Dynamic economic modeling of crop rotation with adaptation practices

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Poster paper prepared for presentation at the EAAE 2014 Congress
'Agri-Food and Rural Innovations for Healthier Societies'

August 26 to 29, 2014
Ljubljana, Slovenia

1. Abstract

We developed a dynamic farm level economic model of crop rotations including nitrogen fertilization, fungicide treatment and liming as adaption practices. Simulations were run at different price and disease scenarios over 30 years. Farmer maximizes present discounted value of futures stream of profits by choosing optimal sequence of four different crops and two types of set aside. Results indicate that crop rotation system favors, or even requires, more crops to tackle against increasing disease pressure. Crop prices play also a key role in providing incentive for farmers to utilize adaptation management.

Keywords: Dynamic optimization, agriculture, climate change, farm management

2. Introduction

Agriculture is challenged by increasingly volatile commodity markets, inevitable climate change and gradually growing environmental constrains. While positive impacts may be anticipated for Northern Europe, increasing climatic variability with higher frequency of extreme events (Trenberth 2011; Field et al., 2012), pest pressure and continuous changes in the regional and global market may present significant challenges for farmers and agricultural production in Nordic countries (Hakala *et. al*., 2011). Crop rotation could maintain the soil productivity, reduce disease risk and pest damage, and thus mitigate yield risks. (Maynard *et. al*., 1997; Hennessy, 2006). In addition, crop rotations in comparison to monocropping could decrease the need of synthetic chemicals inputs and mitigate the greenhouse gas emission. The fungicide treatment is effective against a variety of plant diseases with reasonable costs and it is important in the future if the climate change scenario of high disease pressure is realized. Liming is one of the basic ameliorative measures in order to maintain yields.

The aim of our research is to develop a dynamic economic model of crop rotations with various adaptation practices at a farm, by which we could simulate crop rotation patterns at farm level under different scenarios over 30 years.

3. Methodology

Consider a farmer managing a specific farmland, composed of equally sized parcels within the farm $(p_1,\ldots,p_M)$ located 0–7 km from the farm centre. A farmer plants crops on an annual basis. Assume a farmer maximizes the present discounted value of future stream of profits by choosing the sequence of crops planted. Considering farm level, output prices are fixed. The farmer needs to identify optimal sequence of crops, which can be grown in rotation during the next periods of H years. Six different land use options are included in the model. Nitrogen fertilization and the implied crop yield response based on the earlier approach and choices (selected by Lehtonen 2001) made in the context of Finland, fungicide treatment for barley crop[1] and liming for field parcels (affecting all crops), are incorporated into the model, which are known to affect both yield and cost.

The dynamic model of optimal crop rotation can be formulated and solved via nonlinear programming. Define crops with the superscript *i*. The expected prices of individual crops are represented by $P(c^i)$ (deterministic vector) over time. Subsidies per hectare of each crop is a constant vector described as $S(c^i)$. $C(p,t,c^i)$ is a cost function for cultivating a crop c^i at a parcel p at year t. Considering a finite time horizon, the maximization of the discounted profit function of the farmer's rotation plan is given in (1)–(2):

[1] Due to full parameterization for all the crops are still on-going, we are applying fungicide treatment only for barley parcel, which was extracted and parameterized based on Purola (2013).

$$\underset{A(p,t,c)}{Max}\sum_{t=1}^{H}\sum_{p=1}^{10}\sum_{i=1}^{M}e^{-rt}\Big(Y\big(A(p,t,c^i),p,t,c^i\big)A(p,t,c^i)P(c^i)+S(c^i)-C(p,t,c^i)\Big), \quad (1),$$

$$w.r.t.$$

$$\sum_{\forall c}A(p,t,c^i)=1, \quad (2),$$

where e^{-rt} defines the discount factor, and variable $A(p,t,c)$ describes allocation of land parcel p for a crop c^i at the year t. Equation (2) provides a constraint, which guarantees total land allocation of each field parcel every year. Then, yield function $Y(A(p,t,c),p,t,c)$ describes the yield of a crop c^i on an equally sized parcel p at year t as follows:

