ScotFarm - a farm level optimising model

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Introduction

ScotFarm is a dynamic linear programming (LP) model which optimises farm margins within a number of limiting farm resources. The model was developed at SRUC in 2012 in view to conduct impact assessment of CAP reforms on Scottish farms. Earlier versions of the model have been used in a number of farm level analyses of English dairy farms (Shrestha, 2004) and Irish livestock and crop farms (Shrestha 2006, 2007, 2008; Hennessy et al., 2008). The model is based on farming system analysis where all existing farm activities are inter linked (both in physical and financial aspects) and contribute to the optimal objective function that is maximising farm profit. The farm profit comprised of the accumulated revenues collected from the final product of the farm activities (i.e. crops, animals and milk) plus farm payments minus costs incurred for inputs under those activities. The input costs were replacement costs for livestock, variable costs including labour, feed (excluding grazing) and veterinary costs and overhead costs[1] on farms. The model assumes that all farmers are profit oriented.

Modelling software: The ScotFarm is written and solved in GAMS[2] (General Algebraic Modelling Systems) using CONOPT[3] solver.

Data requirement: The model is based on farming system analysis so requires data that represents all farm activities and both qualitative and quantitative linkage between them. A good data set to run the model is the one which provides both physical and financial data for a farm. A good example of data source is the Scottish Farm Accountancy Survey[4] (FAS) which is equivalent to FADN[5] (Farm Accountancy Data Network) that is collected across EU member states. Similar data such as Farm Business Survey[6] (FBS) in England and National Farm Survey[7] (NFS) in Ireland had been used in the model in the past. Besides farm level data, a number of coefficients, parameters and price information are taken from the literatures (such as Farm Management Handbook[8]), expert knowledge and online market reports (such as QMC market reports).

Model structure:

Model basic assumptions:

The fundamental assumption of the model is that all farmers are profit maximising and use farm resources in optimum way to maximise farm profit. The farm profit is determined by the revenues collected under farm activities plus farm support payments minus variable costs associated with the farm activities, when gross margin is used as a measure of profit, and overhead costs when net margin is calculated. The farm variable and overhead costs are taken from the farm survey data and included following costs.

[1] The overhead costs are only included the model is used to determine farm net margins.
[2] https://gams.com/
[3] http://conopt.com/
[4] http://www.gov.scot/Topics/Statistics/Browse/Agriculture-Fisheries/Publications/FASdata
[5] http://ec.europa.eu/agriculture/rica/
[6] http://www.farmbusinesssurvey.co.uk/
[7] https://www.teagasc.ie/rural-economy/rural-economy/national-farm-survey/
[8] https://www.sruc.ac.uk/info/120376/farm_management_handbook

Variable costs = total variable costs (that includes veterinary and medicine, artificial insemination (AI), disinfectant, detergents, branding, bull hire, marketing, disposal of waste, litter, contract (shearing, dipping etc.); crop expenses including seeds, fertilizers, lime, sprays, contract, irrigation and sundry including production, storage, marketing, levy, inspection charges, boxing)

overheads = Fixed costs (includes machinery, electricity, contract for maintenance, machinery repairs, leasing charges, building repairs, rent, council tax, fuel, water, insurance, taxes, services, telephone, VAT, interests)

For yield from grassland, the model uses following assumptions:

Grassland = Permanent grassland[9] (100% yield) + temporary grassland[10] (100% yield) + rough grazing (25% yield)

Model dynamics

The model is dynamic in a sense that it runs for a number of years and optimises farm profits over that time period. The model is not recursive as it is not executed each year. Although farm activities on a particular farm are based on the activities in the previous year, the decision on farm activities on each year is based on the final optimisation process that takes account of all years the model is running. The outcome of the multiple years is then averaged to provide final results of the model. The model provides a counterfactual comparison between different farm conditions and hence a useful tool in impact assessments of for instant policy reforms.

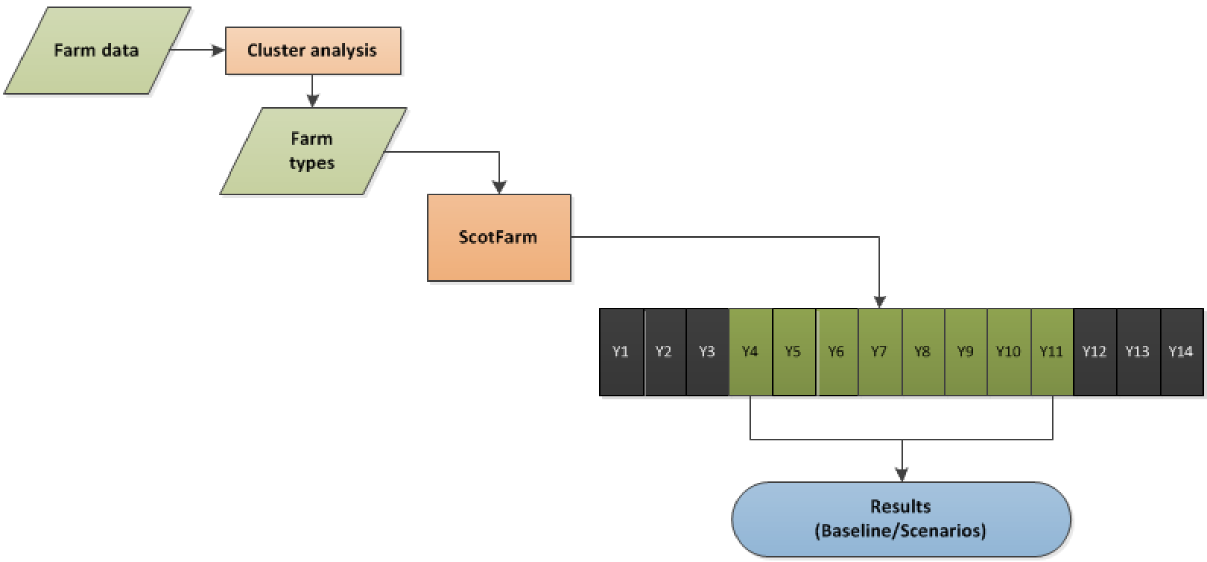


Figure 1: The modelling procedure

Justification of approach

A dynamic LP model, however, has starting and terminal effects that may influence the model results (Ahmad, 1997). The starting effect is due to the model's characteristics of using farm resources as

[9] Permanent grassland cannot be transferred to arable crops less than 5 years
[10] Temporary grassland can be transferred to arable crops any time if needed by the model

optimal levels and hence adjusting the management practises under modelling conditions. The starting effect can be minimised as much as possible by calibrating the model for year 1 and restricting the model to optimise farm margin based on management and resource efficiencies (such as using technological efficiency weightings). The terminal effect makes the model avoid putting inputs on farms and starts offloading farm products to increase farm revenues. This is the case when no restrictions are in place on the final year of the model run. For example, for a beef farm, if there is not restriction on minimum number of animals that should be kept on farm, all beef animals on final year will be sold to maximise farm profits. Providing a minimum number of beef animals would remove this limitation of LP modelling. However, this would put an additional constraint on model which reduces decision making flexibility on farms. An alternative way is to remove results from certain numbers of initial and final years (3-4 years each way) and use the results in the middle part of the model as shown in Figure 1. This will leave the results from the years which are not biased with the starting and terminal effects of LP modelling. The ScotFarm uses this technique to minimise starting and final year effects in the results. For instance, the model runs of farm level data for a number of years (15 years in this case), and providing outputs for each year as shown is Figure 1. The outputs from middle 8 years are then averaged out to provide the farm results under that particular farming condition.

Model components:

The structure of the model is presented in a schematic diagram provided in Figure 2. It consists of four components; dairy, beef, sheep and arable production systems. These systems were constrained by land, labour, feed and stock replacement available to a farm. The total land available to a farm is fixed however farms are allowed to transfer land between different production systems and also re-allocate land to different crop systems. Farms were also allowed to buy in feeds, animal replacements and hire labour if required.

