and fitting ecosystem structure models to them (figure 3). If you take all the records (in this case coverage) of all the species in a community and plot them from the most abundant to least abundant species the result is a curve shape, such shapes are comparable between all ecosystems and generally express the states of health and development in these ecosystems. It could be stated that figure 3 shows the degrees of ecological suitability that the three vegetation communities have.

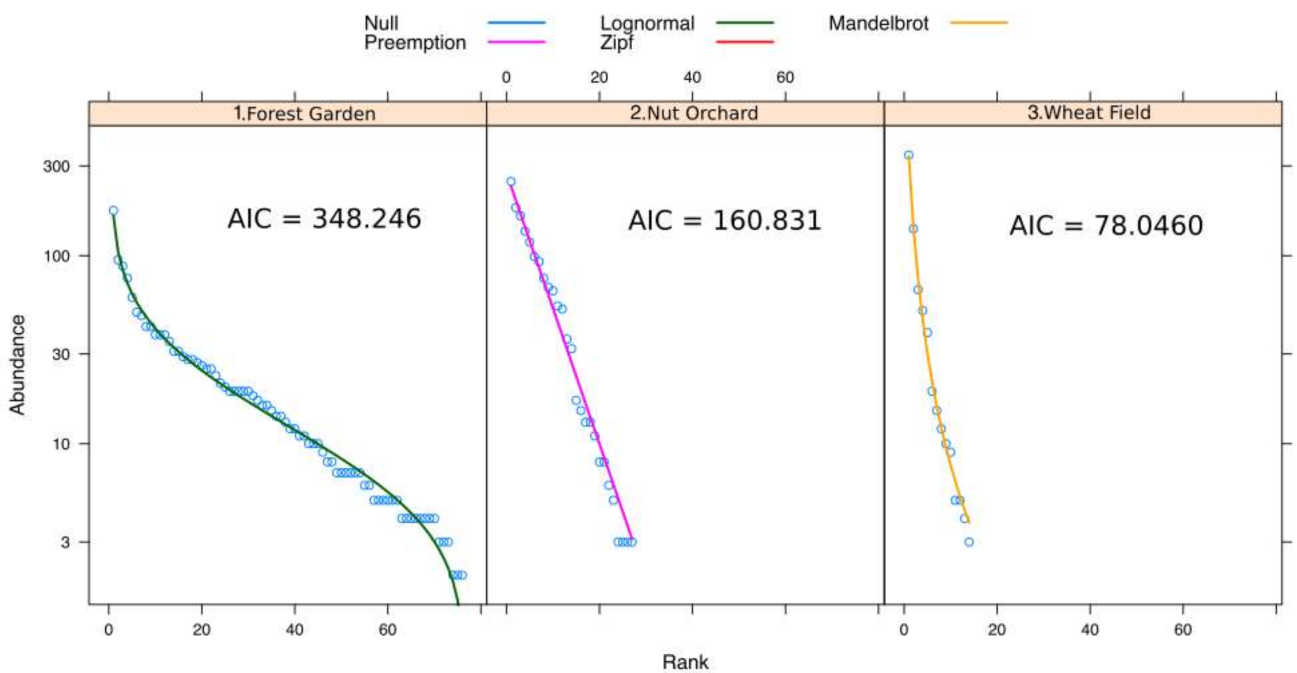


Figure 3: The Rank abundance graphs are visually different, but by fitting them to their best generalised model match we are able to make comparisons between these systems and the global research database which has also used the models. The forest garden fitted the famous lognormal distribution, typical of communities like established tropical rainforests and coral reef fish communities. While both the nut orchard and wheat field fitted the constrained community models Preemption and Mandelbrot, these are typical of communities where management has been performed to favour a few select species, or in unmanaged communities dominated by successful colonisers (think gorse communities in New Zealand). The Mandelbrot is the more severely constrained of the two models.