$$Y(A(p,t,c^i)=\begin{cases}Y_{MEAN}(p,c^i)Y_{RED}(p,t,c^i)(1+L(p,t,c^i)+F(p,t,c^i)-D(p,t,c^i) & if \quad i=barley\\ Y_{MEAN}(p,c^i)Y_{RED}(p,t,c^i)(1+L(p,t,c^i)) & if \quad i=other\ than\ barley\end{cases} \quad (3)$$

where $Y_{MEAN}(p,c^i)$ is endogenously given mean yield of the crop c^i on a parcel p. Assume $Y_{MEAN}(p,c^i)$ is already determined based on optimal use of nitrogen, $Y_{RED}(p,t,c^i)$ is a yield reduction function of the crop c^i due to monocropping; $L(p,t,c^i)$ is a response function of liming treatment; $F(p,t,c^i)$ is a linear response function of fungicide treatment; $D(p,t,c^i)$ is a disease loss function of barley[2].

The cost function of crop c^i at a parcel p at year t could be written as (4):

$$C(p,t,c^i)=\begin{cases}C_{variable}(c^i)+C_{logistics}(p,t,c^i)+C_{fungicide}(c^i)+C_{liming}(p,t,c^i) & if \quad i=barley\\ C_{variable}(c^i)+C_{logistics}(p,c^i)+C_{liming}(p,t,c^i) & if \quad i=other\ than\ barley\end{cases} \quad (4)$$

where $C_{variable}(c^i)$ is the vector variable costs of the crop c^i; $C_{fungicide}(c^i)$ is the sum cost of fungicide substance and labor cost of spreading fungicide for barley[3]. $C_{logistics}(p,t,c^i)$ is the function of logistics costs of crop c^i on a parcel p at year t, described as (5); $C_{liming}(p,t,c^i)$ is the cost function of using liming for crop c^i on a parcel p at year t, described in (6):

$$C_{logistics}(p,t,c^i)=\frac{2\times(tractor\_cost+labour\_cost)\times distance(p)\times treatment\_times(c^i)}{tractor\_speed} \quad (5),$$

$$C_{liming}(p,t,c^i)=39{,}7\times lime(p,t,c^i)-0.685\times[lime(p,t,c^i)]^2 \quad (6),$$

where *tractor_cost* means the cost of using a tractor per hour; *labour_cost* means the labour opportunity cost per hour; *distance (p)* means the distance from the compound to a parcel in km; *treatment_times(c^i)* is the frequency of using a tractor for the crop c^i; *tractor_speed* is the speed of tractor in km/per hour. The lime cost function (6) is a quadratic function. It depends on the amount of lime used ($lime(p,t,c^i)$), to crop c^i on a parcel p at year t.

[2] As we apply fungicide treatment only for barley, therefore the specific disease loss is also referred only to barley.
[3] Fungicide treatment in this study is only applied on barley.

4. Parameter and Data Set

Model is implemented to a typical average sized cereal producing farm in Southwest Finland. Crop yields are the 16-year-average-yields between 1995 till 2011 extracted from farm-level data in Southwest Finland obtained by statistics of Finland. Variable costs and subsidies of four crops are calibrated from a dynamic regional sector model of Finnish agriculture (DREMFIA) (Lehtonen, 2001). Crop yield, variable cost and subsidy data are presented in Table 1.

Table 1. Crop/land, variable costs, subsidies and output prices used in the model.

crop land	Average yield kg/ha $Y_{MEAN}(p,c^i)$	Variable cost €/ha $C_{\text{variable}}(c^i)$	Subsidy €/ha $S(c^i)$	Current price €/kg
Spring wheat	3576	525	532	0.19
Winter wheat	3759	597	647	0.19
Barley	3579	588	532	0.16
Oilseed	1393	540	578	0.37
Set aside	-	233	405	-
NMF[a)]	-	254	575	-

Note: [a)] NMF refers to the nature management field[4].