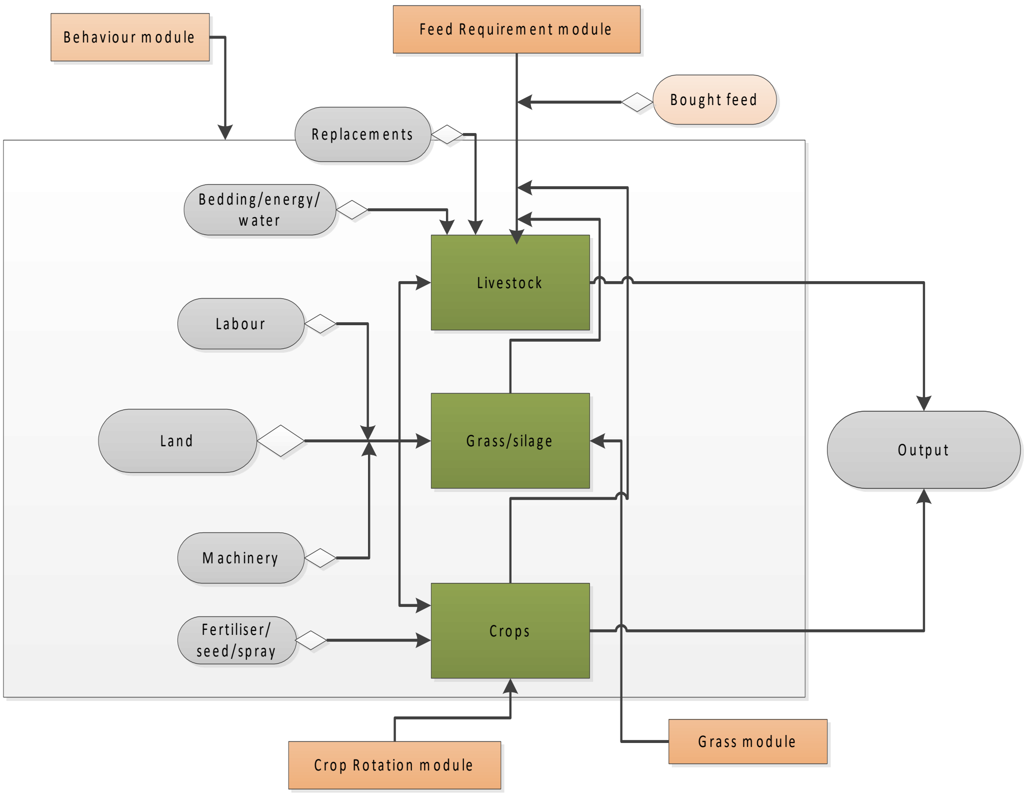


Figure 2: A schematic structure of the ScotFarm model

A detailed description of the components is provided below.

Livestock

The model contains a livestock component which covers all three common livestock production systems in Scotland; dairy, beef and sheep systems. Each of the livestock system uses farm resources and previous year's animal numbers to determine the number of animals kept on farm on a particular year.

Assumptions related to livestock module:

i. All existing activities are available to a farm
ii. All farm animals on a farm have similar production level (one milk yield level, final weight etc.) based on farm level data
iii. Livestock are on optimum feed regime
iv. Mortality rate constant for all farms and all over the years
v. 50% calves born are female
vi. Production level stays the same with all combination of feeds as long as energy and protein requirements are maintained.
vii. All production systems have a pre-set production and replacement cycle e.g., dairy 4 years and beef 8 years.

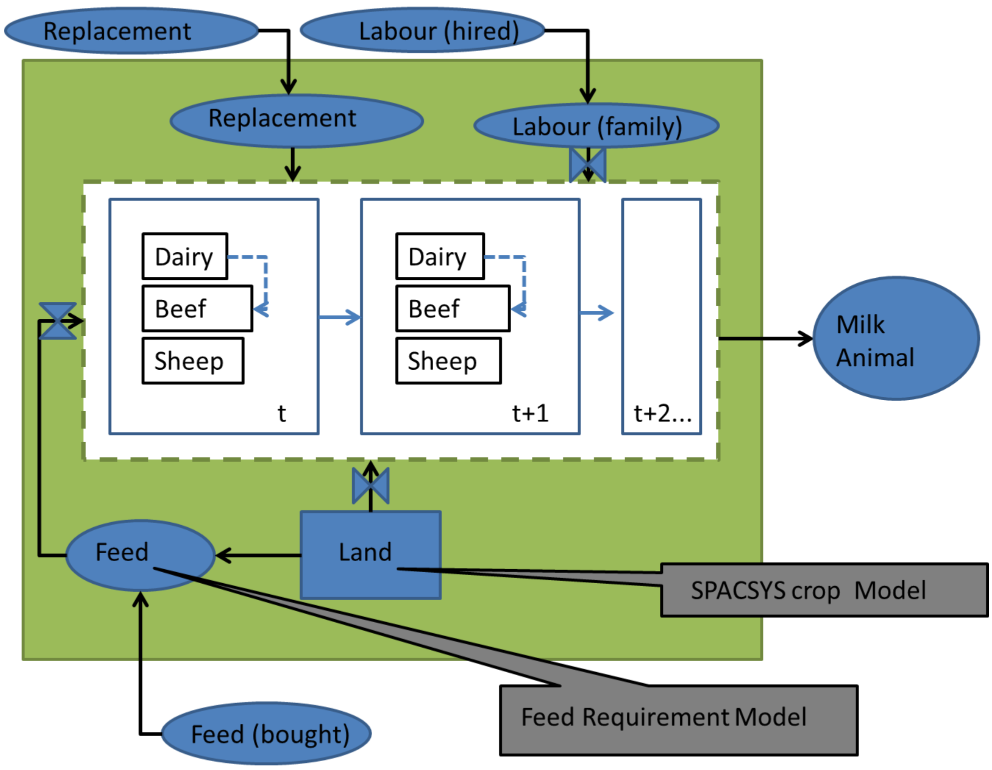


Figure 3: Livestock module

The animal numbers on farm is first set up to the number provided from farm level dataset for the base year, such as described below:

Data initialisation

Starting point where animal numbers (**totani**) are restricted to the numbers from farm level data input (ANI). The number of animals on farms is constrained over an optimal stocking rate and a threshold of maximum number. This is to limit the number of animal to a farm's holding capacity. An optimal stocking rate ensures quality of the grazing land and threshold of certain animal number ensures the number of animals within the holding capacity of the farm such as buildings and milk storage capacity for dairy farms. Farms can however increase animal numbers by increasing farm resources such as renting in land, increasing storage capacity etc.

The dairy system has a four year replacement structure where dairy animals are culled after every four year. Similarly beef and sheep systems followed a two year replacement structure. The animals were replaced by on-farm or off-farm replacement stocks.

```
totani(f,a[11],'t1') = ANI(f,a)
```

Number of animals on farm is restricted to a threshold 'X' times the numbers in the farm level input data. '**X**' depends on the holding capacity of a farm.

```
totani(f,a,t) ≤ ANI(f,a)*X
```

Beef system

There are four categories of beef animals in the model; suckler (**'asc'**), calf (**'asc6'**), 1 year old beef ('ab1')and 2 year old beef ('ab2'). The system in the model has three activities; suckler, rearer and finisher activities. The model selects these activities based on the starting number of the animals and management practices represented in the farm level data. For example if there are no suckler beef on farm in the starting year, the model will not select suckler activity during the model runs.