Soil analysis

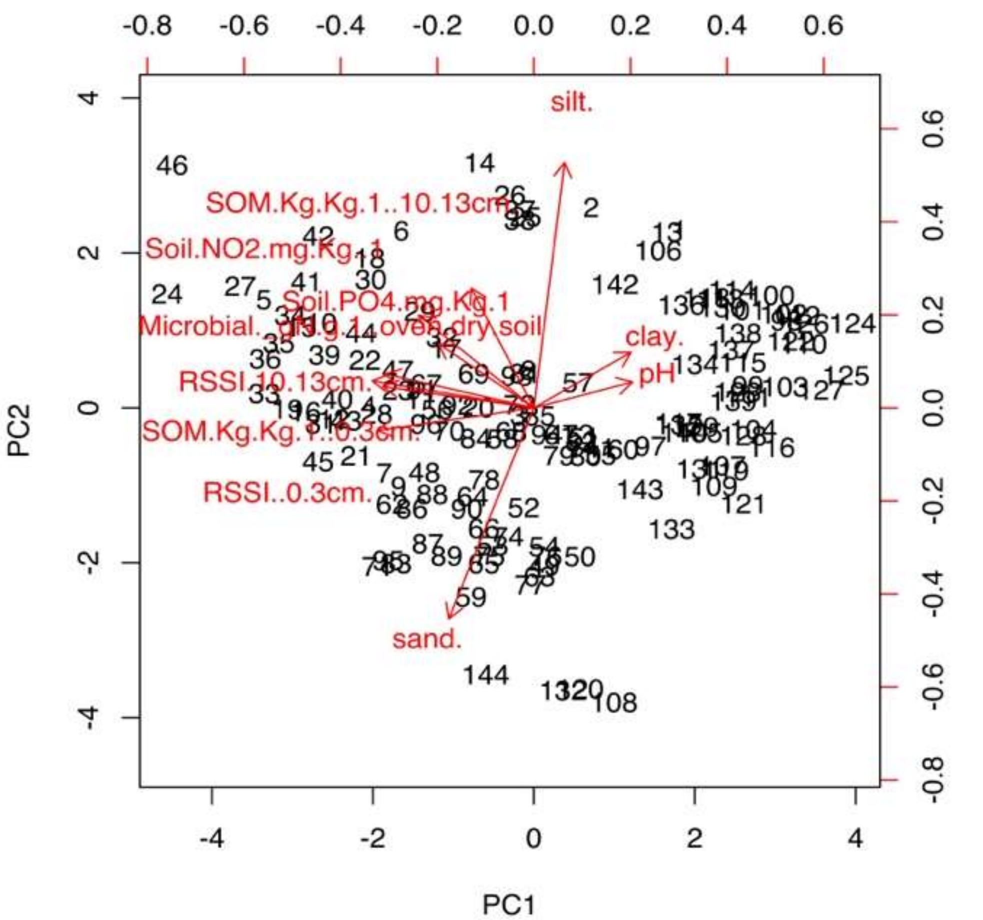
The vegetation analysis has allowed us to say with confidence that the different design considerations have manifested in a quantifiable way. To look at each soil factor individually would also reveal and confirm our predictions about increasing general environmental quality, in-fact the only case where this wasn't true was in the deep organic matter (10-13cm depth) content between the nut orchard and the wheat field, where the wheat field scored higher due to the flipping of soil horizons in the ploughing process. But, as mentioned earlier, we were looking to demonstrate the full-scale response in the soil and not to view components in isolation. For this I used a statistical procedure called principal component analysis to test the soil in its entirety and have tried to explain interpreting these results in figure 4. To briefly summarise, there was a statistically significant improvement across the whole soil between all the sites, therefore fitting our predictions about ecological design principles generating an ecosystem scale response in the soil.

Implications

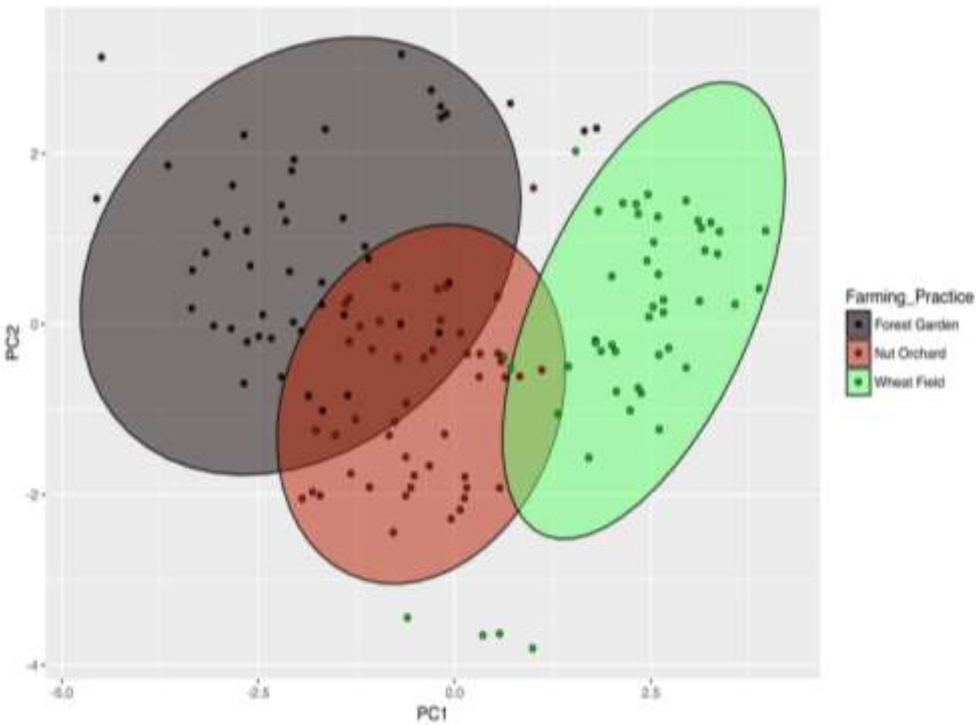
Before discussing the implications of this research project specifically, I must address the huge importance of experimental and visionary trial sites/projects such as the ones analysed in this study (including the wheat field). It is only through creative thinking and pragmatic application that positive changes are made in the world, such small-scale examples in agriculture today give us an early insight to how the future landscape can and must look if we are to solve the problems currently upon us. This research has hopefully done three main things to help the cause for promoting agro-ecology; I will state and explain them in what I believe to be their order of importance (starting with the most important).

