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Modelling the economic performance of Recirculating Aquaculture Systems (RAS) at the farm level

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Abstract

Agricultural production practices are one of the most significant drivers of biodiversity loss and make farming a major contributor to greenhouse gas (GHG) emissions and water pollution. Currently, agricultural policies and farm management interventions at a farm level are designed to contribute to a transformational reform of agricultural systems to improve environmental and economic sustainability. The new Agriculture Act for the UK commits to net zero carbon emissions and policies to enhance environmental stewardship and sustainability and support the production of public goods. Introducing recirculating aquaculture systems (RAS) with farm-based renewable energy (Anaerobic Digestors, AD) provides a novel diversified enterprise for farming systems with considerable but poorly understood economic and environmental benefits. This study conducts farm-based Net Margin analysis to show that an AD unit generating up to 500 kW combined with six to 12 RAS 157 m^3 units for high-value shrimp ("king prawn") production is economically viable on medium and large arable farms in the East of England at 2022 prices. Besides, we explore further key issues such as impacts on other farm activities, land use due to AD feedstock choices, use of digestate and nutrients cycling, among others.

Keywords Farm profitability, diversification, sustainability, land use, net Margin
JEL code Q12, Q15, Q16, Q18, Q20, Q22, Q42

1. Introduction

The derived pressures from the internal (limited natural resources, land degradation) and external environment (agricultural policies, exchange rate, trade agreements) of farming systems demand farmers introduce innovative and alternative food production technologies (Crippa et al., 2021; Foley et al., 2011; Godfray et al., 2010). Notably, production practices and technologies concerning the transformation of food production systems for reducing negative externalities, changing land use patterns and sparing natural resources (land, water) to provide other land-based services (Popp et al., 2017; Weindl et al., 2017). Furthermore, new food technologies and innovation systems can support the diversification of farm profitability leading to its financial sustainability (Salvioni et al., 2020). These new systems can lead to investments in new enterprises often associated with solutions addressing the demand for sustainable diets (Mazac et al., 2022; Parodi et al., 2018). Hence, such products may provide nutritious substitutes for animal-sourced foods while simultaneously reducing environmental pressures generated by livestock systems and supporting the provision of ecosystem services from the agricultural sector. The integration of terrestrial warm-water shrimp ("King prawn") production using recirculating aquaculture systems (RAS) using green energies such as Anaerobic Digestion (AD) has the potential to provide a novel diversified farming output. Literature reports several studies focusing on on-farm enterprises being powered by AD outputs such as greenhouses (Bywater & Kusch-Brandt, 2022) and the use of heat for hot water in buildings and dairy washing in dairy farms (Marañón et al., 2011). Beyond farm activities, AD can also supply energy for campsites (space and water heating) and local food production operations (Bywater & Kusch-Brandt, 2022).

This study assesses the economic viability of terrestrial shrimp production combined with farm-based renewable energy provided by an AD unit in the UK as a first step to quantify and economically value the public goods generated by this transformation. Using a linear programming approach, we model the profitability of shrimp production combined with an AD unit relative to other farm activities in the context of a cereal-dominated farm in the east of England (300 ha).To evaluate the profitability of farm diversification, we observe changes in the whole-farm Net Margin. Besides, this research explores a whole range of key issues related to investment decisions in the context of current policy issues (e.g., environmental goals and energy prices). For example, the choice of AD production capacity and RAS scale, the synergies with other farm activities, impacts on land use due to AD feedstocks choices, and use of digestate and nutrients cycling, among others. The structural, technology and economic data for the farm-type model refers to 2022 data. The data, technical coefficients and resource endowments have been derived from different sources, including the DEFRA Farm Business Survey (FBS), published farm management standards and peer-reviewed published literature. Technical information and critical data on implementing and operational costs for the RAS and AD systems have been provided by industry stakeholders (e.g., data on implementing and operational costs[1]).

2. Methodology

The primary objective is to test the economic viability of RAS & AD in the context of a typical farm system in the UK. The modelling design is adjusted to agricultural systems to explore the impact of RAS & AD on farm profitability. All costs (variable and fixed), including capital costs, are considered during the modelling exercise. To achieve these objectives, we implement a linear programming optimisation technique. The method updates and extends a mathematical algorithm developed by Jones and Salter (2013) using the software GAMS[2], to identify the optimum mix of factors (e.g., inputs, resources use) for the maximisation of farm Net Margin, subject to given constraints (land availability, labour, and capital).