Animal dynamics

The number of animals in each category is determined by the number of animals in the previous year and buying and selling activities in the current year. Suckler beef numbers ('asc') are maintained on farms based on suckler numbers in the previous year. They are regularly replaced by culling and buying. The number can change each year by the model. Calf ('asc6') number equals to number of sucklers and calving and survival rates. Any beef number after 1st year is the number of the animals in the previous year plus numbers of animals bought minus number of animals sold that year.

```
totani(f,'asc',y) = totani(f,'asc',y-1)+ buysuck(f,y)- cullsuck(f,y-1)

totani(f,'asc6',y) = totani(f,'asc',y)*calrate*survrate

totani(f,'ab1',y) = totani(f,'asc6',y-1)- sellcalf(f,y-1) + buybeef1(f,y)

totani(f,'ab2',y) = totani(f,'ab1',y-1)- sellbeef1(f,y-1)
```

[11] All model subscripts are defined in the Index section

Activities and conditions

Beef activities are restricted by following conditions. The number of 1-year old beef animals sold (`sellbeef1`) should be less than total year 1 beef animals on farm. All beef animals are sold when they reach 2 years of age (`sellbeef2`). Sold calf numbers should be less than or equal to the total number of calves on farm.

```
sellbeef1(f,y) ≤ totani(f,'ab1',y);

sellbeef2(f,y) = totani(f,'ab2',y);

sellcalf(f,y) ≤ totani(f,'asc6',y);
```

The suckler replacement cycle is assumed to be 8 years so that **12.5%** of suckler cows are replaced each year. The number of replacement suckler cannot be more that the number of culled suckler cows.

```
cullsuck(f,y) = totani(f,'asc',y)* 0.125

buysuck(f,y) ≤ cullsuck(f,y)
```

Dairy system

The dairy system in the model assumes an average milk yield based on farm data for all animals on farm. The system is assumed to follow 4 years of lactation cycle which means once start lactating, the animals are kept till their fourth lactation.

Animal dynamics

Dairy female calves (`'ac'`) are 50% of calves born to the dairy cows (`'ad'`) based on fixed calving and survival rates. Rest of the calves are assumed to be male and sold immediately.

```
totani(f,'ac',y) = totani(f,'ad',y)*calrate*0.5*survrate
```

Dairy heifers (`'ah'`) in a particular year (`'y'`) are the number of calves in previous year and any heifers bought in that year. Bought heifer number is based on the numbers of the sold (culled) dairy animals. Similarly, dairy numbers is the summation of number of dairy animals and heifers minus the number of culled animals in the previous year. Dairy cycle is assumed to be 4 years so every year dairy animals are culled by 1/4th of the total dairy animals on farm.

```
totani(f,'ah',y) = totani(f,'ac',y-1) + buyheif(f,y)

totani(f,'ad',y) = totani(f,'ad',y-1) + totani(f,'ah',y-1) -
culldairy(f,y-1);
```

Activities and conditions

A quarter of lactating dairy animals is culled (`culldairy`) each year to follow 4-year lactation cycle and is replaced by on-farm heifers and heifers bought in from the market (`buyheif`) bought in. Total milk production is the summation of milk produced by all lactating cows and assumed to be sold in the market. There is no consideration for spillage and own consumption.

```
culldairy(f,y) = totani(f,'ad',y) * 0.25

buyheif(f,y) ≤ culldairy(f,y-1)

totmilk(f,y) = ∑totani(f,"ad",y) * MILKYIELD(f)
```

Sheep system

The number of lamb (`'al'`) in each year is based on number of ewe (`'ae'`), a pre-set lambing and survival rates minus any number of lambs sold that year. Number of sold lamb is constrained over the number of lamb kept on farm. The number of ewe in each year is based on number of ewe the previous year plus any replacement buy the previous year minus number of ewe culled. A condition was set that a farm cannot buy replacement ewe if do not have a sheep system in first year. The replacement (`buylamb`) is restricted to 4 year production cycle and replacement number is also constrained over the culled ewe.

```
totani(f,'al',y) = totani(f,'ae',y)*Lambrate*survratel - selllamb(f,y)

totani(f,'ae',y) = totani(f,'ae',y-1)- sellewe(f,y)+ buylamb(f,y-1)$ANI(f,'ae')
```

Activities and conditions

All lambs are sold within first year of their lives. The culled ewe (`sellewe`) number is restricted to 25% of total ewe number each year. This is based on assumption of 4 year replacement cycle. Finally, the number of replacement should be equal or less than total number of culled ewe.

```
selllamb(f,y) ≤ totani(f,'al',y)

sellewe(f,y) = totani(f,'ae',y)*0.25

buylamb(f,y) ≤ sellewe(f,y)
```

Crop system:

The crop system in the model is constrained over margins generated by each crops. The current version of the model does not take in detailed management practices such as use of machinery, planting and harvesting activities, labour requirements, fertiliser use, crop rotation, irrigation and other crop related activities[12]. These are currently covered by an external crop model, SPACSYS, which generates crop yields, crop rotation and grass yield under a pre-set farm management practices. These crop parameters are used in ScotFarm. The SPACSYS model and its linkages to ScotFarm are described below.

Only the main crops that are available in farm data are included in ScotFarm, however, new crops can be introduced into the system if relevant data (such as yield, gross margin etc.) are available. All crop

[12] Work is undergoing to include crop management practices as well as crop rotation into the ScotFarm.

area is initialised to farm level data and a crop area for a particular year must maintain at least 50% of previous year area. The model assumes that all activities are contracted out and contract costs included in variable costs. If a livestock farm has area under cereal production then it is assumed that all cereal produced is fed to the animal (as whole grain) if the farm data do not show revenue collected from crop production for that farm. Farm decision making on crop area is based on crop yields, gross margins and crop area in the previous year.

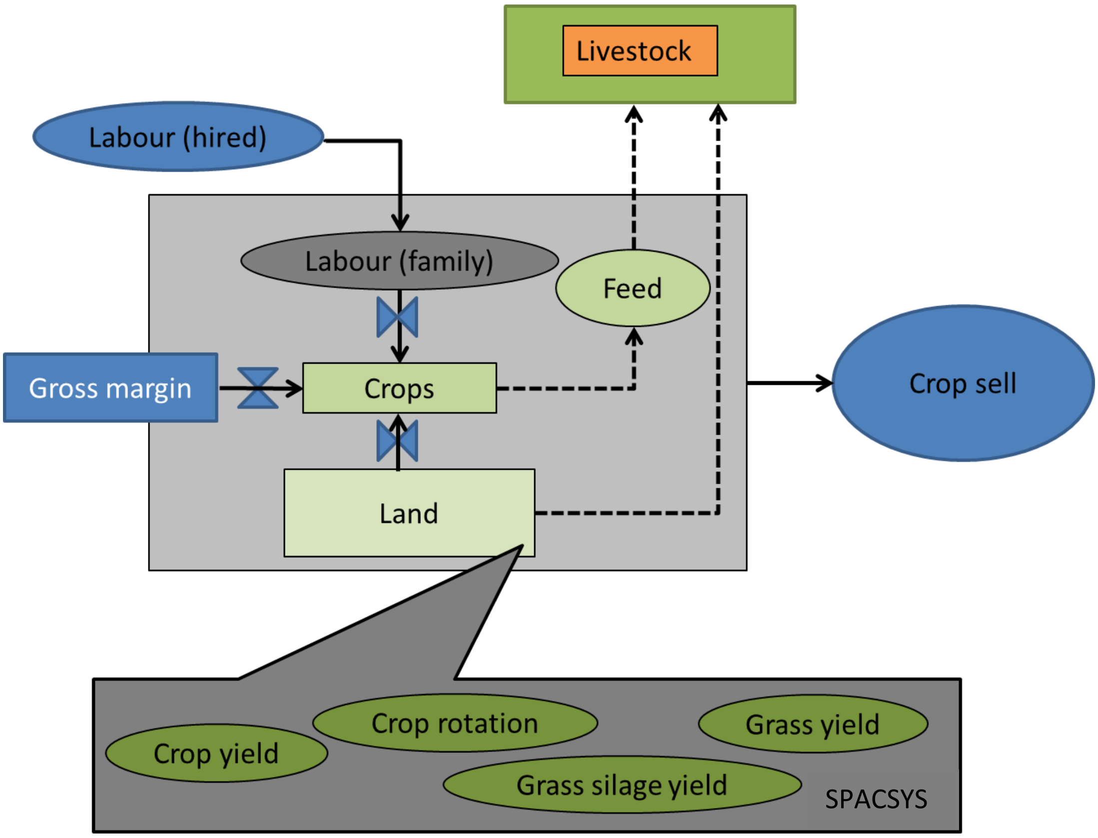


Figure 4: The crop module

Data initialisation

Crop area (`acrop`) under all crops in year one is initialised to the area under crops in farm level data (`CROPINI`). To adjust for a smooth transition of crop area, land area under each crop must be at least 50% of the land area under that crop in the subsequent year. Total land area under all crops (`aland`) should be equal to arable land available on farm.

$$(f,c,'y1') = \sum CROPINI(f,c)$$

$$acrop(f,c,y) \geq \sum acrop(f,c,y-1) * \mathbf{0.5}$$

$$aland(f,y) = \sum acrop(f,c,y)$$

Additional constraint is placed to restrict particular crop area not be more than 5 times (an arbitrary threshold) than initial area at any year.

```
acrop(f,c,y) ≤ ∑CROPINI(f,c) * 5
```

SPACSYS[13] (Davide Tarsitino)

SPACSYS is a dynamic deterministic model which operates on a daily time step at field scale. It represents the soil profile using a multi layers approach which enables it to account for water and soil nutrients movements. It comprises five interconnected sub-models; plant, soil C, soil N, weather and soil temperature. In addition several management practices can be simulated (e.g. grazing, ploughing, organic/mineral fertiliser application etc.). It has been previously validated for plant growth (Bingham end Wu, 2011) and soil N and C dynamics (Zhang et al 2016).

