Letter

Design of sustainable dryland crop rotations require value judgements and efficient trade-offs

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Abstract

In agriculture, sustainability is framed as an aspiration to achieve multiple goals including positive production, environmental and social outcomes. These aspirations include: increasing production of nutritious food; minimising risk and maximising resilience in response to climate variability, fluctuating markets and extreme weather events; minimising impacts on global warming by reducing emissions; efficiently using limited resources; minimising negative on-site and off-site impacts; preserving biodiversity on farm and in nature; and achieving positive social outcomes reflected in farmers’ incomes (revenue and profit). Here we used cropping systems simulation to assess multiple (11) sustainability indicators for 26 crop rotations to quantify their sustainability throughout Australia’s subtropical cropping zone. Results were first expressed via a series of maps quantifying the minimal environmental impacts of attributes such as N applied, N leached, runoff and GHG emissions of the 26 crop rotations while identifying the locations of the optimal rotation for each attribute. Inspection of these maps showed that different rotations were optimal, depending on both location and the attribute mapped. This observation demonstrated that an 11-way sustainability win-win across all attributes was not likely to happen anywhere in the cropping zone. However, rotations that minimised environmental impacts were often among the more profitable rotations. A more holistic visualisation of the sustainability of six contrastingly sites, using sustainability polygons, confirmed that trade-offs between sustainability indicators are required and highlighted that cropping in different sites is inherently more or less sustainable, regardless of the rotations used. Given that trade-offs between the various sustainability attributes of crop rotations are unavoidable, we plotted trade-off charts to identify which rotations offer an efficient trade-off between profit and other sustainability indicators. We propose that these maps, sustainability polygons and trade-off charts can serve as boundary objects for discussions between stakeholders interested in achieving the sustainable intensification of cropping systems.

1. Introduction

To achieve a food-secure world without considerable loss of biodiversity and accelerated climate change requires crop yields to increase without expanding existing farmland, while substantially reducing negative environmental impacts on these lands. This will require the development of more productive, resilient, sustainable and socially responsible agricultural systems (Cassman and Grassini 2020) where farmers’ reward is comparable with the rest of their societies (Fischer and Connor 2018). The UN’s Sustainable Development Goal 2 is to end hunger, achieve food security and improved nutrition and promote sustainable agriculture by 2030 (UN 2019). In Australia, the National Farmers’ Federation (NFF) has set ambitious production targets to grow the value of Australian agriculture from around $60 billion in 2019
to $100 billion by 2030 (NFF 2019) while also committing Australian agriculture to play its role in moving towards an economy-wide climate neutral goal by 2050 whilst maintaining productivity and profitability (NFF 2020). For such national and global goals to be achieved agricultural science must provide a fuller accounting of both the costs and benefits of alternative agricultural practices as the basis of policy, ethics and action to maximise the net benefits of agriculture (Tilman et al 2002).

The many potential impacts of farm management on environmental and economic sustainability were summarised in a meta-analysis of the international literature on sustainable agriculture (German et al 2017; table 1). In an Australian context, Hochman et al (2013) proposed nine desirable attributes of a sustainable agriculture system emphasising a more holistic view of farming, going beyond efficiencies of single inputs into a single field in a single season to consideration of efficiencies of whole systems over decades (Hochman et al 2013; table 1).

In addition to the need for best practice in management of each crop, the design of crop rotations affects the economic and environmental performance of cropping systems. Crop rotations alter the species diversity and cropping intensity, which in turn impact on the abiotic and biotic environment by influencing soil nutrient and water balances, suppressing pests and diseases, changing nutrient and sediment loads, and the visual appearance of agricultural landscapes (Schönhart et al 2011, Collins and Norton 2020). Crop diversity in rotations has the potential to significantly reduce synthetic inputs such as nitrogenous fertilisers and herbicides and to reduce freshwater toxicity without compromising yield and profitability (Davis et al 2012). Rotations modify the soil environment by influencing the removal of nutrients from a soil, the return of crop residues, the dynamics of microbial communities, soil physical properties and carbon sequestration (Cresswell and Kirkegaard 1995, Ball et al 2005, Angus et al 2015, Wang et al 2015, Kumar et al 2019). The inclusion of pulse crops in rotations can significantly reduce the need for synthetic sources of nitrogen (e.g. Peoples et al 2009). The design of rotations can have an impact, which is mostly but not always positive (e.g. Owen et al 2018), on the incidence and severity of certain disease problems (Thompson et al 1999, Peters et al 2003, Kirkegaard et al 2004, Smith et al 2004, Lawes et al 2013, Reen et al 2014). With a few noted exceptions (Lawes and Renton 2010, 2015, Davis et al 2012) these studies are focussed on one or two indicators of sustainability of specific management interventions and their impacts are measured in a single crop (mostly wheat) rather than over the whole cropping system. There is a need for context-specific evidence of the effects of different management interventions on a whole suite of aspects of sustainability and for minimising negative impacts and dealing with trade-offs between competing sustainability imperatives over the whole crop rotation (Jarvis et al 2011, Kragt et al 2012, Hochman et al 2013, German et al 2017).