Figure 4 (following pages):

These graphs (called biplots) are a 2D representation of the principal component analysis. The first thing to note is that they are both the same graph but with different factors overlaid onto them. This is an apparent and strong demonstration in the degree of environmental change we can produce by designing and implementing ecologically suitable agro-ecosystems. (The statistical analysis was actually performed on a 4D equivalent of this, which is not visually interpretable).



(Fig 4.1) This graph has each sample site depicted as black numbers, these are plotted in relation to their scores across the soil variables. The soil variables each have a red arrow representing them; the arrow points in the direction of an increase in value for that variable. Essentially you can see that all the environmental soil variables are increasing to the left of the graph.



(Fig 4.2) On this graph, the sites are in the exact same position and still relate to the soil variables but are instead represented as dots and have been colour coded to show which site they belong to. Circles have been drawn around the groups to show the degree of separation the sites have in terms of their soil characteristics.

1. Demonstrating our ability to design and maintain functioning and somewhat self-regulating ecosystems.

As was addressed early in this report, it is our removal of naturally developed ecosystems (with the ability to perform vital functions for the total environment) that has created almost all of our land-based issues. The most common reaction to such issues is to overcome them with technological solutions, many of which are creating new problems unpredicted by their inventors. In this report I have applied rigorous and carefully selected scientific analyses to demonstrate how ecologically informed agricultural design can seemingly reinstate such developmental functions, while supplying the food, fuels and fibres to humanity. If we are capable of doing this, as the research suggests, then it is reasonable to state we are setting up a self-regulating systems capable of adjusting to problems and providing services far beyond those that we currently understand though science. This is of such high importance because it demonstrates a route through which we can retract ourselves from the domination and direct control of biogeochemical processes.

2. Breaking a radically different type of agriculture into the scientific literature and setting up a research framework for others to use/improve upon.

In reading this report (and for myself conducting the research) it is easy to stop and ask "why go to such specific lengths to demonstrate something so obvious?"…. Because that (or possibly even more) is the level of detail required to break into the scientific literature and be taken seriously by peers. Although academia is not the business of going out and re-designing farms, I believe a lot of global interest can come out of getting more sites like the forest garden project and nut orchard into the scientific realm. For that reason, I have every intention of publishing a shortened version of my thesis within a scientific journal. Clearly stating a method for researching such sites, which after a couple of weeks of learning, anyone could perform, is an excellent way to make sure we are contributing to a comparable body of work and makes sure we have a strong leg to stand on when people ask, "but does it really work?"

3. The contemporary global problems in which the datasets from this study have demonstrated a solution to.

This topic would be typical of most scientific studies aiming to tackle a specific problem. From the organic matter recordings we were able to calculate the accumulation of carbon in the top 10cm of the forest garden soil (by assuming a similar soil carbon level to the wheat field when the project was started); the result was an average addition of 870kg of soil carbon per hectare per year. This is one of the fastest soil carbon accumulation rates recorded for temperate agriculture; it accedes accumulation rates in UK studies looking at transitions from arable to native woodland and greatly exceeds more gradual agroforestry such as alley cropping. With our current atmospheric carbon problems this is an important result. Likewise, the nutrient contents of the forest garden and nut orchard, along with their ability to almost completely resist erosion provides a possible solution to over enrichment of waterways by agricultural nutrients. The reason I have under-stated these findings is not because I don't think they are important, but because if the first implication I stated is true, then we would expect these results. In fact, I would be confident to predict that the same three-step trend is present in songbird diversity, insect biomass, people's serotonin responses when visiting, the water quality and many more variables that we could study between these sites.

A final consideration to make is that my environmental analysis is only a piece of the puzzle for researching these systems. We must look at crop production, economic returns, cultural compatibility (including diets) and levels of demand/consumption to find out where and how such agro-ecosystems fit into the landscapes of our future.

This article is a summary of the thesis submitted to Plymouth University for a Master of Research in Sustainable Environmental Management. Photos by Patrick Kendrew.