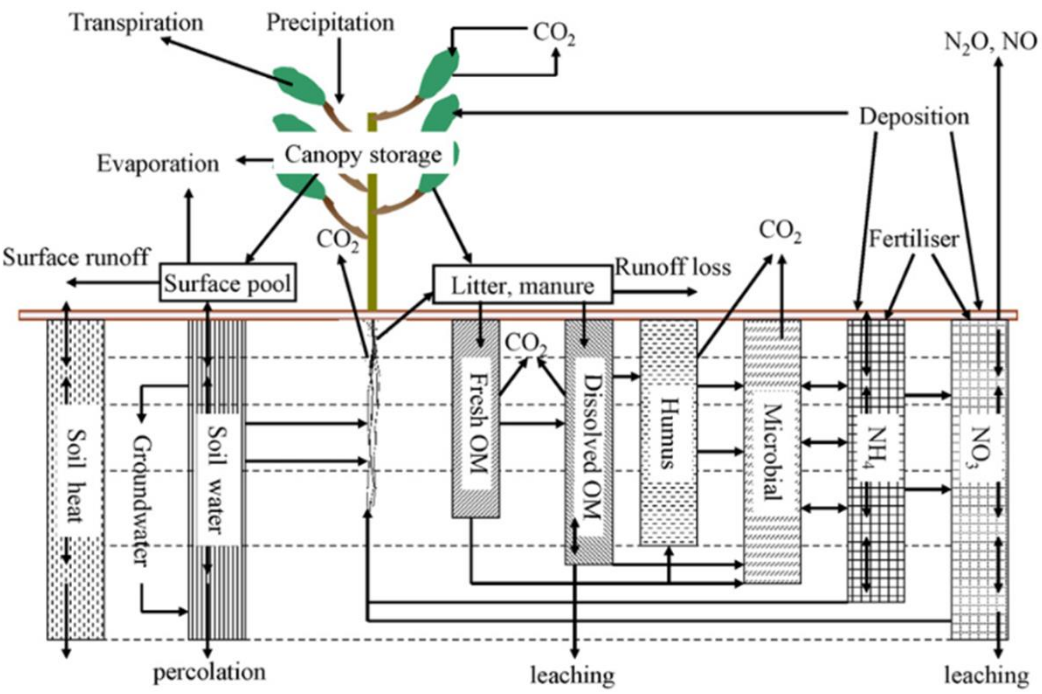


Figure 5: A schematic diagram of SPACSYS

Source: (Wu el. al., 2007)

Model linkage

Soft link

The soft link between SPACSYS and ScotFarm is achieved by feeding crop outputs from SPACSYS such as crop and grass yields and crop rotation to be used in ScotFarm directly. For this the assumption

[13] A more detail description is available @ https://www.soil-modeling.org/test_models/model-descriptions/syspac

behind both of the model needs to be consistent as much as possible such as use of fertiliser, stocking density, crops in rotation, grazing pattern, silage cuts, soil type and location of the modelled farm.

*Emulator link (*supported by BIOSS, University of Edinburgh*)*

The hard linkage of the two models is achieved by using an emulator (XXX). The emulator is a statistical tool that has been developed at the BIOSS, University of Edinburgh. The emulator takes on outputs from both SPACSYS and ScotFarm under a set of pre-conditioned scenarios and generates model outputs based on these two sets of outputs for optional scenarios (Figure 6). This linkage can run a number of analyses in a short span of time so is useful in saving modelling time and also to test new scenarios.

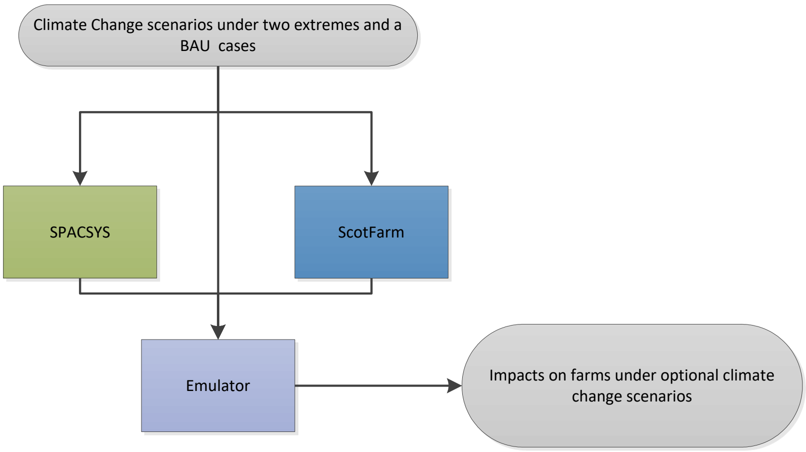


Figure 6: Linkage of SPACSYS and ScotFarm using an emulator

Farm resources

Land

Total agricultural land is assumed to be fixed in the model. However, this assumption can be removed to allow land transaction by adding renting/letting or selling/buying land activity. For that, one condition needs to put in place that if a farm is renting in then there must be a farm letting out land. Total agricultural land (tland) is made up of arable land (aland), grassland – permanent/temporary (gland) and rough grazing land (RG_land).

tland(f,y) = aland(f,y) + gland(f,y)+ RG_land(f)

Grassland consists of grassland used for grazing (gfland), for grass silage (gsland) and hay (ghland). It is assumed that farmers can reallocate land to grazing or silage/hay production based on feed requirement for animals on farms.

gland(f,y) = gfland(f,y)+ gsland(f,y)+ ghland(f,y)

Grassland is used to put in stocking rate (STR) constraint on total number of animal on a farm. The stocking rate on each farm is fixed to the existing data inputs assuming that all farms were operating under optimum stocking rate. Two rates STR on temporary and permanent grassland and STR2 on rough grazing land are used to differentiate land capabilities.

```
totani(f,a,y)*LU(a) ≤(gland(f,y))*STR(f)+ RG_land(f)*STR2(f)
```

Land transaction

Farms are allowed to rent in and let out land if that activity is possible. Under such case, additional land variables rent land (r_land) let land (l_land).

```
tland(f,y) = aland(f,y) + gland(f,y)+ RG_land(f)+ r_land(f) –
l_land(f)
```

This constraint, however, works better if total accumulated land area is used at a regional level (`Reg_land`). A farm under that condition can only rent in land if other farms in the region are letting their land out.

```
Reg_land('y1') = FARMLAND(f)

Reg_land(y)= ∑tland(f,y) + ∑r_land(f) – ∑l_land(f)
```

Labour

It is assumed that all labour used in the model is skilled labour. Labour requirement (`LAB`) for each of the farm activity is taken from literature (such as Farm Management Handbook). Total labour hour (`tlab`) is determined by first using family labour (`flab`) and only if additional labour is required, labour is hired (`hirelab`). Total labour hour available on farm is based on assumption that 1 Man Unit provides **'2200 hours'** of labour on farm annually. `LAB_cost` is the minimum agricultural wage per hour.

```
livlab(f,a,y)= totani(f,a,y) * LAB(a)

tlab(f,y) = livlab(f,a,y)

tlab(f,y) ≤ flab(f)*2200) + hirelab(f,y)

tlabcost(f,y)= hirelab(f,y)*LAB_cost
```

Feed

A feed module was developed in Excel and calculates weight gain of an animal each day based on Brody growth function (Kaps et al., 2000) as follows;

$$W_t(t) = A - (A - W_{t0})e^{-kt}$$

Where, W_t is weight at given time t in days; W_{t0} is the weight at birth; A is the mature weight; k is the maturing rate index.