In a recent publication, Hochman et al (2020) explored the yield gap of crop rotations, in contrast with yield gaps of individual crops, in Australia’s subtropical grain zone. That paper focused on energy, protein, revenue and profit as indicators of the water-limited production potential of 26 crop rotations. It also investigated the trade-off between profit and risk, to help explain why producers may choose rotations that are suboptimal from a production or yield point of view. Here we seek to investigate the sustainability of these crop rotations by using quantitative indicators of sustainability (table 1) to identify which rotations cause the least impacts on environmental indicators such as greenhouse gas (GHG) emissions, soil erosion, nitrate leaching and the use of synthetic N fertiliser and herbicides.

In the present study, we investigate the above-mentioned environmental indicators on the same 26 crop rotations described in Hochman et al (2020) over the Subtropical Grain Zone of Australia. This region takes in central and southern Queensland through to northern New South Wales as far south as Dubbo. Average annual rainfall in this zone ranges between 350 mm yr$^{-1}$ in its western margins and 750 mm yr$^{-1}$ in its eastern margins. The seasonal (degree of summer dominance) distribution of rainfall tends to be increasingly summer dominant from south to north (about 60%-80%). Similarly, temperatures tend to increase in the north westerly direction. The summer dominance of rainfall in this cropping zone allows for dryland summer crop production, but with the high moisture-storing capacity of the clay-based soils of this region, supplemented by some winter rainfall, crops that grow during the winter are also successfully produced. This cropping zone is particularly interesting as it offers a wide range of choices between crop types, growing seasons and cropping intensities. For each sustainability indicator, we map at each location the average annual value of the rotation with the most favourable indicator value and identify which rotation achieved these favourable indicator values. For each environmental indicator these maps represent the minimal impacts that these rotations could have at any location. The crop rotations are further evaluated here in terms that integrate productivity indicators such as energy, protein, revenue, profit and downside risk, with environmental indicators such as net GHG emissions, deep drainage, runoff, N applied, NO$_3$− leached, soil organic matter decline and fallow herbicide applications. We use sustainability polygons (adapted from Ten Brink et al 1991, Moeller et al 2014, Hochman et al 2017) to investigate and visualise the possibility of win-win
rotations that maximise productivity and profitability while minimising environmental impacts. We also use specific environment-profit trade-off plots (e.g. profit versus net GHG emissions plots) to identify the most efficient trade-offs between productivity and environmental indicators at specific sites.

2. Materials and methods

Twenty-six rotations were selected through focus groups of growers and consultants across the Northern Grain Zone of Australia to ascertain a wide range of crop rotations that are currently practised by progressive growers in different locations. The 26 rotations vary in their complexity (number of different crops in a rotation), cropping intensity (measured as crops per year), crop types (cereal crops, pulses, oil crops) and growing season (summer versus winter crops). To determine the water-limited yields and sustainability of the 26 rotations, simulations were run with the Agricultural Production Systems Simulator (APSIM Version 7.9; Holzworth et al. 2014) using at least 30 years of historical daily temperature, rainfall and solar radiation data from 858 weather stations with up to three soil types per weather station per rotation. The management of each crop and of the fallow periods was in accordance with best management practice such that each crop could achieve its water-limited yield potential while fallows were managed by retaining standing stubble and by zero tillage and application of herbicides 2 weeks after a weed germination event to minimise water and nutrient losses. The simulations of all crop rotations were phased, so that each field, its crop or fallow, and year of the rotation was exposed to each year of the climate record (thus requiring the simulation of over 8 million sites x soils x fields x years). A more detailed description of the simulation rules was provided in Hochman et al. (2020). Simulation outputs from the APSIM model were selected to address the sustainability criteria proposed by Hochman et al. (2013) and German et al. (2017) as indicated in table 1. They include annual average values per hectare of: yield, biomass, grain N, grain protein, N fertiliser applied, grain oil (canola), runoff, deep drainage beyond the root zone, NO_3^- leached beyond the root zone, number of fallow herbicide applications (assuming that herbicides are applied 4 weeks after a germinating rainfall event), change in soil organic carbon (SOC) and GHG emissions (i.e. N_2O and CO_2 emissions from loss of soil organic matter, as CO_2 equivalents (CO_2e) as described in Hochman et al. (2017) and based on Huth et al. (2010)). Post simulation processing enabled calculation of additional outputs such as energy and protein using the USDA Nutrient Database for Standard (Release 28, 2016) and revenue, profit (gross margins expressed in $ ha$^{-1}$ yr$^{-1}$) and risk (expressed as the gross margin exceeded in 80% of years) using median commodity prices (adjusted for inflation, transportation, grading or bagging costs) for the years 2008–2017 (Zull et al. 2020).

