Farmers' Spending on Variable Inputs Tends to Maximise Crop Yields, Not Profit

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We estimate the marginal returns to spending on Crop Variable Inputs (CVI) (such as fertilizers and crop protection), to explore whether observed spending maximises physical or economic returns to farmers. Data are taken from the Farm Business Survey for 2004-2013, where gross margins and input spending are available, in over 10,300 crops of conventional winter wheat or oilseed rape in England and Wales. Marginal spending on CVIs generate financial returns significantly less than £1 per marginal pound spent. This suggests that expenditure on CVIs exceeds an economic optimum that would maximise profit. However marginal physical products (crop yields) are positive, but small and significantly different from zero. This suggests that, on average, farmers approximately maximise yields. These results hold across a wide range of alternative economic models and two crop species. Similar results have been reported in estimations for Indian grain production and for maize in China. In practice, farmers are making decisions on input use in advance of having information on a variety of factors, including future yield, product quality and price, making it difficult to optimise input levels according to expected profit. Farmers may be consistently optimistic, prefer to avoid risk, or deliberately seek to maximise yields. Some farmers may put on the standard recommended application irrespective of input or expected output price. It is also possible that advice may sometimes aim to maximise yield, influenced by an incentive to encourage greater sales. Excessive input use both reduces private profits and is a cause of environmental damage. There are thus potential private as well as social benefits to be gained from optimising levels of input use.

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1. Introduction

Crop production incurs a mix of fixed and variable costs - such as the costs of seeds, fertilizer and pesticides - the levels of which vary in direct proportion to the level of production. Crop *profitability* critically depends on the costs of these variable inputs (Lawes and Gilbert 1879; Barnard and Nix 1979; Cato, cited in Campbell 2000; Van Alfen 2014), termed the Variable Costs of Production.

Typically, in agricultural production fixed costs account for about 60 per cent of total costs and variable costs about 40 per cent (Lang 2015). While fixed costs are by definition not readily altered from year to year, farmers have control over the levels of variable inputs and hence the level of variable costs. Thus decisions as to what level of variable inputs to apply are a significant determinant of the profitability of crop production. For example, in the 2012 harvest year, in production of (non-organic) winter wheat in England, variable costs (VC) accounted for 41 per cent of crop economic output (CEO). The resulting Gross Margin (GM=CEO-VC) was 59 per cent of crop economic output. After deducting 60 per cent of crop economic output for fixed costs, this results in a negative net profit in wheat production, for this year before taking account of subsidies (Lang 2015).

In classic production economics, profit will be maximised when, for each individual input, the Value of the Marginal Product (VMP) (the revenue gained by the farmer from the sale of the output generated by the last unit of input) is equal to the Marginal Cost (MC) (the cost of the last unit of input). Prior to this point, further units of input will increase profit, beyond this point costs will exceed revenue. In order to maximise profit, then farmers may be expected to follow this rule (Nelson and Ibach 1957; Barnard and Nix 1979; Olson 2004; IFIA 2007; Defra 2010).

In practice, the position is more complex. Farmers have to decide *ex ante* on the levels of inputs to apply, in advance of knowing the conditions under which production will take place or the price at which their product will be sold. In this context, farmers may simply follow a standard recommendation, irrespective of the current or expected circumstances, or they may take a risk averse approach and apply higher levels of inputs in order to ensure that they achieve a 'good' yield.

Evidence from other countries suggests that farmers may on average apply higher levels of inputs than maximise financial return. Research in China on current Chinese maize cultivation practices (Xu *et al* 2014) estimates that farmers could increase profits, and save US$50/hectare in variable costs for nitrogen, by applying an average of 67kg/ha (30%) less nitrogen than average farmer practice of 224 kgN/ha maize. This was based on 408 trials over 2010-2012 in the prime maize growing region of the eastern seaboard states. Moreover, Zhang *et al* (2015) observe marginal losses of Rm0.1-0.55 per marginal Rm spent on pesticides. In Indian grain production, using World Bank (2014) functions, average marginal returns were estimated to be small - with marginal production being circa Rs0.45 of cereals/ per Rs of fertiliser spending (a loss of Rs 0.55 /Rs at the margin)[1]).

At a global level, it is estimated that current world cereal production could be achieved, with approximately 50 per cent less nitrogen (Mueller *et al* 2014), if application rates were optimised across the world. Under this scenario, Mueller *et al* (2014) estimate for England that nitrogen applications would decrease by 27%, from an assumed average application across all grains in the year 2000 of 127kgN/ha[2].