Energy and protein requirements for individual animal each day for maintenance, growth, pregnancy and lactation are then determined based on Alderman & Cottrill (1993).

For example total energy requirement (T_e) is calculated as follows;

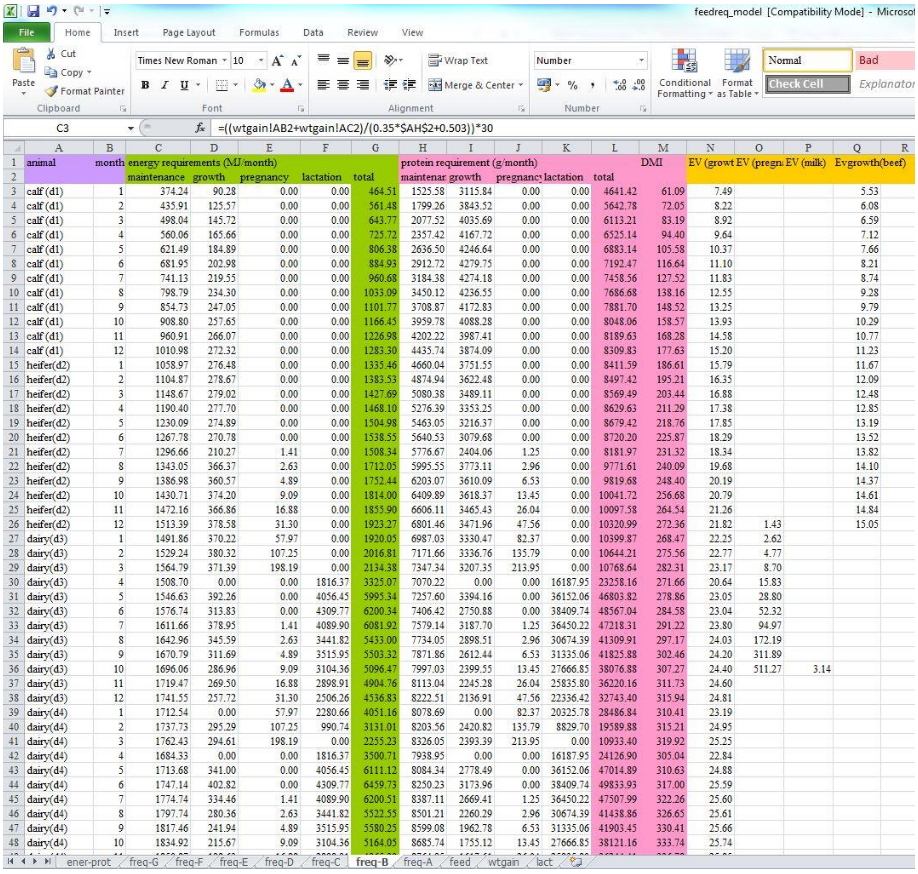
$$T_e = M_e + G_e + P_e + L_e \qquad \forall\ t$$

Where, M_e = energy requirement for maintenance; G_e = energy requirement for growth; P_e = energy requirement for pregnancy and L_e = energy requirement for lactation.

Each of the components in above equation is determined separately for example, energy requirement for maintenance is determined as follows;

$$M_e = (F + A)/k_m$$

Where, F = fasting allowance; A = activity allowance and k_m = efficiency coefficient for maintenance.



	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q
1	animal	month	energy requirements (MJ/month)					protein requirement (g/month)					DMI	EV (growt	EV (pregn	EV (milk)	Evgrowth(beef)
2			maintenance	growth	pregnancy	lactation	total	maintenar	growth	pregnancy	lactation	total					
3	calf (d1)	1	374.24	90.28	0.00	0.00	464.51	1525.58	3115.84	0.00	0.00	4641.42	61.09	7.49			5.53
4	calf (d1)	2	435.91	125.57	0.00	0.00	561.48	1799.26	3843.52	0.00	0.00	5642.78	72.05	8.22			6.08
5	calf (d1)	3	498.04	145.72	0.00	0.00	643.77	2077.52	4035.69	0.00	0.00	6113.21	83.19	8.92			6.59
6	calf (d1)	4	560.06	165.66	0.00	0.00	725.72	2357.42	4167.72	0.00	0.00	6525.14	94.40	9.64			7.12
7	calf (d1)	5	621.49	184.89	0.00	0.00	806.38	2636.50	4246.64	0.00	0.00	6883.14	105.58	10.37			7.66
8	calf (d1)	6	681.95	202.98	0.00	0.00	884.93	2912.72	4279.75	0.00	0.00	7192.47	116.64	11.10			8.21
9	calf (d1)	7	741.13	219.55	0.00	0.00	960.68	3184.38	4274.18	0.00	0.00	7458.56	127.52	11.83			8.74
10	calf (d1)	8	798.79	234.30	0.00	0.00	1033.09	3450.12	4236.55	0.00	0.00	7686.68	138.16	12.55			9.28
11	calf (d1)	9	854.73	247.05	0.00	0.00	1101.77	3708.87	4172.83	0.00	0.00	7881.70	148.52	13.25			9.79
12	calf (d1)	10	908.80	257.65	0.00	0.00	1166.45	3959.78	4088.28	0.00	0.00	8048.06	158.57	13.93			10.29
13	calf (d1)	11	960.91	266.07	0.00	0.00	1226.98	4202.22	3987.41	0.00	0.00	8189.63	168.28	14.58			10.77
14	calf (d1)	12	1010.98	272.32	0.00	0.00	1283.30	4435.74	3874.09	0.00	0.00	8309.83	177.63	15.20			11.23
15	heifer(d2)	1	1058.97	276.48	0.00	0.00	1335.46	4660.04	3751.55	0.00	0.00	8411.59	186.61	15.79			11.67
16	heifer(d2)	2	1104.87	278.67	0.00	0.00	1383.53	4874.94	3622.48	0.00	0.00	8497.42	195.21	16.35			12.09
17	heifer(d2)	3	1148.67	279.02	0.00	0.00	1427.69	5080.38	3489.11	0.00	0.00	8569.49	203.44	16.88			12.48
18	heifer(d2)	4	1190.40	277.70	0.00	0.00	1468.10	5276.39	3353.25	0.00	0.00	8629.63	211.29	17.38			12.85
19	heifer(d2)	5	1230.09	274.89	0.00	0.00	1504.98	5463.05	3216.37	0.00	0.00	8679.42	218.76	17.85			13.19
20	heifer(d2)	6	1267.78	270.78	0.00	0.00	1538.55	5640.53	3079.68	0.00	0.00	8720.20	225.87	18.29			13.52
21	heifer(d2)	7	1296.66	210.27	1.41	0.00	1508.34	5776.67	2404.06	1.25	0.00	8181.97	231.32	18.34			13.82
22	heifer(d2)	8	1343.05	366.37	2.63	0.00	1712.05	5995.55	3773.11	2.96	0.00	9771.61	240.09	19.68			14.10
23	heifer(d2)	9	1386.98	360.57	4.89	0.00	1752.44	6203.07	3610.09	6.53	0.00	9819.68	248.40	20.19			14.37
24	heifer(d2)	10	1430.71	374.20	9.09	0.00	1814.00	6409.89	3618.37	13.45	0.00	10041.72	256.68	20.79			14.61
25	heifer(d2)	11	1472.16	366.86	16.88	0.00	1855.90	6606.11	3465.43	26.04	0.00	10097.58	264.54	21.26			14.84
26	heifer(d2)	12	1513.39	378.58	31.30	0.00	1923.27	6801.46	3471.96	47.56	0.00	10320.99	272.36	21.82	1.43		15.05
27	dairy(d3)	1	1491.86	370.22	57.97	0.00	1920.05	6987.03	3330.47	82.37	0.00	10399.87	268.47	22.25	2.62		
28	dairy(d3)	2	1529.24	380.32	107.25	0.00	2016.81	7171.66	3336.76	135.79	0.00	10644.21	275.56	22.77	4.77		
29	dairy(d3)	3	1564.79	371.39	198.19	0.00	2134.38	7347.34	3207.35	213.95	0.00	10768.64	282.31	23.17	8.70		
30	dairy(d3)	4	1508.70	0.00	0.00	1816.37	3325.07	7070.22	0.00	0.00	16187.95	23258.16	271.66	20.64	15.83		
31	dairy(d3)	5	1546.63	392.26	0.00	4056.45	5995.34	7257.60	3394.16	0.00	36152.06	46803.82	278.86	23.05	28.80		
32	dairy(d3)	6	1576.74	313.83	0.00	4309.77	6200.34	7406.42	2750.88	0.00	38409.74	48567.04	284.58	23.04	52.32		
33	dairy(d3)	7	1611.66	378.95	1.41	4089.90	6081.92	7579.14	3187.70	1.25	36450.22	47218.31	291.22	23.80	94.97		
34	dairy(d3)	8	1642.96	345.59	2.63	3441.82	5433.00	7734.05	2898.51	2.96	30674.39	41309.91	297.17	24.03	172.19		
35	dairy(d3)	9	1670.79	311.69	4.89	3515.95	5503.32	7871.86	2612.44	6.53	31335.06	41825.88	302.46	24.20	311.89		
36	dairy(d3)	10	1696.06	286.96	9.09	3104.36	5096.47	7997.03	2399.55	13.45	27666.85	38076.88	307.27	24.40	511.27	3.14	
37	dairy(d3)	11	1719.47	269.50	16.88	2898.91	4904.76	8113.04	2245.28	26.04	25835.80	36220.16	311.73	24.60			
38	dairy(d3)	12	1741.55	257.72	31.30	2506.26	4536.83	8222.51	2136.91	47.56	22336.42	32743.40	315.94	24.81			
39	dairy(d4)	1	1712.54	0.00	57.97	2280.66	4051.16	8078.69	0.00	82.37	20325.78	28486.84	310.41	23.19			
40	dairy(d4)	2	1737.73	295.29	107.25	990.74	3131.01	8203.56	2420.82	135.79	8829.70	19589.88	315.21	24.95			
41	dairy(d4)	3	1762.43	294.61	198.19	0.00	2255.23	8326.05	2393.39	213.95	0.00	10933.40	319.92	25.25			
42	dairy(d4)	4	1684.33	0.00	0.00	1816.37	3500.71	7938.95	0.00	0.00	16187.95	24126.90	305.04	22.84			
43	dairy(d4)	5	1713.68	341.00	0.00	4056.45	6111.12	8084.34	2778.49	0.00	36152.06	47014.89	310.63	24.88			
44	dairy(d4)	6	1747.14	402.82	0.00	4309.77	6459.73	8250.23	3173.96	0.00	38409.74	49833.93	317.00	25.59			
45	dairy(d4)	7	1774.74	334.46	1.41	4089.90	6200.51	8387.11	2669.41	1.25	36450.22	47507.99	322.26	25.60			
46	dairy(d4)	8	1797.74	280.36	2.63	3441.82	5522.55	8501.21	2260.29	2.96	30674.39	41438.86	326.65	25.61			
47	dairy(d4)	9	1817.46	241.94	4.89	3515.95	5580.25	8599.08	1962.78	6.53	31335.06	41903.45	330.41	25.66			
48	dairy(d4)	10	1834.92	215.67	9.09	3104.36	5164.05	8685.74	1755.12	13.45	27666.85	38121.16	333.74	25.74			