Outputs representing various environmental attributes of simulated rotations were mapped onto the grain cropping land-use areas of the subtropical grain zone using the National Land Use of Australia version 4 (2005–6) (ABARE-BRS 2010) data at 1.1 km$^2$ pixel size. Production attributes were mapped previously (Hochman et al. 2020). The environmental attribute values of each weather station were interpolated over the whole cereal land use surface of subtropical Australia using local variogram kriging (Haas 1990) which was performed using the gstat R package (Pebesma 2004). Each map provides an interpolated surface of the value of the rotations that results in the most desirable value of any output. In the case of production outputs such as yields and profit, the maximum values were mapped, while for the environmental outputs such as GHG emissions or N leached, the minimum values and the rotations that produced those values were mapped.

Rotations can be compared based on multiple (production and environmental) sustainability

| Table 1. Matching of quantitative sustainability indicators to the nine desirable attributes of sustainable agriculture and aspects of sustainability. |
|---------------------------------|-------------------------------------------------|-------------------------------------------------|
| Desirable attribute of sustainable agriculture (Hochman et al 2013) | Aspects of sustainability (German et al 2017) | Sustainability indicators (this study) |
| (a) Increased production | Yield | Revenue, energy, protein |
| (b) Efficient use of resources | Water use efficiency, nutrient use Efficiency | N applied |
| (c) Impact on climate | GHG emissions | GHG emissions |
| (d) Minimal impacts on soil health | Soil fertility | NO_3^- leached, runoff, deep drainage, soil organic matter |
| (e) Minimal offsite impacts | Hydrology | Deep drainage, runoff |
| (f) Minimal risk | Costs | Profit and downside risk |
| (g) Preservation of biodiversity on farm | Biodiversity, pest regulation | Herbicide applications |
| (h) Preservation of biodiversity in nature | Biodiversity, pest regulation, pollination | Revenue (via its impact on land sparing) |
| (i) Positive social outcomes | Welfare, profit | Profit, risk |
attributes to identify the most desirable rotation for any attribute and location. To provide a holistic graphic representation of multiple indicators, we produced sustainability polygons to compare different rotations at nine representative locations in the subtropical cropping zone. These polygons are designed to provide a visual summary of the relative sustainability of competing crop rotations. Each sustainability indicator is represented by a scaled value where the most desirable outcome (highest or lowest depending on context, e.g. highest profit or lowest GHG emissions) is represented at the outside edge of the polygon while the least desirable outcome is represented towards the centre of the polygon.

Using sustainability polygons implicitly implies equal weighting for all indicators. Two criteria are applied to assess whether one rotation is more sustainable than another. First, the rotation for which all the indicators are higher than the alternate option can be considered more sustainable, or a multi win-win for all attributes. Ideally, the most profitable rotation will have all values close to the perimeter of the polygon. However, in most locations and for any crop rotation, only some indicators will be close to the perimeter while others will be closer to the centre requiring a trade-off between the indicators. In this case a second criterion is the shaded area within the polygon, where the area encompassed within the most sustainable rotation would be larger than the areas encompassed by the other rotations.

In the second case, the final choice between alternate rotations may require various stakeholders such as farmers and policy makers to place value based weights on the various sustainability indicators. Relative weighting of indicators is essentially value based but might be informed by the importance that farmers and other stakeholders assign to each indicator as well as by the range of values that each indicator displays.

Allowing that sustainability polygons may not always resolve a trade-off between any two attributes, we also employed a trade-off analysis in which, for each of the 26 rotations, the values of competing attributes (e.g. GHG emissions and profit) are plotted as points on an x–y chart. A line describing efficient trade-offs between two attributes is drawn by moving from the highest point (e.g. most profitable rotation) on the Y axis down to the next highest point (i.e. rotation) to its left (e.g. less GHG emissions). This is repeated until the leftmost point is reached. The resultant line represents a Pareto front named after Pareto (1906) who introduced the concept of non-inferior solutions in the context of economics. Here we describe this front as an efficiency trade-off frontier. All points below and to the right of this efficiency trade-off frontier represent rotations with less efficient trade-offs than at least one of the rotations on the frontier.