But this is not always the case. In Sweden for example, at the peak of post-war technical change in farming and in the context of strong policies to boost production, farmers were estimated to be able to achieve marginal products of $3.5-to-2.1 per marginal $1 of fertiliser expenditure (Heady and Dillon 1961). In less intensive systems, Kenyan farmers were recently estimated to achieve much higher returns, with a ratio for VMP to MC measured at 1.7 (Sheahan *et al* 2013).

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[1] Author calculations based on averages for the breadbasket areas of 'High Yields - where production was Not Growing'.

[2] This figure seems low given BSFP 2014 recommendations in excess of this level.

The level of input use in crop production also has wider social implications. Leaching of chemicals from agricultural production represents a significant external cost due to its impacts on water quality (Carpenter *et al* 1998). The standards set under the EU Water Framework Directive are likely to require a reduction in levels of diffuse pollution from agriculture (Sutton 2011). These same arguments apply to the use of pesticides.

This implies that the social cost of input use exceeds the private cost, and hence that the socially optimal level of input use will be lower than the privately optimal level. The social cost includes costs that are not borne by producers but by other actors or society more generally. The private cost is borne by producers only. Thus, some estimates suggest that the Socially Optimal N-Rate is at least 50 kgN/ha less than the Privately Optimal N-Rate (which does not account for social costs or other externalities), determined by the European Nitrogen Assessment (Brink and van Grinsven, 2011), for cereals in Northern Europe[3].

The efficiency of input use is thus an issue of importance, both for the private financial performance on farms as well as for public policy making. Levels of current spending on fertilisers and other variable inputs may not be optimal. It is therefore important to explore the position in the UK as there has been no systematic analysis of farm business data in order to assess these issues. So, the objective of this paper is to quantify the marginal returns to crop variable input spending, drawing on data from the Farm Business Survey, in order to assess the efficiency of input spending rates on crop farms in England.

2. Method

The analysis used the fixed effects econometric analysis to extract deterministic relationships from economic datasets (Mundlak 1961). It is a powerful technique developed in the late 1950s and is now a standard approach in many fields of financial, real estate and economic analysis (Brooks 2014; Angrist and Pischke 2009). Mundlak's (1961) methodology obtains coefficients that are free of management bias by controlling for other sources of

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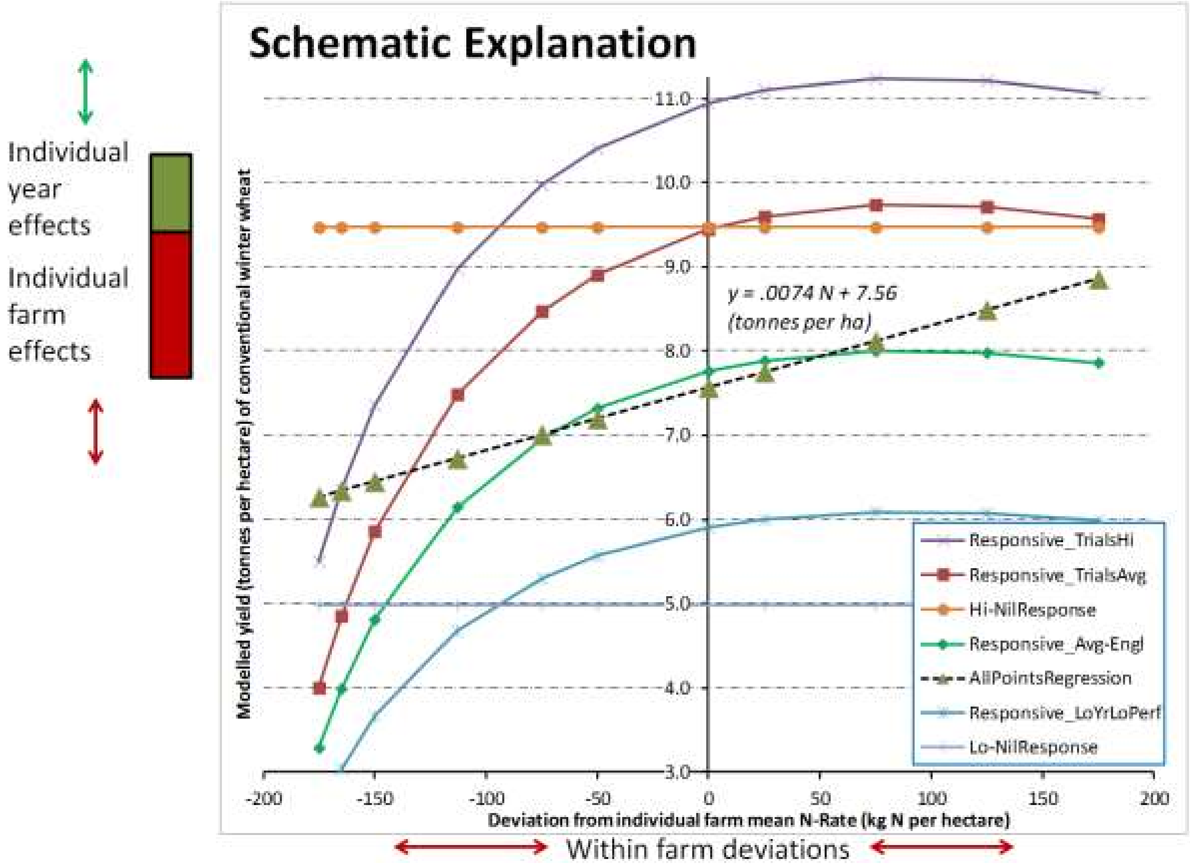
[3] Which Brink and van Grinsven (2011) posit could incur a 20 per cent yield penalty. However in England it is estimated that this is likely to incur an aggregate yield penalty of only 5 per cent (ADAS, pers. comm.).