Figure 6: A snippet of feed requirement module

Besides energy and protein requirements, dry matter intake (DMI) by individual animals is also determined in the module based on weight gain and metabolisabilty of a feed. This provides a constraint on the voluntary feed intake by an animal. A snippet of the module in excel is provided above(Figure 6).

Feeds available to the livestock on farm are taken from existing farm data which includes fresh grass, grass silage, hay (maize silage), concentrate, whole grains and others. Dry matter function, energy and protein contents for each of the feed are taken from literature. An example of the feed content is provided in Table 1.

Table 1: Feed contents

Feed	Dry matter (kg/kg)	Energy (MJ/kg)	Protein (kg/kg)
Fresh grass	1	11.2	0.16
Grass silage	1	10.6	0.13
Concentrate	0.86	15	0.36
Hay	0.85	8.6	0.09
Whole grain	0.86	13.8	0.13
Maize silage	0.29	11.3	0.09

Feed system

The feed system in the model uses all available feed at first and brings in bought feed when required. Total number of animal that can be kept on farm is constrained under their requirements of energy (`ENREQ`), protein (`PREQ`), feed intake (`DMI`) and availability of total feed (`mfeed`) that fulfil those requirements.

```
totani(f,a,y)*ENREQ(a,m) ≤ ∑ mfeed(f,a,y,m,b)*ENFEED(b))
totani(f,a,y)*PREQ(a,m) ≤ ∑ mfeed(f,a,y,m,b)*PRFEED(b))
totani(f,a,y)*DMI(a,m) ≤ ∑ mfeed(f,a,y,m,b)*DMFRAC(b))
```

All available feed is determined by the land to produce that feed and specific yield for a particular farm. Yield for fresh grass, grass silage and hay are taken from SPACSYS which uses farm data (stocking rate, location and soil type) to simulate these feed yields. A grass switch (`GRASS_SWT`) is used to allow grazing on field (based on a threshold grass quantity (0.5 t/ha) available on field. This switch ensures the minimum amount of grass required on land for grazing. It is assumed that once silage is cut (based on 1-, 2- and 3-cut options), land under silage production can be used for grazing. A silage switch (`GSILAGE_SWT`) is used to control grazing option on silage land. SPACSYS do not consider rough grazing conditions for grass growth simulation, hence, it is assumed that rough grazing can produce around 30% of grass growth in a temporary/permanent grassland. Besides on-farm production of grass silage, farms are also allowed to buy grass silage from market if necessary.

```
∑mfeed(f,a,y,m,"fg"))  ≤ gfland(f,y)*GRASS_YIELD(m)*
                           GRASS_SWT(m)+ gsland(f,y)*GRASS_YIELD(m)
                           *GSILAGE_SWT(m) + RGRAZ(f)
                           *GRASS_YIELD(m)*GRASS_SWT(m)*0.3;

∑mfeed(f,a,y,m,"hay")) ≤ ghland(f,y)*HAYYIELD;
```

```
∑mfeed(f,a,y,m,"gsil")) ≤ gsland(f,y)*SILAGE_YIELD(m)*1000 +
buysil(f,y,m);
```

The compound feed in the model comes from two sources, on-farm produced feed crop ($acrop_{fc}$) which is mostly cereal used as 'whole grain feed' and concentrates bought from the market. There is a minimum (or/and maximum) allotment of concentrate feed used on a farm that is controlled by 'CONCUSE' for each animal category.

```
∑mfeed(f,a,y,m,'conc')) ≥ totani(f,a,y)*CONCUSE(a);

∑mfeed(f,a,y,m,'grain')) ≤ ∑(acrop(f,fc,y)*CROPYIELD(fc)) ;
```

Price projections

There are two sources from where prices are gathered: i) Farm survey data and ii) market data. To account for a possible impact of future commodity prices, price projections were used to represent price changes over the model time frame. The price projections are taken from external partial equilibrium (PE) model namely FAPRI[14] model. The requirement is that the conditions and assumption behind the scenarios used for the price projection needs to be similar to the conditions and assumption in ScotFarm. An example is provided in Figure 7 below, which provides the FAPRI-UK price projections (index 2010 prices) for different agricultural commodities in the UK. The price projections are used as indices and included in ScotFarm to generate revenue and cost of each production activities.