3. Results and discussion

The 26 rotations selected from the focus group interviews (table 2) represent current practice by progressive growers in different parts of the subtropical cropping zone. These rotations are not equally represented in the subtropical cropping zone. However, it is interesting to observe that collectively they exhibit considerable variation in terms of the levers available to growers designing them. Among these rotations the average cropping intensity was 0.96 with a range of 0.5–1.33 crops per year; average crop diversity was 3.04 with a range of 2–4 crops per rotation. Winter crops dominated over summer crops, accounting on average for 67% of crops with a range of 20%–100%. Cereal crops made up an average 66% of crops with a range of 50%–100%. Pulse crops made up on average 27% of crops with a range of 0%–50% while oil crops made up on average 7% of crops with a range of 0%–50%.

3.1. Mapping rotations that minimise environmental impacts

Each production and environmental attribute of the 26 rotations was mapped separately onto each weather station (location) within the extent of the crop land use area of the subtropical grain production zone. These maps were then aggregated so that the ‘best’ performing rotation for that attribute was mapped to each location. This is illustrated in figure 1 for four environmental attributes: N applied, N leached beyond the rooting zone, runoff and GHG emissions (maps of the other environmental attributes; SOC change, deep drainage and herbicide use are in figure 1(A) (available online at stacks.iop.org/ERL/16/064067/mmedia) in the appendix, while maps of the production attributes of energy, protein, revenue, profit and risk were published in Hochman et al 2020). The average annual amount of N applied can be minimised throughout the subtropical grain zone by adopting the N rotation (which happens to be the rotation with the lowest N requirement; figure 1(a)). The N rotation is a low cropping intensity (two crops in 4 years) wheat-chickpea rotation with 18 months fallow periods between crops. The presence of a legume crop and the long fallow periods which provide for an extended period in which mineralisation of soil organic N can occur, minimise the need for adding N fertiliser to optimise wheat yields. However, increased mineralisation may lead to depletion of SOC and increases the risk of leaching N beyond the rooting zone.

Minimising the leaching of N beyond the reach of crop roots (figure 1(b)) is achieved by seven different rotations depending on their location, indicating that rotation choice would need to be targeted to different environments to minimise this risk. The F rotation, with its high cropping intensity (four crops in 3 years) and a balance (50:50 mix) of cereals and legumes,
Table 2. The 26 crop rotations evaluated. Where: x = fallow (~6 months), Ba = barley, Ca = canola, Ch = chickpea, Fb = fababean, Mg = mungbean, So = sorghum and Wh = wheat.