unobserved heterogeneity. These potential sources include both those permanent factors specific to an individual farm and farmer, such as soils, farm specific fertility and persistent weed burdens, aspect and location, education and skill, as well as those factors specific to an individual year, such as market and weather conditions. We use the fixed effects estimation because it is expected that some of the variables not considered in the model (and therefore would otherwise appear in the error term) might be correlated with the independent variables (e.g. management, which is not included in the model, and therefore is part of the error term, may affect the use of inputs and make the regression coefficients biased) (Brooks 2014; Angrist and Pischke 2009; Chavas *et al* 2010). The remaining variation thus represents the variation within farms, essentially the individual farmers' deviations from their own average spending on variable costs (adjusted for general inflation).

This is illustrated, schematically, in Figure 1. The vertical axis is modelled wheat yield, and the horizontal axis is deviation (from the assumed optimum average application rate). Each curve represents an assumed class of result (farm*year) for an average farm. These are then normalised with fixed effects for individual years and individual farms, so that all of the points are brought to one curve and can then be regressed against deviation from the assumed optimum application rate.

Figure 1. Schematic representation of the analysis - which illustrates the normalisation by "Year" and "Farm" Fixed Effects (vertical constants), and the use of "within farm variation in fertilizer use" (within farm deviations - from the farm optimum) - to normalise horizontally.



We focus in this paper on how farmers respond by adjusting input application rates, when for example relative prices of fertilisers or grains change. In order to assess how farmers optimise expenditure on variable inputs, we use historic spending on fertilisers, seeds or chemicals - unadjusted except for general changes in inflation.

For the linear case, the within farm variation (in spending on crop-variable-inputs), with fixed effects for farms and years, is given as:

$$\text{Output}_{ti} = a + b_1\mathbf{Ferts} + b_2\mathbf{Sprays} + b_3\mathbf{Seed} + b_4\mathbf{Othr} + c_t\text{Year}_t + c_i\text{Farm}_i + e_{it}$$

Where the dependant variable is Output per hectare (in year $_t$, on farm $_i$), being either Crop Gross Margin (GM) (£ per hectare), Crop Economic Output (CEO) (£ per hectare), or Crop Yield (Yld) (kilograms per hectare). These variables were regressed on farm deviations from the mean spending rate of each individual farm: for fertilisers (**Ferts**); all crop protection (**Sprays**); seeds (**Seed**); and other crop variable costs (such as agronomy charges, baling twine or packaging, but excluding heating and drying costs or fuel because spending on fuel for machinery is not allocated to specific crops in the Farm Business Survey) (**Othr**).

Spending variables in the above equation are expressed as individual-farm-deviations from the individual-farm-mean, in £ per hectare. That is to say within farm variation in spending per hectare, e.g. a series of [$Fert_{ti}$ minus $Mean\_Fert_i$]. Year and Farm effects, ($Year_t$ and $Farm_i$), are dummy variables for each respective degree of freedom (t-1 and i-1) (to average out variation between years and between farms). And e_{it} is the residual variation (Farms*Years).