2.1. The arable farm model

The arable farm model emulates a 300 hectares arable farm in the East of England, divided into 12 fields of 25 ha each[3]. Defra Farm Business Survey data for 2020-2021 shows an average size of 298 ha for cereals-dominated farms in this region (Duchy College, 2022). The farm model can deploy different enterprises, including AD, AD & RAS, using selected inputs (e.g., seeds, fertilisers, feedstocks for AD, feed for prawns) and resources (labour and land). Most of the data refers to 2022. The model is based on a year business cycle reflecting only annual agricultural and non-agricultural activities. In this regard, we model land utilisation according to the net economic margins the various enterprises can earn. Thus, each farm activity contributes to the total Net Margin of the farm as a whole but is subject to constraints,

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[1] The work on which this study is based is part of a project titled "Transformational blueprint for a blue economy on UK terrestrial farms: integrating sustainable shrimp", funded by UKRI, Biotechnology and Biological Sciences Research Council.

[2] https://www.gams.com/

[3] To increase the realism of the models, we use a factor varying between 0.65 and 1.35 for each field to express variation in yields.

such as the availability of land and labour, the availability of inputs produced by the farm (e.g., the case of feedstocks) and rotational requirements[4]. As detailed by Jones & Salter (2013), the mathematical structure of the model is:

Maximise $Z = \sum_{ij} C_{ij} \times X_{ij}$

Subject to: $Ax \leq b; x \geq 0$

where Z is a scalar product representing the objective function, C_{ij} is the vector of Net Margin contributions for each farm enterprise, i, over j farm fields, X_{ij} is the vector of crop areas; A is the matrix of input/outputs specifying the quantity of input i required per unit of output j. b represents resources endowment and input availability.

To reduce complexity, the model contains only the main crops plus a percentage of the more minor crops. Table 1 shows the list of farm enterprises and inputs for the farm model, including some intermediate products, such as forage crops. These forage crops can support AD production enterprises (e.g., AD) and, consequently, AD outputs (e.g., electricity and heat) for RAS production. Regarding labour, the model is provided with 660 man-days for farming activities (one farmer plus two full-time workers working 220 days per year). Additional labour can be purchased as contractors' time. For AD & RAS, labour is included as a specific cost, given the need for specialised labour and AD & RAS size/capacity.

Regarding farming outputs and nutrient requirements, Table 2 shows the average yields for farming enterprises considering the whole crop, the seed/tubers/beet and residues. The nutrient requirements reflect common commercial practice, and they must be met each year by fertiliser applications. Fertilisers can be supplied from purchased inputs or AD digestate, where the latter is available (see section 2.2.3 for details).

Data on food and feed crop commodities and inputs prices and margins are detailed in Table 3. The higher margins for cereals and combined crops using 2022 prices have also been published by specialized reports (Topliff, 2022).

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[4] For example, a minimum of 1/3 of the farm must be sown to break crops i.e., a rotation requirement to establish a break crop every third year.

Table 1. List of enterprises and inputs included in the farm model

Enterprises/activities
Cereals – Winter Wheat, Winter Barley, Winter Oats, other (Triticale)
Other crops - Peas/beans (for stockfeed), Sugar beet, Potatoes, Rapeseed, Field-scale vegetables (Swedes)
Forage crops – maise, fodder beet
Anaerobic Digestor (AD)
Recirculating Aquaculture System (RAS)
Inputs
Agricultural labour – regular, casual/seasonal, contractors
Seed, sprays, fertilisers, and other crop costs
Agricultural machinery costs – fuels/oils, repairs, depreciation
General farming costs - Land and property, miscellaneous
AD costs – equipment, feedstocks preparation, digestate processing
RAS costs – equipment, water, prawn juveniles, electricity and heat

Source: Adapted from Jones & Salter (2013)

Table 2. Average yields and Nutrients requirements of crop enterprises available to the farm model