| Rotation | Coded description | Year 1 | Year 2 | Year 3 | Year 4 | Year 5 | Year 6 | Year 7 |
|----------|------------------|--------|--------|--------|--------|--------|--------|--------|
|          |                  | Summer | Winter | Summer | Winter | Summer | Winter | Summer | Winter |
| A        | xCxWh            | Fallow | Canola | Fallow | Wheat  | —      | —      | —      | —      |
| B        | xWhxWhxCa        | Fallow | Wheat  | Fallow | Wheat  | Fallow | Canola | —      | —      |
| C        | xWhxWhxCh        | Fallow | Wheat  | Fallow | Wheat  | Fallow | Chickpea | —      | —      |
| D        | SoxMgWhxCh       | Sorghum | Fallow | Mungbean | Wheat  | Fallow | Chickpea | —      | —      |
| E        | SoChxWhx         | Sorghum | Chickpea | Fallow | Wheat  | Fallow | Fallow | —      | —      |
| F        | SoChxWhxMgx      | Sorghum | Chickpea | Fallow | Wheat  | Mungbean | Fallow | —      | —      |
| G        | xWhxChxWhxCa     | Fallow | Wheat  | Fallow | Chickpea | Fallow | Wheat  | Fallow | Canola | —      | —      | —      |
| H        | xWhxChxWhxMgx    | Fallow | Wheat  | Fallow | Chickpea | Fallow | Wheat  | Mungbean | Fallow | —      | —      | —      |
| I        | SoxSoChxWhxx     | Sorghum | Fallow | Sorghum | Chickpea | Fallow | Wheat  | Fallow | Fallow | —      | —      | —      |
| J        | SoxSoxSoChxx     | Sorghum | Fallow | Sorghum | Fallow | Sorghum | Chickpea | Fallow | Fallow | —      | —      | —      |
| K        | SoxSoxMgWhxxx    | Sorghum | Fallow | Sorghum | Fallow | Sorghum | Mungbean | Wheat  | Fallow | —      | —      | —      |
| L        | SoxChxWhxx       | Sorghum | Fallow | Fallow | Chickpea | Fallow | Wheat  | Fallow | Fallow | —      | —      | —      |
| M        | SoxWhxWhxx       | Sorghum | Fallow | Fallow | Wheat  | Fallow | Wheat  | Fallow | Fallow | —      | —      | —      |
| N        | xWhxxxxChxx      | Fallow | Wheat  | Fallow | Fallow | Chickpea | Fallow | Fallow | —      | —      | —      |
| O        | xWhxBaxWhxCa     | Fallow | Wheat  | Fallow | Barley | Fallow | Wheat  | Fallow | Canola | —      | —      | —      |
| P        | xWhxBaxChxCa     | Fallow | Wheat  | Fallow | Chickpea | Fallow | Wheat  | Fallow | Canola | —      | —      | —      |
| Q        | xWhxBaxWhxCh     | Fallow | Wheat  | Fallow | Barley | Fallow | Wheat  | Fallow | Chickpea | —      | —      | —      |
| R        | SoxWhxChxWhxxx   | Sorghum | Fallow | Fallow | Wheat  | Fallow | Chickpea | Fallow | Wheat  | Fallow | Fallow | —      | —      |
| S        | SoxWhxChxWhxMgx  | Sorghum | Fallow | Fallow | Wheat  | Fallow | Chickpea | Fallow | Wheat  | Mungbean | Fallow | —      | —      |
| T        | SoxSoxSoChxWhxx  | Sorghum | Fallow | Sorghum | Fallow | Sorghum | Chickpea | Fallow | Wheat  | Fallow | Fallow | —      | —      |
| U        | SoxSoxSoxWhxMgx  | Sorghum | Fallow | Sorghum | Fallow | Sorghum | Fallow | Sorghum | Wheat  | Mungbean | Fallow | —      | —      |
| V        | SoxChxWhxChxWhxx | Sorghum | Fallow | Fallow | Chickpea | Fallow | Wheat  | Fallow | Chickpea | Fallow | Wheat  | Fallow | —      | —      |
| W        | SoxChxWhxFbxWhxx | Sorghum | Fallow | Fallow | Chickpea | Fallow | Wheat  | Fallow | Fababean | Fallow | Wheat  | Fallow | —      | —      |
| X        | SoxSoxSoxChxWhxx | Sorghum | Fallow | Sorghum | Fallow | Sorghum | Fallow | Sorghum | Fallow | Chickpea | Fallow | Wheat  | Fallow | —      | —      |
| Y        | xWhxWhxBaxChxWhxCa | Fallow | Wheat  | Fallow | Wheat  | Barley | Fallow | Chickpea | Fallow | Wheat  | Fallow | Canola | —      | —      |
| Z        | SoxSoxSoFbxWhxChxWhxx | Sorghum | Fallow | Sorghum | Fallow | Sorghum | Fababean | Fallow | Wheat  | Fallow | Chickpea | Fallow | Wheat  | Fallow | —      | —      |
high crop diversity (four different crops) and a balance of summer: winter crops is prominent among these rotations since it is effective in capturing and utilising rainfall and hence in minimising water and nitrogen leaching events. The H rotation is more successful in preventing leaching in the southern, more winter-dominant rainfall, parts of this cropping zone as three of its four crops are winter crops.

Runoff (figure 1(c)) is an indicator of potential soil erosion and offsite impacts. Depending on their location seven different rotations minimise runoff. Rotations D and K are prominent among the rotations in the northern part of the Subtropical cropping zone, where rainfall is more summer-dominant, while rotations O, Q and T are more prominent in the southern parts. These rotations tend to have either high cropping intensity (D) or to be high (≥75%) in cereal crops (K, O, Q and T) which tend to produce more stubble that reduces runoff during fallow periods.

GHG Emissions (figure 1(d)) are minimised by four diverse rotations (C, F, H and Q) depending on their location. These rotations share a moderate to high cropping intensity (1.0–1.33 crops per year) and 25% to 50% pulse crops. In combination these attributes allow these rotations to build up or maintain SOC in favourable seasons compared to other lower intensity systems.