While this is a production function, in the sense that we calculate effects on output of production factors, for unobserved factors of production (the omitted variables), it depends on terms that are specific to each individual farm and to each individual year. The $b_{1\ to\ 4}$ coefficients are thus the linear effects, because they represent the return to changes in spending on these inputs at the margin. They are thus the tangents (for limited variation) to the aggregate production function, for GM, CEO or Yld, of an additional one £ per hectare spent on that particular Crop Variable Input beyond the individual farm mean, averaged across years and farms. These coefficients therefore represent 'marginal profit' (Gross Margin), 'marginal economic output' (Crop EO), or 'marginal physical product' (Yield), per marginal cost. Or, put more simply, the effect of the last pound of spending on these variables.

It should be noted that other model specifications that have been adopted in the literature, including translog and quadratic forms (Brooks 2014; Angrist and Pischke 2009; Chavas *et al* 2010), were also tested. Models were tested too for within year variation between farms with proxies for known variation in farm characteristics (so, in that case, the residual variation was farm). All-inputs-variation for between-farms variation in farm-mean spending was similarly modelled. Results from these alternative models are not presented as no materially different results were observed.

The regressions are generally assumed to be independent of scale effects, because the factors of interest are variable costs which vary in direct proportion to the scale of the enterprise expressed per unit area (hectares) of sown land. This is the dimension that is used in practice, and understood, by farmers. It is also the correct dimension in which to analyse the effect of changing the *rates* of spending on these variable costs. Hence we do not investigate the substitutability of land, labour, machinery and fertilisers (Clark *et al* 2013).

Regressions were estimated with and without population weights which aggregate on unrelated strata variables (Defra 2015). As may be expected, this weighting increased standard errors, by around 2%, for the coefficients that are of interest.

3. Data

Data were drawn from the Farm Business Survey (Defra 2015), which is a stratified, random unbalanced, panel survey including 1,656 farm businesses in England and Wales that have more than €25,000 standard agricultural output and a labour input greater than 0.5 full-time-equivalents. The analysis here uses derived variables and measures of: Gross Margins (GMs), yields, and variable costs of conventional winter wheat and conventional winter oilseed rape over the harvest years 2004 to 2013 inclusive (Table 1).

Winter Wheat: The mean total area of crop sown was 82.9 hectares per farm (all of which were non-organic, or conventional, crops) and mean grain yield per hectare per farm business was 7.8 tonnes per hectare (Table 2 and Appendix I). No one crop on any one farm in any year had zero economic output (and so it was not necessary to exclude any crop so as to be able to fit the Translog model detailed below).

Winter Oilseed Rape: The mean total area per farm was 51.0 hectares and mean yield 3.4 tonnes per hectare per farm business (Appendix II), of which only one crop in one year on one farm had zero economic output. This was excluded from the sample so as to be able to fit the Translog model.

Given a mean total area per farm of 201 hectares, and utilised agricultural area of 194 hectares, this stratified random sample (of up to 8% of all cereals and general cropping farms in England and Wales) closely resembles the typical cropping patterns in English grain production, where cereal farms had in 2012 a mean area of 200 hectares with 75 hectares of winter wheat (Lang 2015).

All financial values were deflated to 2013 pounds sterling (£) using standard GDP deflators from UK HM Treasury.

Table 1. FBS sample for gross margins 2004-2013.

	Conventional Winter Wheat	Conventional Winter Oilseed Rape
Crops (of one arable "non-organic" crop species, on one farm, in one year)	6,948	3,449
Farms in sample	1,656	895
Years (2004/5-2013/14)	up to 10	up to 10
Farms with at least 4 or more years' observations	789	502

Table 2(a). Ten year average costs and output in the FBS gross margins sample 2004-2013 (£/ha). Performance bands were ranked by gross margin per hectare. (s.e.m. in parenthesis)