Crop enterprise	Average yield (t/ha)			Nutrient requirements (kg/ha)		
	Seed, Tubers, Beet	Residues (biomass)	Whole-crop	Nitrogen (N)	Phosphate (P)	Potassium (K)
Winter wheat	8.6	11.7	38.6	190	60	90
Winter barley	6.4	7.8	37	140	62	77
Winter oats	6.5	8.7	37	80	55	101
Other cereals (triticale)	6.0	4.5	31.3	125	50	50
Oilseed rape	3.4	-	46.2	160	49	39
Field peas	4.4	6.0	40.1	0	36	40
Field beans	3.8	6.0	50.7	0	47	52
Sugar beet	58.6	20	82	120	62	131
Potatoes (maincrop)	45.0	0	45	179	50	292
Maise (forage)	NA.	0	45.4	70	25.9	81.4
Fodder beet (forage)	60.0	35.0	91	125	150	60
Field-scale veg (swedes)	75.0	20.0	95	60	24.5	84

Sources: For average crop yield (seed t/ha) see Redman (2022) and AHDB UK Delivered Prices for 2020-2023 (weekly average. Data available at https://ahdb.org.uk/ [retrieved on 14/02/2023]. See Jones & Salter (2013) for crop residues and whole-crop yields. For nutrient requirements, see Redman (2022).

Table 3. Food and feed crop prices, inputs, and margins *at 2022 prices*.

Variables	Winter Wheat	Winter barley	Oats	Other cereals (triticale)	OSR	Peas	Beans	Sugar beet	Potatoes	Maise	Fodder beet	Field vegetables (Swedes)	Grass silage
Outputs													
Yield (t/ha)	8.6	7.3	6.1	4.5	3.5	4.0	4.3	77.0	50.4	37.0	70.0	70.0	42.0
Price (£/t)	225.0	200.0	200.0	215.0	515.0	310.0	285.0	40.0	190.0	36.0	40.0	117.0	45.0
Price Straw in Swath (£/t)	173.0	198.0	198.0	173.0									
Total output (£/ha)	2108.0	1658.0	1418.0	1140.5	1802.5	1240.0	1225.5	3080.0	9576.0	1332.0	2800.0	8190.0	1890.0
Variable costs													
Fertilizer (£/ha)	533.0	428.0	329.0	328.0	410.0	91.0	118.0	495.0	843.0	250.0	443.0	232.0	425.0
Sprays (£/ha)	278.0	212.0	154.0	90.0	253.0	150.0	149.0	265.0	628.0	70.0	140.0	14.0	5.0
Seed (£/ha)	97.0	119.0	99.0	85.0	74.0	134.0	156.0	230.0	1109.0	209.0	242.0	209.0	26.0
Other variable costs (£/ha)	0.0	0.0	0.0	0.0	0.0	0.0		380.0	1893.0			1686.0	
Casual labour (£/ha)	0.0	0.0	0.0	0.0	0.0	0.0		668.6				480.0	
Gross Margin (£/ha)	1200.0	899.0	836.0	637.5	1065.5	865.0	802.5	1041.4	5103.0	803.0	1975.0	5569.0	1434.0
Fixed costs													
Labour (£/ha)	69.1	69.1	69.1	69.1	62.4	59.1	59.1	189.4	601.7	177.2	267.3	980.6	213.0
Other fixed costs	565.0	565.0	565.0	565.0	620.0	620.0	620.0	620.0	620.0	565.0	620.0	565.0	565.0
Net Margin (£/ha)	565.9	264.9	201.9	3.4	383.1	185.9	123.4	232.0	3881.3	60.8	1087.7	4023.4	656.0

Notes:

- For crop prices, yield (corresponds to "Average" value), seed, fertiliser, sprays, and prices for forage/silage see (Redman, 2022) . Wheat, Cereals and OSR commodity prices checked with AHDB UK Delivered Prices for 2020-2023 (weekly average).
- Price for Swedes estimated from various sources such as Price for Field vegetables (Swedes) from Farmers Weekly Horticultural prices 2023 and Defra (National average wholesale prices of home-grown horticultural produce).
- 'Other fixed costs' (£/ha) are estimated based on total farm fixed costs (including total power, machinery and overheads, excl. Labour) for "mainly cereals" (200-300 ha) and "general cropping" farms (over 250 ha) for cereals and rest of crops, respectively (Redman, 2022, pp 232).
- Grass silage data based on 2 cuts per year from intensively managed leys.
- 'Other variable costs' are notional costs for expenditures such as packaging, grading, storage and marketing