Additional maps of depletion of SOC, fallow herbicide use and deep drainage (figure 1(a)) show that the high cropping intensity rotations D and F minimise herbicide usage, while deep drainage beyond the depth of maximum rooting is mostly minimised by rotation F with a couple of exceptions.
2020 illustrates that there are assumptions, rotation F covers a greater area and as such it might be considered the most sustainable rotation for a sodosol in Emerald even though it is slightly less profitable and riskier than rotation J.

Without going into a detailed description of the remaining four sites, figure 2 illustrates that there are always trade-offs between some desired attributes. Figure 2 also shows the difference between sites in the overall sustainability of any crop rotation and in the rotations that are the most sustainable at each site. The implication of this is that there does not seem to be an easy shortcut to estimating the most sustainable rotation as this seems to vary by location and soil type as well as the values based weighting that may be applied to different indicators.

3.3. Trade-off analysis

Growers, policy makers and other stakeholders who may narrow their rotation choice to a contest between two indicators such as GHG emissions and profit can apply a trade-off analysis to help clarify their choices. In figure 3, rotation D (sorghum/fallow/mungbean/wheat/fallow/chickpea) is the most profitable rotation at five of the six sites (Dubbo, Gunnedah and North Star in NSW, and Dalby, and St George in Qld) while rotation C (fallow/wheat/fallow/wheat/fallow/chickpea) has the lowest GHG emissions at these sites. Rotation F (sorghum/chickpea/fallow/wheat/mungbean/fallow) at North Star, Dalby and St George, along with rotation H (fallow/wheat/fallow/chickpea/fallow/wheat/mungbean/fallow) at Dalby represent further efficient trade-off options. At the Emerald site, rotation J (sorghum/fallow/sorghum/fallow/sorghum/chickpea/fallow) is the most profitable rotation where rotation F has the lowest GHG emissions. At each of the sites in figure 3, efficient rotations are joined by the dotted line which represents the efficient trade-off frontier. Rotations on this efficiency trade-off frontier are Pareto optimal with respect to profit and GHG emissions. For any rotation that is not on this line there is a rotation along the efficiency trade-off frontier which is both more profitable and has lower GHG emissions. While a rotation that is not on the frontier may have other desirable properties, such a low runoff, it represents an inefficient trade-off between profit and GHG emissions. All other rotations (shown in figure 3 as letters below and to the right of the efficiency trade-off frontier) represent both lower profit and higher emissions than one of the rotations on the frontier and are therefore less efficient trade-offs between these two sustainability indicators.

These observations have implications for policy. For example, if an aim of policy is to reduce GHG emissions, what policy lever is likely to be effective in encouraging growers to reduce their emissions? Is carbon trading likely to work and if so at what price? The answer to this depends on where the farmers are with respect to the efficient trade-off between profit

3.2. Sustainability polygons

Specific trade-offs for each location are represented by sustainability polygons (figure 2) in which the various productivity and environmental attributes of different rotations can be visualised. At each of the six sites we selected three rotations for comparison as more rotations created an unacceptable level of visual confusion (the other three sites, Moree and Narrabri in NSW and Roma in QLD are shown in the appendix, figure 2(A)). The rotations selected were efficient trade-offs between profit and risk (Hochman et al 2020). We chose to highlight these rotations as we believe these are important criteria in growers’ minds, though other criteria could have been used to shortlist the rotations. For Gunnedah, a relatively favourable cropping environment, the most profitable rotation (D; sorghum/fallow/mungbean/wheat/fallow/chickpea) is also most favourable in terms of revenue, depletion of SOC and herbicide use. It is close to best for runoff, energy produced, and N leached. It is intermediate for protein produced. It is less favourable than the other two rotations (C and N) in terms of N applied, and downside risk and is equal second in terms of GHG emissions. A less intensive, more summer and cereal dominant rotation (J; sorghum/fallow/sorghum/fallow/sorghum/chickpea/fallow) is the most profitable in Emerald and is also the most profitable (or equal) in terms of risk, energy, revenue and runoff. It is less favourable than the other two rotations (F; sorghum/chickpea/fallow/wheat/mungbean/fallow and X; sorghum/fallow/sorghum/fallow/sorghum/chickpea/fallow/wheat/fallow/fallow) in terms of protein and N applied and intermediate in terms of depletion of SOC, herbicide use, GHG emissions and N leached. Rotation choice depends on values based weights ascribed to the sustainability indicators and weights ascribed to each indicator may well vary between different stakeholders. If equal weights are assumed, rotation F covers a greater area and as such it might be considered the most sustainable rotation for a sodosol in Emerald even though it is slightly less profitable and riskier than rotation J.