£ / hectare sown (in 2013 GBP)	**Winter Oilseed Rape - all**	**Winter Wheat - all**	**Wheat Low 25% Performance**	**Wheat Mid 50% Perf.**	**Wheat High 25% Performance**
Fertilisers (average)	178.5 (1.352)	160.7 (0.909)	166.2 (2.967)	161.4 (1.246)	157.4 (1.437)
Crop protection (average)	151.5 (0.988)	153.9 (0.633)	148.7 (1.881)	154.6 (0.874)	155 (1.044)
Seeds (average)	49.04 (0.482)	59.9 (0.321)	64.47 (1.04)	61.32 (0.429)	55.92 (0.525)
Other Variable Costs (average)	21.58 (0.481)	26.5 (0.504)	28.99 (1.592)	28.64 (0.735)	22.21 (0.71)
Total Variable Costs	400.6	401.0	408.4	406.0	390.5
Crop produced (tonnes/ha)	3.415 (0.0144)	7.811 (0.0193)	7.129 (0.0595)	7.729 (0.0256)	8.203 (0.0312)

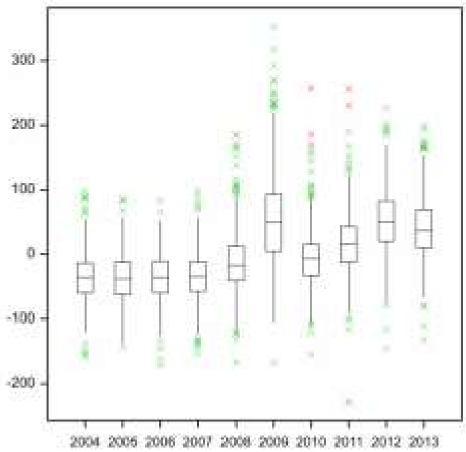
Table 2(b). Ten year average costs and output in the FBS gross margins sample 2004-2013 (£ per tonne). Performance bands were ranked by gross margin per hectare.

£ / tonne grain (in 2013 GBP)	**WOSR - all**	**Winter Wheat - all**	**Wheat Low 25% Performance**	**Wheat Mid 50% Performance.**	**Wheat High 25% Performance**
Fertilisers (average)	52.3	20.6	23.3	20.9	19.2
Crop protection (average)	44.4	19.7	20.9	20.0	18.9
Seeds (average)	14.4	7.7	9.0	7.9	6.8
Other Variable Costs (average)	6.3	3.4	4.1	3.7	2.7
Total Variable Costs	117.3	51.3	57.3	52.5	47.6
Crop Economic Output (average)	298.4	135.2	124.6	133.8	140.8
Gross Margin	181.1	83.9	67.3	81.3	93.2
Number of crops in sample	3,449	6,948	910	3,680	2,358

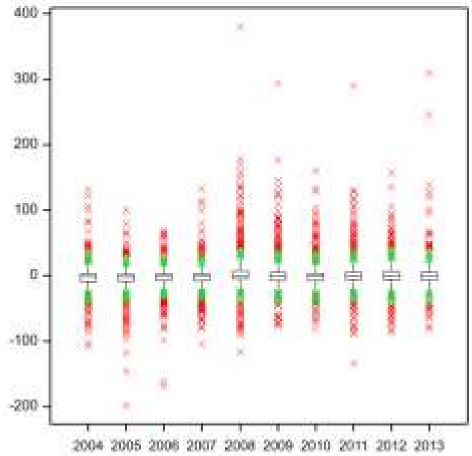
There do not appear to be systematic biases or consistent trends in relative spending on inputs. For example, Figure 2 shows the distribution of farm deviations from individual farm mean spending in winter wheat on variable inputs, across the time series. As can be seen, the range of deviations within each year is fairly small, indicating that farmers did not typically vary practice greatly.

Figure 2. Distribution of farm deviations, from individual farm mean spending in winter wheat on fertilisers, other crop costs, seeds, and crop protection, by years (£ per hectare).