2.2. AD unit

2.2.1. Capacity

Following the study of Jones & Salter (2013) & Parsons Brinckerhoff, (2015), the model adopts an AD output capacity of 500 $kW_{electricity}$ continuous. The biogas is used in combined heat and power (CHP) equipment. While operating for 95% of the year (allowing for maintenance and repairs) at a scale of 500 kW, with an electrical conversion efficiency of 35%, the AD unit would generate 4,161,000 kW h of electricity from a throughput of 1,194,735 m^3 of methane per year. An on-farm AD plant will range between the scale of 250-500kW band (average of 479kW) (Parsons Brinckerhoff, 2015) and a smaller 150 kW band (Bywater and Kusch-Brandt, 2022). These examples vary between using crops and agricultural slurry/manure as their primary feedstock (Lukehurst, 2019). The model will adopt this AD unit based on the contribution of AD to the farm's Net Margin, and feedstock availability, and all digestate produced can be applied to the farm's land (subject to nutrient application rates not exceeding nutrient requirements).

2.2.2. AD Costs and revenues

Since AD is a new activity on the farm, capital costs must be accounted for this new investment. According to available sources on a per kW basis, as shown in Table 4, the establishment cost of a 500kW AD is assumed to be £2.9 million. Similar estimates are available in Redman (2022). Assuming all capital costs were borrowed, and assuming loan repayment over ten years, average repayment charges at 4% interest on borrowing of £2.9M would be approx £357,544. According to Table 5, the operational cost estimates for 500kW AD are £143,237.

Table 4. The capital cost of AD installation, on a per kW basis, at a range of AD unit sizes.

AD unit size (kW)	Capital cost (£M)	Capital cost per kW (£)
<250kW	1.44	5,953
250 - 500kW	1.45 – 2.9	5,804
>500	2.23	4,465

Source: estimates reported by Parsons Brinckerhoff (2015) and applied by researchers (e.g. Bywater and Kusch-Brandt (2022). Capital cost per kW (£) corresponds to Parsons Brinckerhoff Central Case (i.e., median)

Table 5. Operating *cost* estimates for 500kW AD based on published data.

Item	Value	Unit	Running costs for 500kW AD (£/year)	Sources
AD operation and maintenance	2.5%	Percentage of capital value	72,500 (Based on £2.9M)	(Bywater & Kusch-Brandt, 2022; Redman, 2010)
CHP operation and maintenance	£0.017	£/kWh produced	70,737 (Based on 4,161 mW produced)	(Bywater & Kusch-Brandt, 2022; Jain, 2013)
Total (£/year)			£143,237	

Related to revenues from AD output, these are generated by selling electricity to the national grid. The quantity of sold electricity depends on the scenarios modelling (see section 3). According to Ofgem data, electricity prices based on Day Ahead Baseload Contracts for 2022 averaged £0.211/kWh (Ofgem, 2023a). Regarding the average Feed-in tariff, we estimate £0.045/kWh based on Ofgem's available data (Ofgem, 2023b). Thus, total receipts for electricity generation are £0.256/kWh.

2.2.3. AD feedstocks and nutrients from digestate

AD feedstocks are derived solely from the crops that can be grown on the farm. They are crop residues and crops diverted from food or feed use which may be grown specifically for the digester and harvested whole-crop (sometimes semi-ripe) and ensiled for storage. Although there is a need for information on potential biogas and methane yields, literature reports large intra- and inter-crop variations (Y. Zhang et al., 2021). In this regard, the model relies on estimations (see Table 6) from the ADAT energy balance modelling tool[5] developed by the University of Southampton (University of Southampton, 2017). Several studies have used the ADAT tool (Bywater & Kusch-Brandt, 2022; Suhartini et al., 2021; W. Zhang et al., 2020).

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[5] http://borrg.soton.ac.uk/resources/adat/ [retrieved on 20/Feb/2023]

Table 6. Methane yields (m^3/t fresh material, FM) and nutrient content from the AD digestate for crops.

Crop	Methane yield (m^3/t FM)		Nutrient content (kg/t whole crop)		
	Residues	Whole (green) crop	Nitrogen (N)	Phosphate (P)	Potassium (K)
Winter wheat	141	115	3.5	0.35	3.85
Winter barley	119	115	3.5	0.35	3.85
Winter oats	203	76	5.4	0.9	7.8
Other cereals (triticale)	141	122	3.9	0.78	3.9
Oilseed rape	253	50	3.42	0.54	3.78
Field peas	237	47	3.5	0.5	3.7
Field beans	237	47	3.5	0.5	3.7
Sugar beet	32	76	1.76	0.44	2.2
Potatoes (maincrop)	-	27	3.5	0.55	4.95
Maise (forage)	201	98	3.9	0.6	3.6
Fodder beet (forage)	49	70	1.8	0.4	4.2
Field-scale veg (swedes)	31	70	3.1	0.33	1.98

Source: The ADAT tool (University of Southampton, 2017).