Without going into a detailed description of the remaining four sites, figure 2 illustrates that there are always trade-offs between some desired attributes. Figure 2 also shows the difference between sites in the overall sustainability of any crop rotation and in the rotations that are the most sustainable at each site. The implication of this is that there does not seem to be an easy shortcut to estimating the most sustainable rotation as this seems to vary by location and soil type as well as the values based weighting that may be applied to different indicators.

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These observations have implications for policy. For example, if an aim of policy is to reduce GHG emissions, what policy lever is likely to be effective in encouraging growers to reduce their emissions? Is carbon trading likely to work and if so at what price? The answer to this depends on where the farmers are with respect to the efficient trade-off between profit

3.2. Sustainability polygons

Specific trade-offs for each location are represented by sustainability polygons (figure 2) in which the various productivity and environmental attributes of different rotations can be visualised. At each of the six sites we selected three rotations for comparison as more rotations created an unacceptable level of visual confusion (the other three sites, Moree and Narrabri in NSW and Roma in QLD are shown in the appendix, figure 2(A)). The rotations selected were efficient trade-offs between profit and risk (Hochman et al 2020). We chose to highlight these rotations as we believe these are important criteria in growers’ minds, though other criteria could have been used to shortlist the rotations. For Gunnedah, a relatively favourable cropping environment, the most profitable rotation (D; sorghum/fallow/mungbean/wheat/fallow/chickpea) is also most favourable in terms of revenue, depletion of SOC and herbicide use. It is close to best for runoff, energy produced, and N leached. It is intermediate for protein produced. It is less favourable than the other two rotations (C and N) in terms of N applied, and downside risk and is equal second in terms of GHG emissions. A less intensive, more summer and cereal dominant rotation (J; sorghum/fallow/sorghum/fallow/sorghum/chickpea/fallow) is the most profitable in Emerald and is also the most profitable (or equal) in terms of risk, energy, revenue and runoff. It is less favourable than the other two rotations (F; sorghum/chickpea/fallow/wheat/mungbean/fallow and X; sorghum/fallow/sorghum/fallow/sorghum/chickpea/fallow/wheat/fallow/fallow) in terms of protein and N applied and intermediate in terms of depletion of SOC, herbicide use, GHG emissions and N leached. Rotation choice depends on values based weights ascribed to the sustainability indicators and weights ascribed to each indicator may well vary between different stakeholders. If equal weights are assumed, rotation F covers a greater area and as such it might be considered the most sustainable rotation for a sodosol in Emerald even though it is slightly less profitable and riskier than rotation J.

Without going into a detailed description of the remaining four sites, figure 2 illustrates that there are always trade-offs between some desired attributes. Figure 2 also shows the difference between sites in the overall sustainability of any crop rotation and in the rotations that are the most sustainable at each site. The implication of this is that there does not seem to be an easy shortcut to estimating the most sustainable rotation as this seems to vary by location and soil type as well as the values based weighting that may be applied to different indicators.
and GHG emissions. If most farmers are operating on the efficiency trade-off frontier, then the price of reducing their emissions must match the value of the trade-off. To equitably compensate a North Star grower to move from rotation D to rotation C would cost on average $530/t CO$_2$e/yr. At St George this would cost $900/t CO$_2$e/yr, while at Emerald, moving from J to F would cost an average of $345/t CO$_2$e/yr. Hence, in terms of profit foregone per tonne of CO$_2$e mitigated, the efficient profit-GHG emission trade-offs in figure 3 are an order of magnitude more expensive than current carbon trading market values (e.g. $16/t realised at the September 2020 auction by the Australian government’s Emission Reduction Fund; www.cleanenergyregulator.gov.au/ERF/Pages/Auctions%20results/September%202020/Auction-September-2020.aspx or $15/t CO$_2$e offered by Greenfleet; www.greenfleet.com.au/offset?product_type=individual&web_category=86). This means that the price required to encourage growers on

Figure 2. Sustainability polygons for three rotations representing efficient profit: risk trade-offs at six contrasting sites (Dubbo, Gunnedah and North Star in NSW, and Dalby, St George and Emerald in Qld). Table 1 provides a legend of the letters and their designated rotations.
the frontier to switch to a less profitable rotation is too high compared with other emission mitigation options available to policy makers. If, however, most growers’ rotations are not on the trade-off frontier, they could be encouraged through extension to transition from their current rotation to one that is on the profit-GHG emission frontier and represents a win-win for both profit and GHG emissions.