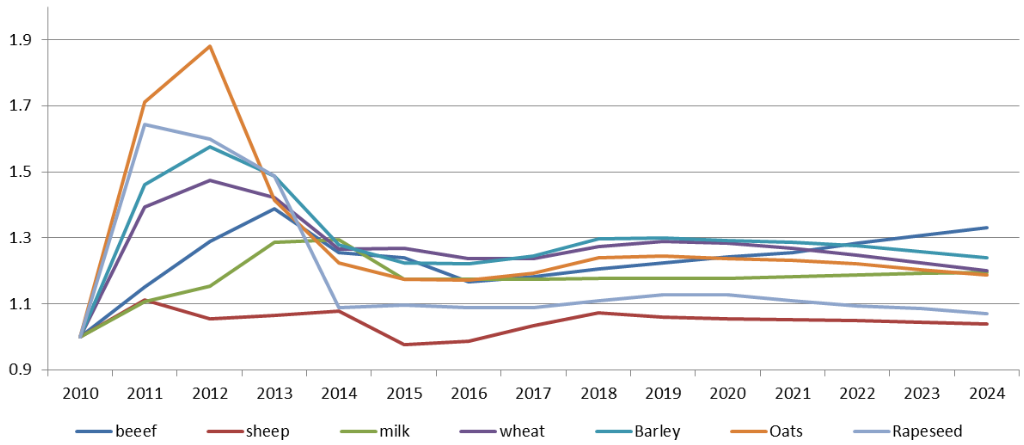


Figure 7: The FAPRI-UK price projections for different agricultural commodities (index to 2010 prices)[15].

[14] For details please see http://www.fapri.iastate.edu/models/

[15] https://www.afbini.gov.uk/publications/fapri-uk-baseline-projections-2015

Farm margins

The model can produce farm gross margins or net margins based on data availability and requirement of specific margins for a study. Farm margin for each of the production system is determined separately. For example, dairy margins (`DairyM`) is the summation of total revenues from milk sell, male calf sell and culled dairy animals minus replacement costs, variable costs and feed costs. The price indices ('DI','BI', 'SI', 'VID' 'VIB' and 'SIB') are taken from a PE model as described above. The coupled farm payments are linked with respective production activities and added to the production margins. For instance for Scottish livestock farms, Voluntary Calf Payment Scheme (`VCS_calf`) and Voluntary Ewe Payment Scheme (`VCS_ewe`) are added while determining the Beef and Sheep margins.

Dairy margin

```
DairyM  = totmilk(f,y)*MILKPrice(f)*MI(y)

           +  sellmcalf(f,y)* CALFPrice(f)*DI(y) +
             culldairy(f,y)*DAIRYPrice(f) *DI(y) -
             buyheif(f,y)*HEIFPrice(f) *DI(y)- ∑
             totani(f,ads,y)*LU(ads)*(VARCosts(f))*VID (y))-
             ∑(mfeed(f,ads,y,m,"conc")*CONCPrice*0.001)*CI(y)) +
             mfeed(f,ads,y,m,"gsil")* SILAGE_Price))
```

Beef margin

```
BeefM = sellcalf(f,y)*CALFPrice(f)*BI(y) +
           sellbeef1(f,y)*BEEF1Price(f)*BI(y) +
           sellbeef2(f,y)*BEEF2Price(f)*BI(y) +
           cullsuck(f,y)*CULLPrice(f) )*BI(y) -
           buycalf(f,y)$ANI(f,'asc6')*CALFPrice(f)*BI(y) -
           buysuck(f,y)$ANI(f,'asc')*SUCKPrice(f)*BI(y) -
           buybeef1(f,y)$ANI(f,'ab1')*BEEF1Price(f)*BI(y) - ∑
           totani(f,ab,y)*(VARCosts(f)*VIB(y)*LU(ab))) -
           totani(f,a,y)*OH ∑(mfeed(f,ab,y,m,'conc')
           *CONCPrice*0.001)*CI(y)) + totani(f,'asc6',y)*VCS_calf
```

Sheep margin

```
SheepM = selllamb(f,y)* LAMBPrice(f) * SI(y) +
          sellewe(f,y)*EWEPrice(f) * SI(y)  -
          buylamb(f,y)$ANI(f,'ae')*LAMBPrice(f)* SI(y) - ∑
          totani(f,ass,y)*LU(ass)*0.05*VIS(y)) -
          ∑(mfeed(f,ass,y,m,'conc') *CONCPrice*0.001)*CI(y)) +
          totani(f,'ae',y)*VCS_ewe
```

Crop margin

```
CropM = ∑ acrop(f,c,y)*CROPGM(c)*CrI (c,y))
```

Farm profits (Objective Function)

The model maximises farm profits which is the sum of margins from farm activities, subsidy payments (Basic Payment Scheme (BSP) and Area of Natural Constraint payments (LFAS) minus labour costs (tlabcost), feed production costs (GCosts, SCosts and HCosts) and overhead costs (OHCosts). The decoupled farm subsidies (BPS[16] and LFAS) are added to total farm margin. The fixed costs (OHCosts) can be used in the objective function if farm net margins are to be examined.

```
Tfgm = DairyM + BeefM + SheepM + CropM + BSP + LFAS
                - tlabcost - buysil*SILAGEPrice - gfland*GCosts -
gsland*SCosts - ghland*HCosts                           ( - OHCosts)
```

This set up of the objective function maximises the individual farm margins over the time frame of the model runs. The farms are not linked with each other hence all farms would have individual margins regardless of farm activities chosen by individual farms. The farms can be linked together with interacting activities between farms such as land transactions, herd movements (replacements, buying and selling activities), farm resource exchanges (feed, machinery, manure/slurry). These interacting activities can be restricted at a regional or national level. With these activities, farm margins optimisation of any single farm will rely on farm activities on other farms. For example, a profiting farm can expand its production activity and maximise its profits by acquiring more land. But this is only possible if there are other farms selling their land.

[16] BSP is linked with farm land by using the rates of farm payment (region1, region2 and region 3 rates) under the categories of land available on farms. This is calculated at pre-modelling stage and the calculated payments for each farm are then included in the model.

Additional constraints used in ScotFarm

The model has flexibility to include constraints to analyse additional characteristics of farm production such as N2O emission from crop production and crop risk. These constraints are described below.

Soil N_2O emission constraint (S Shrestha, V Eory and K Topp)

N_2O emission is a major greenhouse gas (GHG) emission produced through crop production activities on a farm. Due to growing concern about climate change, focus on sustainable farm production, green economy and Scottish government's aims to reduce GHG emissions from agriculture, we included a soil N_2O emission constraint in the crop component of ScotFarm. This enabled the model to determine N_2O emission from crop production and further added to objective function of the model to optimise farm activities to minimise emissions. The N_2O emission constraint is added as a simple soil N_2O emission calculator was developed based on the IPCC 2006 guidelines (IPCC 2006) considering the UK country specific calculations in the latest UK Greenhouse Gas Inventory (Brown et al. 2017). We assume that inorganic N is the only form of N applied to the crops, there is no N mineralisation happening and the cropping activities take place on mineral soils. The farm N_2O emission from crop production is the total emissions from the use of synthetic fertiliser, organic fertiliser and crop residues. The constraint is formulated as follows;

$$\begin{aligned} N_2O\ \text{emission} = &\sum SF_{c,p}*(ESF_{c,p} + EA * AFract_p + EL * LFract_p) \\ &+ \sum OF_{c,p}*(EOF_p + EA*AFract_p + EL * LFract_p) \\ &+ \sum (ESF_{c,p} + EL * LFract_p)* CrpResd_{c,p} \qquad \forall\ f,y \end{aligned}$$

Where,

C = crop type; p = management practice; f = farms; y = years;

SF = synthetic N fertiliser applied [kg N ha^{-1} y^{-1}];

ESF = emission factor of synthetic fertiliser [kg N_2O-N (kg N input)$^{-1}$];

EOF = emission factor for organic N applications [kg N_2O-N (kg N input)$^{-1}$];

EA = emission factor from atmospheric deposition of N [kg N_2O-N (kg N volatilised)$^{-1}$];

AFract = fraction of synthetic N fertiliser type f that volatilises [kg N (kg N input)$^{-1}$];

EL = emission factor from N leaching and runoff [kg N_2O-N (kg N leached and runoff)$^{-1}$];

LFract = fraction of N inputs/mineralised that is lost through leaching and runoff [kg N (kg N input)$^{-1}$];

CrpResd = N in residue of crop [kg N ha^{-1}]