Related to nutrients from the AD digestate, the model makes them available as fertilisers for use on the farm in the current year. The nutrient value of the digestate depends on the crops used in the AD unit as feedstocks. In this regard, it is assumed that nutrients remain unaltered by digestion. Like methane yields by crops, data on nutrients in different crops varies according to methods and other variables. Therefore, the model also uses estimations from the ADAT tool (University of Southampton, 2017) as a trusted source, as displayed in Table 6.

2.3. The RAS unit

2.3.1. Capacity and costs

The model integrates the possibilities of warm-water "king prawn" production by adding multiples RAS units. Project partners have provided cost estimates in this section (RAStech, personal communication, February 2023). A RAS system implemented at the farm level can combine tanks of 157 m^3 volume. These units consider a total water usage by year of around 204 m^3 considering 0.3% water change by year. Also, this unit requires 25 kWh for electricity and heating requirements supplied by the AD unit.

As with AD, capital costs must be accounted for RAS as a new enterprise in the farm. The establishment cost of a 157 m^3 unit is assumed to be in the range of £90,000-£100,000. Assuming all capital costs were borrowed and loan repayment over ten years, average repayment charges at 4% interest on borrowing are estimated at around £12,000 per annum. Regarding operational costs, the model considers estimates for the annual running cost of around £120,000. This estimate considers variable (water supply and effluent treatment, prawn juvenile, feed, among others) and fixed (water testing, maintenance, among others) costs.

2.3.2. Revenues and use of shrimp waste as fertiliser

Regarding revenues from sales of prawn meat, they are based on a yield of 4-8 kg/m^3 per cycle (3-5 per year) per unit. Additional revenues are based on the sale of exoskeleton chitin from shrimp waste. Alternatively, shrimp waste can be used as fertiliser due to its nutrient content for use on the farm following the same approach for AD digestate. In this regard, reported estimates for Nitrogen (N), Phosphate (P) and Potassium (K) of 5, 4 and 1.3 kg/ton of shrimp waste, respectively (Dufault & Korkmaz, 2013; Suwoyo et al., 2019).

3. The scenarios

The farm model is run multiple times to produce scenarios reflecting prices and levels of technology prevailing in 2022. The first or baseline scenario provided the situation on the selected farm system in the East of England in 2022. The second or AD scenario provides the farm model with only a 500 kWh AD as a new, and the third or AD & RAS scenario provides the farm model with AD combined with enterprise RAS as a farm activity. Considering that a 500 kWh AD produces outputs enough to freely supply energy and heat six to 12 tropical shrimp units, under the AD & RAS scenario, two variants are explored. The first variant, AD & RAS (6), deploys six unit of RAS, with the AD unit providing 30% of its output to these units and the rest being sold to the grid as electricity. The second, AD & RAS (12), deploys 12 RAS units powered by 60% of the AD unit and the rest sold as electricity. We construct these variants based on energy (electricity and heat) requirements for a 157 m^3 RAS unit of 25 kWh. The scenarios are as follows:

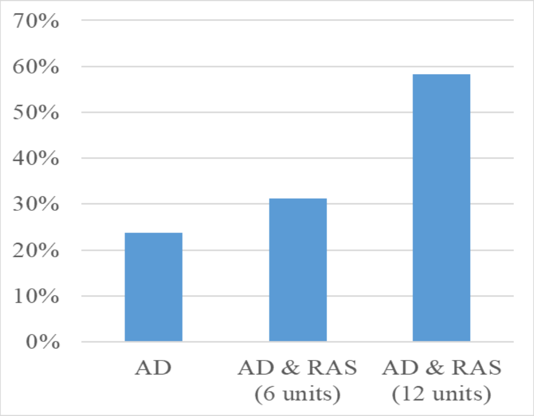
1. The Baseline Scenario: Maximisation of farm Net Margin
2. Scenario 2: Maximisation of farm Net Margin with AD
3. Scenario 3: Maximisation of farm Net Margin with AD & RAS
    a. Variant 1: Six RAS units
    b. Variant 2: 12 RAS units