A farm includes 10 parcels, whose distances to the farm centre vary between 0 and 7 km, providing the average of the distance 2.9 km in the region (Hiirola & Ettanen 2013). Liming data are obtained from Käytännön maamies[5] Fungicide treatment is currently applied only to barley, but will be defined on other crops as well in the future versions of the model.

Table 2 present the yield penalty matrix settings for scenario analysis. We provide additional high yield penalty matrix in comparison to current/low yield penalty matrix. The values in both tables are based on expert's opinion of MTT plant scientists, and they are to be further proved by robust scientific references. Therefore, we generate six scenarios based on different levels of price and disease pressure, called S1-S6 described in detail as follows: S1: high- disease-pressure vs. high-price; S2: high-disease-pressure vs. current-price; S3: high-disease-pressure vs. low-price; S4: low-disease-pressure vs. high-price; S5: low-disease-pressure vs. current-price; S6: low-disease-pressure vs. low-price

Table 2. Yield penalty matrix under low and (high) disease pressure: $T(c^i, c_2^i)$

Crops	S.Wheat	W. Wheat	Barley	Oilseed	Set-aside	NMF
S. Wheat	0.98(0.95)	0.98(0.95)	0.99(0.98)	1.00(1.00)	1.00(1.00)	1.00(1.00)
W. Wheat	0.98(0.95)	0.98(0.95)	0.99(0.98	1.00(1.00)	1.00(1.00)	1.00(1.00)
Barley	0.99(0.98)	0.99(0.98)	0.99(0.98)	1.00(1.00)	1.00(1.00)	1.00(1.00)
Oilseed	1.00(1.00)	1.00(1.00)	1.00(1.00)	0.70(0.60)	1.00(1.00)	1.00(1.00)
Set-aside	1.00(1.00)	1.00(1.00)	1.00(1.00)	1.00(1.00)	1.00(1.00)	1.00(1.00)
NMF	1.00(1.00)	1.00(1.00)	1.00(1.00)	1.00(1.00)	1.00(1.00)	1.00(1.00)

[4] http://www.mavi.fi/fi/oppaat-ja-lomakkeet/viljelija/Documents/Hakuoppaat/Hakuopas%202013.pdf
[5]http://kaytannonmaamiesfi.virtualserver27.hosting.fi/wp-content/uploads/2013/12/nopeavaikutteinen_2012.pdf

5. Results and discussion

Figure 1a and Figure 1b show the simulated development of land allocation over the next 30 years under two extreme scenarios S1 and S6. Clearly, when the price is high, the wheat dominates the land allocation. Particularly, winter wheat provides higher gross margins than spring wheat due to its slightly higher yield and some agri-environmental subsidy payments incentivizing winter time vegetation. Meanwhile, set aside would not be an option in land allocation decision at all for farmers under high price scenarios. When output prices are low even with low disease pressure as portrayed in S6, spring wheat wins winter wheat over in the land allocation as its variable cost is lower. Furthermore nature management field (NMF) is more attractive option for farmers despite its higher cost, due to agri-environmental subsidies. However, the NMF subsidy is paid only on max 15 % of a total farm area of a farm in the agri-environmental program. Most of the nature management field area is maintained in distant parcels where the logistic costs are the largest. Also due to the higher logistic costs, liming adaptation is less favorable in the distant parcels.

Both S1 and S6 indicate that oilseed is a good break crop for cereals, but it is cultivated infrequently due to its lower gross margin compared to wheat, and high yield penalty on successive cultivation on the same field parcel over years. Interestingly, barley dominates oilseeds in the most of years in the scenario S1 and vice versa in all years in S6. This is because of the yield gains of barley due to the fungicide treatment, in S1 where the output price in S1 stays in a high level. (See also Table 3). Therefore, oilseed dominates barley only when the disease pressure is low and the crop prices sustain low as well, as in S6.