Trade-off analysis of profit versus other environmental indicators (N applied, deep drainage, N...
leached, herbicide use, runoff and SOC change) are provided in the appendix (figures 3(A), 4(A), 5(A), 6(A), 7(A) and 8(A), respectively). While each site has its own set of rotations on the efficiency trade-off frontier, rotations D, C, F and J are often on the frontier for most of the sites and environmental indices. This observation is consistent with the idea of sustainable intensification and is supported by other studies (e.g. Grassini and Cassman 2012, Rosenzweig et al 2018).

3.4. Further considerations

We propose that the maps polygons and trade-off analysis may be used as boundary objects (Cash et al 2003, Mollinga 2010) to translate research findings into action through facilitated conversations between researchers, growers, policy makers and other stakeholders who may seek to influence growers’ decisions. Used in well facilitated settings, these tools can enable stakeholders with different or even conflicting views to visualise a wide set of complex considerations and better understand the wide implications of the change they desire.

Although not directly analysed in this study, it is interesting to consider the impact that the future adoption of efficient trade-offs would have on crop diversity at a landscape scale. The average mix of grain crops in the subtropical grain zone over the period from 2010 to 2017 was 52% wheat, 15% sorghum, 15% chickpea, 11% barley, 3% canola, 3% mungbean and 1% fababean. This mix adds up to 78% cereals and 82% winter crops (ABS 2018). It is not possible to gauge the cropping intensity from these data but the impact on crop diversity, crop composition and crop seasonal distribution can be estimated. If we assume that different value judgments made by neighbouring growers would result in rotations C, D, F and J becoming dominant, how would these compare with the current mix? Rotations D and F, with four different crops, are quite diverse with a 50:50 balance between cereal and pulse crops and between winter and summer crops and are therefore likely to make a positive contribution to crop diversity. Rotations C and J are less diverse with just two crops each.

The scope of this simulation-based investigation is limited to those aspects of sustainability that can be investigated by the simulation model used in this research (APSIM). This precludes quantification of important rotational benefits such as enrichment of soil microbial communities, improved soil physical properties, reduced load of soil borne pathogens, more abundant pollinators and other beneficial insects, and reduced populations of harmful insects. From an economic point of view the use of median commodity prices, rather than a stochastic approach to prices, may underestimate the value that crop diversification can provide through greater resilience to market price fluctuations. We acknowledge that these omissions are likely to bias results such that the overall benefits of the more diverse crop rotations may be under-valued.

4. Conclusions

Maps showing the minimum annual amounts of environmental impacts, such as the amount of N fertiliser applied, N leached beyond the rooting zone, runoff and GHG emissions of 26 crop rotations in Australia’s Northern Grain Zone demonstrate that different rotations are best for different environmental imperatives.

Since no single rotation is best for all attributes, sustainability polygons offer a holistic visualisation tool for appreciating the trade-offs that must be considered when selecting the most sustainable rotation for any location. Where trade-offs must be made between any two sustainability indicators, efficiency trade-off frontiers can be plotted, and the resulting frontiers can show which rotations may be discarded as non-efficient trade-offs between the two sustainability imperatives. This considerably narrows the choice between rotations to a value judgement about the relative importance of trading-off one sustainability indicator against another.

From the maps, sustainability polygons and trade-off analysis conducted in this research we conclude that the perfect rotation for the subtropical cropping zone cannot be identified. However, in contrast with the oft-stated assumption of a negative correlation between intensification and sustainability of agriculture, trade-off charts comparing profit with environmental indicators invariably showed that the rotation that minimised the environmental impact was among the more profitable rotations. At a landscape scale, it is desirable that diverse rotations exist side by side, so the adoption of multiple efficient rotations in trade-off charts may well be a positive outcome. We conclude that the sustainable intensification of agriculture in the subtropical cropping zone is feasible if we do not allow the perfect to be the enemy of the good.

The maps, polygons and trade-off plots described here can help us appreciate the challenge of designing sustainable cropping systems. They can also serve as boundary objects for discussions about sustainable intensification of cropping systems in a dryland subtropical cropping environment between researchers and other stakeholders such as farmers, advisers and policy makers.

Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: https://data.csiro.au/collections/collection/CIcsiro:50344v2/DItrue
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Credit authorship contribution statement

Zvi Hochman: conceptualisation, methodology, simulation design, analysis, visualisation, writing and editing. Javier Navarro Garcia: data management, visualisation, writing—review and editing. Heidi Horan: simulation, writing—review and editing. Jeremy Whish: simulation design, Lindsay Bell: conceptualisation, selection of candidate rotations, writing—review and editing.

Conflict of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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