4. Results & Discussion

4.1. The Baseline Scenario: Maximisation of farm Net Margin

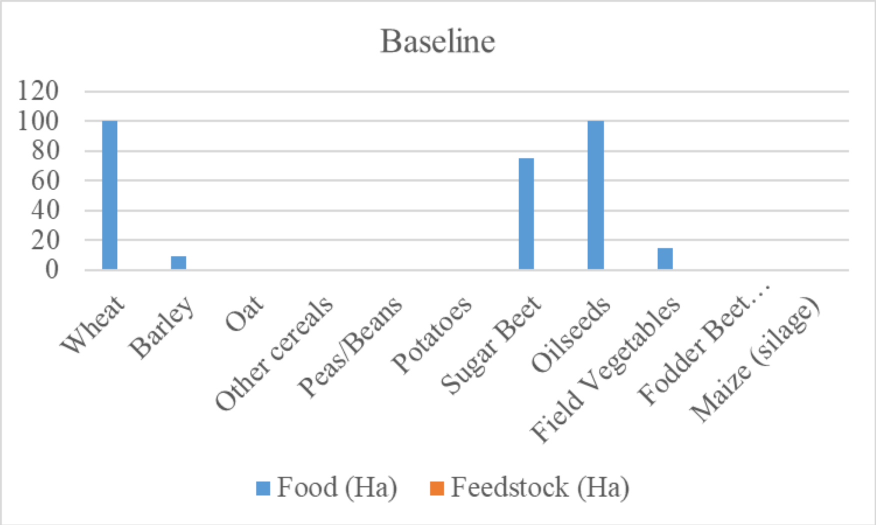
The Baseline scenario represents the operation of the cereals-dominated farm with no AD or AD & RAS as diversification opportunities. In this regard, this baseline allows us to validate the model and to evaluate changes in the Net Margin of the whole farm due to the AD and AD & RAS introduction. In this regard, Figure 1 shows the changes in the Net Margin for all scenarios using the Baseline as a reference. We discuss these changes in the following sections.

Figure 1. Whole-farm Net Margin change compared to Baseline



Regarding cropping pattern and, from an agronomic or real-world expectation, the Baseline scenario output produces realistic outcomes as shown in Figure 2: a typical cereal-arable rotation with about one-third of the farm under cereals (100.2 and 9.6 ha of wheat and barley, respectively) and two-thirds combinable crops such as sugar beet, rapeseed and field vegetables. This cropping pattern is entirely feasible, particularly given the higher prices of cereals in 2022. In the following sections, we compare how cropping patterns can change due to the introduction of AD and AD & RAS and how these diversifications impact the purchase of nutrients and the whole farm's Net Margin.

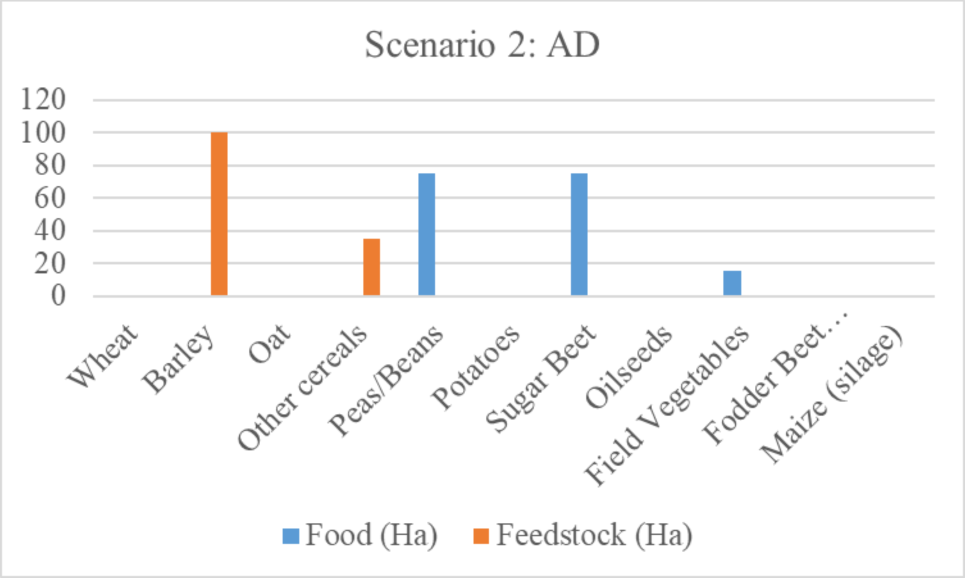
Figure 2. The farm model - Baseline results for cropping pattern