The N2O emission is first converted to total carbon costing and then included in the objective function of the model. The total carbon costing is formulated as follows;

$$TCOST = N_2O\ emission * CO_2eqv * CCOST * 0.001 \quad \forall\ f,y$$

Where, TCOST = total carbon costing; CO_2eqv = CO_2 equivalent of N_2O emission; CCOST = price of traded carbon (£/tCO_2e)

Crop risk modelling

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Introduction

Resource allocation decisions in agriculture are risky in the sense that outcomes from a particular allocation of land, labour and capital are uncertain: yields vary, animals are subject to diseases, prices for price-inelastic commodities change proportionately more than the corresponding changes in supply that drives the price changes. This affects farmers directly through the mostly widely used measure of enterprise outcome, the Gross Margin i.e. Sales (usually termed 'Output' to show that valuations reflect non-cash items such as stored grain, or transfers between enterprises) net of Variable Costs of Production. Gross Margins for agricultural enterprises, both crop and livestock based, are variable. This is not a problem for a farmer who is indifferent to this variability (is 'risk neutral'); however, most studies find that farmers are risk averse, to different degrees. Any risk averse farmer will be willing to accept lower levels of profitability in return for a reduction in variability of profit, as driven by variability in Gross Margin. This reduction can be achieved in different ways: an arable farmer can use crop protection methods to control disease and therefore yield variability. Livestock farmers use veterinary services in a similar way to reduce livestock production losses. Use of insurance, contracts, including futures markets, building Balance Sheet resilience (improving ratios of assets to liabilities) are all ways of managing risk.

From a farm level perspective, risk can be included in modelling studies in a number of ways: see Ramsden and Wilson (2016) for a review. In the absence of any specific information about an individual's attitude to risk, in this analysis we use a representative Scottish arable farm, growing some combination of winter wheat, winter barley, spring barley, winter oats and winter oilseed rape. Profitability is assumed to be a function of Gross Margin per hectare and the farmer's decision on how much land to allocate to each crop. Risk is assumed to be a function of individual crop variability and the covariance between different crops; total farm variability (risk) is then a product of the individual variances and co-variances and the amount of land allocated to each crop.

Modelling methodology

Using national yield data for Scotland from 1999 to 2018, we calculated mean yields and co-variances of yield between the above five crops, Table 1. All are positive; however, despite this, there is scope for growing crops in combination to reduce variability as the co-variances in many cases are less than the variances: e.g. the variance of winter barley is 0.23 tonnes per hectare but the co-variances between winter barley and spring barley, oats and oilseed rape are all less than 0.23 tonnes per hectare.

Table 1: Average yields and co-variance of five main crops in Scotland.

Crops	Mean yields (t/ha)	Co-variances				
		Winter wheat	Winter barley	Spring barley	Oats	Oilseedrape
Winter wheat	8.30	0.3522	0.2276	0.1209	0.1529	0.1013
Winter barley	7.20	0.2276	0.2310	0.0863	0.0866	0.1142
Spring barley	5.63	0.1209	0.0863	0.1196	0.1144	0.0728
Oats	5.66	0.1529	0.0866	0.1144	0.2191	0.0768
Oilseedrape	3.51	0.1013	0.1142	0.0728	0.0768	0.1277

Seven cropping plans were tested. These are not particularly representative of what farmers are doing in Scotland; the intent is more to illustrate the effect of different cropping plans – of differing levels of diversification, as this is the only risk management 'tool' we consider here – on risk and production, with the latter measured by total production of all crops across the 100 hectares. The different cropping plans are shown in Table 2, together with the associated production and level of risk, as measured by standard deviation (i.e. the square root of the total plan variance). The most productive and variable cropping plan is just to grow winter wheat: Total average production is 824 tonnes with a standard deviation of 59 tonnes per hectare. Assuming a normal distribution for wheat yield (not tested), a farmer would expect production to be within 705 and 943 tonnes 95% of the time (plus or minus two standard deviations from the mean). Table 2 shows that different cropping plans trade-off between production and variability in different ways – the most diversified combination, including all five crops in equal amounts (20 hectares) reduces production to 612 tonnes and standard deviation to 37 tonnes. A three crop plan of spring barley, oats and oilseed – chosen as low covariance crop combinations – gives the lowest risk of the plans considered, with a standard deviation (33 tonnes) that is nearly half that of the winter wheat. However, production is also a lot lower, at a mean of 506 tonnes across the 100 hectares.

Table 2: Production variability under different crop combinations

Production tonnes	Var	SD	Rotation	Areas	Bottom
824	3522	59	WW	All wheat	705
596	1706	41	WW OSR	Split	513
580	1470	38	WW OSR WB	Thirds	503
620	1423	38	WW OSR WB SB	Quarters	545
612	1343	37	Five crops	Fifths	539
623	1531	39	WW OSR WB O	Quarters	545
506	1105	33	Low CV	SB O OSR	439

Note that although it is the most variable option, the bottom value of the 95% range (705 tonnes) is still greater than the bottom of the low co-variance plan (439 tonnes). Indeed, winter wheat dominates all the other plans in that its 95% range does not overlap with the 95% range for any of the other plans: all are lower, despite being less variable. This result goes a long way to explain why winter wheat is the preferred crop in locations that are suited to its production (from an agronomic perspective).

When Gross Margins are constructed (i.e. multiplying the yield data by current output prices for each of the five crops and deducting current Variable Costs) the rankings – now in terms of average profitability and standard deviation of profit – of each of the plans don't change much: variability is still driven by variability of yield. Table 3 presents results from the most recent ten years of Gross Margins under the assumption that, from a decision making perspective, more recent information on risk and profitability is more important. Wheat still performs the well; however, the highest mean profit is achieved with winter wheat and oilseed rape (£82,507); this combination also has the highest standard deviation (£11,307), more than twice standard deviation of the low covariance plan (£4,574) Again, the high performance plan, although more risky as measured by variability, has a 95% range that is above any of the other, more diversified, plans. From a policy perspective, this is an interesting result. Risk aversion is not a fixed attribute – farmers learn, particularly from other farmers. Furthermore, increases in wealth (Assets less Liabilities, that is 'Net Worth') will tend to encourage risk taking activity, in the sense of a greater willingness to accept variability. If farmers could be encouraged to accept more variability – to become more resilient – they would also deliver more productivity, other things being equal. A more fully specified farm model than that employed here – one that captured rotational constraints, fertility building aspects of different rotations (break crops, cover crops), environmental constraints and losses and so forth – could determine the extent to which these productivity improvements could be delivered to Scottish Agriculture.

Table 3: Gross margin variability under different crop combinations

Total GM	Var	SD	Rotation	Areas	Bottom
81609	118505232	10886	WW	All wheat	0
82507	127857814	11307	WW OSR	Split	0
77717	92715445	9629	WW OSR WB	Thirds	0
75455	68081250	8251	WW OSR WB SB	Quarters	0
71563	55454233	7447	Five crops	Fifths	0
72287	67840051	8237	WW OSR WB O	Quarters	0
51511	20918859	4574	Low CV	WB SB O	0

Linkage with ScotFarm

The crop risk model links with ScotFarm with a 'soft' linkage. Production and gross margin variability are determined for all crop combinations based on historical crop combinations and are ranked based on the extent of variability. This ranking of different crop and crop combinations is taken as risk factor for the modelling purpose. The model, thereafter, maximises farm profits minimising risk associated with each crop or crop combinations. Scotfarm, however, can use these rankings differently according to the purpose of the model run (study requirement). For example, if farms are categorised in different groups of 'risk averseness', rankings will be weighted according to the risk group. Thus, a 'risk-taking' farm can select activities which are riskier but with higher returns whereas a 'risk-averse' farm will select activities that generate lower risk.

Appendix

Table A1: Subscripts used in the model

index	description
f	farms
y	years
m	months
a	livestock category
‘asc’	suckler
‘ac’	calf
‘ah’	heifer
‘ad’	dairy
‘asc6’	beef calf
‘ab1’	1 year old beef
‘ab2’	2 year old beef
‘al’	lamb
‘ae’	ewe
c	crops
b	feed
‘fg’	fresh grass (grazing)
‘gsil’	grass silage
‘hay’	hay
‘conc’	concentrate
‘grain’	whole grain feed produced on farm

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