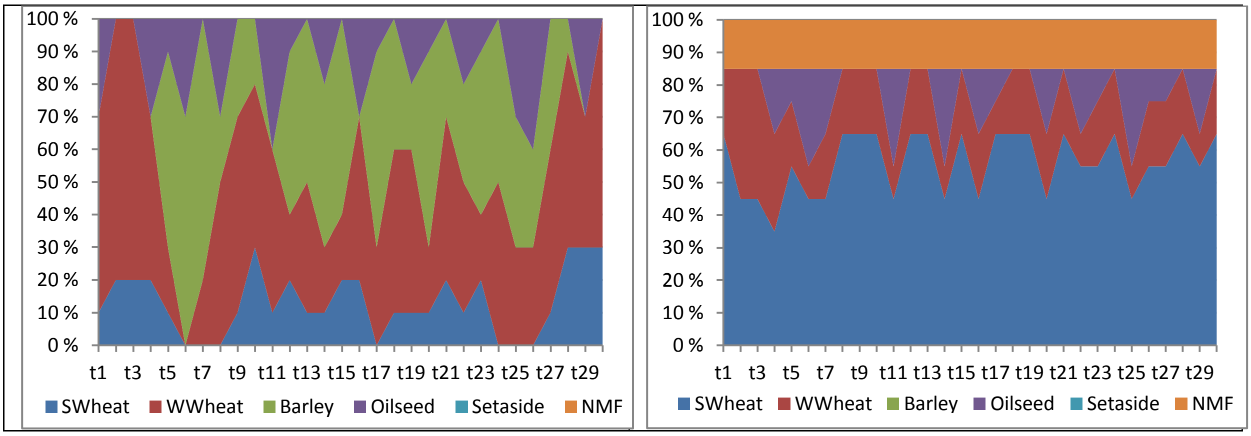

Figure 1a. Land allocation under S1: high- disease-pressure vs. high-price and S6: low-disease-pressure vs. low-price.

Table 3. Initial and simulated average yields (kg/ha), profit, pH value and number of fungicide treatment over the next 30 years.

		S1	S2	S3	S4	S5	S6
Avg. Yields	S.wheat (3557)	3347(-6.4%)	3351(-6.3%)	3224(-9.8%)	3520(-1.6%)	3503(-2.0%)	3429(-4.1%)
	W.wheat(3794)	3485(-7.3%)	3451(-8.2%)	3412(-9.2%)	3681(-2.1%)	3678(-2.2%)	3654(-2.8%)
	Barley (3550)	3591(+0.3%)	3274(-8.5%)	3214(-10.2%)	-	-	-
	Oilseed (1393)	1549(+11.2%)	1539(+10.5%)	1505(+8.0%)	1562(+12.1%)	1555(+11.6%)	1535(+10.2%)
Average profit, 1000 €		117	82	55	133	95	63
Fungicide, Nr. of applications		102	0	0	0	0	0
Average soil pH		6.73	6.68	6.43	6.73	6.70	6.40

6. Conclusion

In this study, we developed a dynamic farm level economic rotation model. It can be used in analyzing optimal crop rotation system with various adaptation practices. Our study indicates that crop rotation is favored, or even required in the future, since more crops and their true rotation are needed to tackle against increasing disease pressure due to climate change. Nevertheless, encouraging market conditions, e.g. high output prices play a key role in providing incentives for farmers to utilize adaptation management such as fungicide treatment and liming. Moreover, yield gap, the difference between potential yields and actual yields, can be also narrowed down, or kept almost constant, by combining crop rotation with other management practices, despite increasing plant disease pressure. Interaction between different practices and also their influence to environment should be considered more closely. Liming doesn't only increase yield, it also decreases the need of phosphorus fertilization and improves nutrient utilization.

Increasing disease pressure in the future is taken into account in breeding for more disease resistant cultivars. However, these robust cultivars might lose some of their yield potential. Therefore, the trade-off between fungicide treatment costs and yield gain is an important area of application of the model. The model can also be used in evaluating the value of new cultivars better tuned to increasing length of growing season and better tolerating adverse conditions, such as a possible worsening of early summer drought in future climate. The model provides important (sensitivity) analysis on the role prices of inputs and outputs as well as policy constraints on adaptation.

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