4.2. Scenario 2: Maximisation of farm Net Margin with AD

The results when AD is introduced in the fam model demonstrate that this technology is commercially viable at 2022 prices[6] on larger-scale commercial farms. Under this scenario (see Figure 3), the feedstock for the AD comes primarily from 135 ha of harvested whole-crop cereals (Barley and Triticale). Three crops are produced for sale as food and livestock feed in the rest of the farmland, these being peas and beans (75 ha), sugar beet (75 ha) and field vegetables (15) ha. Under this scenario, the emphasis on providing feedstocks for the AD has replaced the food crops stated in the Baseline case. It is interesting to note two aspects here. First, the use of cereals as feedstocks when there are other alternative crops with higher yields of methane (see Table 6) but barley and triticale represent lower enterprise net margins. Second, this scenario does not feature maise (silage), typically grown as feedstock when an AD plant is introduced in farms. Although whole-crop yields of barley, triticale and maise are similar (see Table 2), maise offers a lower methane yield and, consequently, a lower net margin for AD.

Figure 3. Cropping pattern of the farm model Scenario 2: Maximisation of farm Net Margin with AD



Regarding nutrient requirements for crops in this scenario and, consequently, savings in fertiliser purchases, Table 7 compares with the baseline. Overall, the introduction of AD results in saving in all nutrients due to the cycling of digestate from cereals crops back onto the

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[6] Alternative analysis using lower electricity prices (e.g., average for last decade) shows that AD is not commercially viable in a scenario of high crop prices (e.g., cereals).

land, especially for nitrogen and potassium, which fall 69% and 62%, respectively, due to the rich content of these nutrients in cereals whole-crops (see Table 6). Related to the whole-farm Net Margin, under the current scenario, there is a 24% increase on the baseline (see Figure 1) due to revenues from crops and electricity sales.

Table 7. Whole-farm purchase of nutrients under the Baseline and Scenario 2:AD

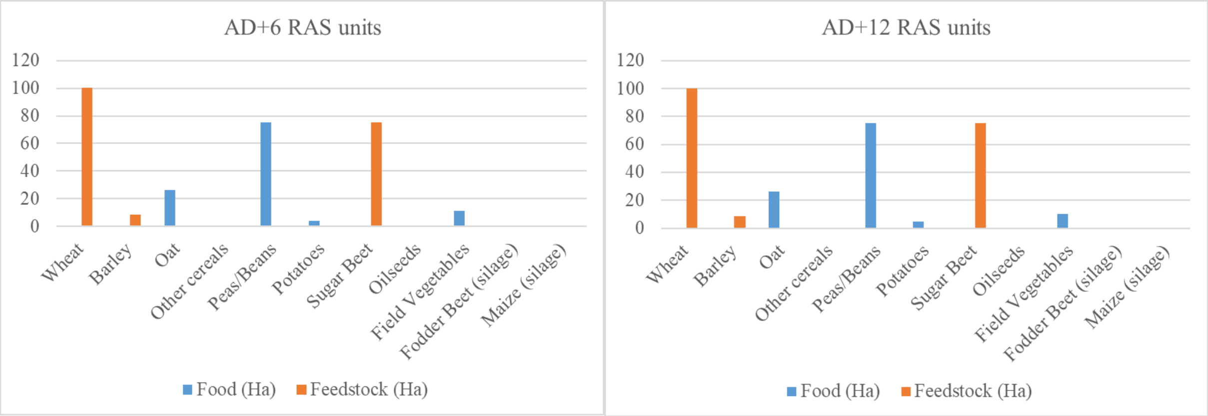
Nutrient	**Baseline Scenario (kg)**	**Scenario 2: AD (kg)**	**Percentage change**
Nitrogen (N)	46,314	14,214	-69.3%
Phosphorous (P)	16,534	14,795	-10.5%
Potassium (K)	24,750	9,263	-62.6%

4.3. Scenario 3: Maximisation of farm Net Margin with AD & RAS

As introduced above, we model two variants of this scenario whose results are compared to the baseline. In these variants, the general conditions applying in scenario 2:AD are carried over, but RAS units are added as new enterprises. In the following, we present results related to cropping pattern, whole farm net Margin and fertiliser purchases compared with the baseline.

First, when AD & RAS are jointly introduced in the model, as shown in Figure 4, the feedstock for the AD unit comes from 100, 8 and 75 ha of wheat, barley and sugar beet, whole-crop harvested. Four crops are produced for sale as food and livestock feed, these being oats, peas and beans, potatoes and field-scale vegetables, with peas and beans as the larger crop since it is used as breaks in the cereals rotation, as well as providing crop residues for the AD unit. Increasing from six to 12 RAS units generates no changes in the cropping pattern. These cropping patterns in Scenario 3 obey a maximisation for electricity sales in the AD unit using wheat and sugar beet as feedstocks, given their higher methane yields per ha. Recalling the Scenario 3 configuration, for six and 12 units, 30% and 60%, respectively, of AD output is used for the energy requirements of the RAS enterprise.

Figure 4. The farm model Scenario 3: Maximisation of farm Net Margin with AD & RAS, 6 and12 units variants



Regarding margins, the scenario considering the AD unit plus six and 12 RAS units for prawn production increases by 31% and 58%, respectively, the whole-farm Net Margin compared with the baseline scenario (see Figure 1). To this increase contributes the sales of prawn meat (around 30 and 60 tonnes p.a. for 6 and 12 RAS units, respectively), sales of exoskeleton chitin from waste shrimp, the revenue from selling remanent electricity to the grid (AD unit supplying 30% and 60% of its output for electricity and heat consumption for six and 12 RAS units, respectively), the sales of food crops and, the savings in fertilisers purchases due to the content of nutrients in the digestate. In this regard, Table 8 shows nutrient purchases under these two variants of scenario 3: AD & RAS, where it can be seen significant changes in purchases of fertilisers including a 100% saving in potassium purchases.

Table 8. Whole-farm purchase of nutrients under the Baseline and Scenario 3:AD & RAS (Similar results between six and 12 units deployment)

Nutrients	Baseline (kg)	AD & RAS (kg)	% change
Nitrogen (N)	46,314	8,726	-82.1%
Phosphorous (P)	16,534	12,510	-26.7%
Potassium (K)	24,750	0	-100.0%

5. Conclusion

The current research has conducted farm-based net margin analysis to show that an AD unit generating up to 500 kW combined with six to 12 RAS 157 m^3 units for prawn production is economically viable on medium and large arable farms in the East of England at 2022 prices.

Thus, we show that AD & RAS can compete economically with alternative use of crops to secure a supply of feedstocks.

Regarding our modelling approach, the Baseline scenario represented the operation of a cereals-dominated farm without diversification opportunities such as AD or AD & RAS. This baseline allows for model validation and evaluation of changes in the farm's Net Margin due to the introduction of AD and AD & RAS. The model produces realistic outcomes with a typical cereal-arable rotation.

The introduction of AD technology in the farm model demonstrates its commercial viability at 2022 prices on medium and large-scale commercial farms. This diversification leads to a 24% increase in the whole farm's net Margin compared to the baseline. When AD & RAS are jointly introduced in the model, the whole-farm Net Margin increases by 31% and 58%, for six and 12 RAS units, respectively, compared with the baseline scenario. The feedstock for the AD comes primarily from harvested whole-crop cereals. Furthermore, the introduction of AD and AD & RAS results in savings in all nutrients due to the cycling of digestate from crops back onto the land.

Although the positive impact on whole-farm Net Margin by integrating shrimp production in a terrestrial setting combined with farm-based renewable energy has been demonstrated, it is necessary to incorporate and discuss the spatial variations among production systems in the UK as the next steps in this work. Bringing farm models within a spatially explicit framework will allow the identification of which farms should/should not undertake shrimp production and where, why, and what happens to other activities and land use. Moreover, explore this spatial linkage to ecosystem service consequences of this uptake and understands how the Public Money for Public Goods (PMPG) principle within the Agriculture Act affects this result by establishing the impacts of different, spatially targeted, subsidy schemes and rates of support upon uptake of shrimp production on UK farms.

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