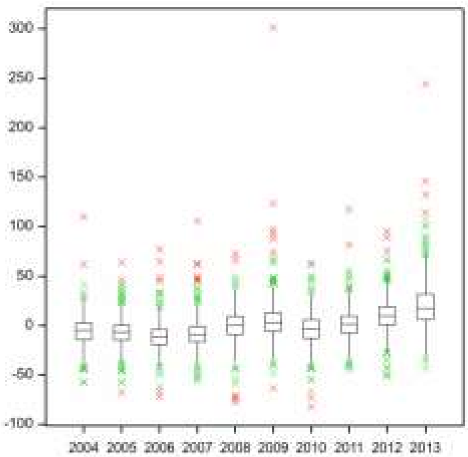
Fertilisers



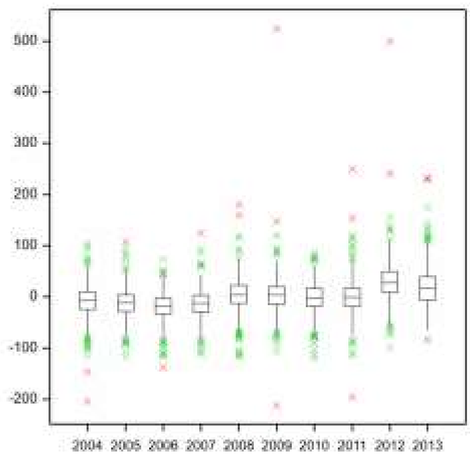
Other crop spending



Seeds



Crop protection



4. Results

Marginal coefficients for GM, for both winter wheat and winter oilseed rape, of spending an extra unit on Fertilizers, Sprays, Seed and Other inputs beyond the individual farm means are all negative, significantly different from zero (Table 3). And is robust to alternative model specifications (for instance the Wald-Wolfowitz runs test was 173 for GM on "within-farms-fertiliser-variation", associated with 1% of the observed variance, and $p < 0.001$).

The marginal GM coefficients thus imply that marginal expenditure is loss making, i.e. the marginal GM is negative because marginal costs exceed marginal returns. Marginal coefficients for Economic Output are positive. Consistently with this, marginal coefficients for physical production (yield) are small, but positive, and significantly different from zero (Table 3). This may suggest that the input variables are causally related to yield, but the responses at the margin are small or, in other words, near the peak of the response curve and very close to maximum yield for that input, other things being equal. This indicates that the marginal unit of input increases production but not sufficiently to pay back the cost of the input.

Table 3. Marginal returns of variable inputs observed in 10 years of the Farm Business Survey (2004-2013) for conventional crops of Winter Wheat and Winter Oil Seed Rape

Model	Dependent variable*	Ferts†	Sprays†	Seeds†	Other Variable Costs†	sample	pseudo r^2	Observation Standard Error
Wheat (within+years+farms)	£GM/ha	***-.85 (.065)***	***-.45 (.089)***	***-1.24 (.164)***	***-.54 (.107)***	5,341	59.3	1,182
Wheat (all / unweighted)	£GM/ha	***-.85 (.061)***	***-.50 (.081)***	***-1.19 (.148)***	***-.58 (.103)***	6,948	58.0	205
Winter Oilseed Rape	£GM/ha	***-.76 (.095)***	***-.26 (.127)***	***-1.48 (.228)***	***-.08 (.231)***	2,927	61.2	232
Economic product (Wheat)	£EO/ha	***.18 (.062)***	***.48 (.085)***	***-.23 (.156)***	***.41 (.102)***	5,341	64.3	125
Translog (Wheat)	£EO/ha	***.22 (.097)***	***.30 (.127)***	***.25 (.219)***	***.19 (.126)***	5,341	66.7	-
Wheat yield (within+years+fa	kg/ha	***1.51 (0.34)***	***3.72 (0.47)***	***-0.76 (0.87)***	***1.62 (0.56)***	5,341	51.4	6,231
Wheat yield (all/unweighted)	kg/ha	***1.39 (0.33)***	***3.42 (0.44)***	***-0.89 (0.80)***	***2.18 (0.55)***	6,948	53.2	1,102
Winter Oilseed Rape	kg/ha	***0.66 (0.27)***	***2.68 (0.36)***	***-1.21 (0.65)***	***2.38 (0.66)***	2,927	37.3	659
Wheat nil PeaBeanPots$_{(t-1)}$	kg/ha	***0.31 (0.53)***	***3.65 (0.75)***	***-0.66 (1.25)***	***1.50 (0.84)***	2,410	49.0	6,679

*£GM/ha is Gross Margin (in £GBP per hectare). £EO/ha is Economic Output (in £GBP per hectare).
kg/ha is grain yield per hectare sown. Unless otherwise stated all regressions are for wheat,
weighted and only include farms with >=4 observations. Standard errors are in parentheses.
Marginal economic outputs, for the Translog, were estimated at mean values.
†deviations from individual farm means (in £GBP per hectare)

Table 4. Marginal physical product (yield) of conventional Winter Wheat, with interaction terms for Peas-or-Beans on-farm in the preceding year

Dependent variable is kg wheat yield per hectare			
Parameter	**estimate**	**s.e.**	**t prob (est)**
w/i Farms Fertilizers (£/ha)	***1.60***	0.41	<.001
w/i Ferts.PYPeaBnGT0	***-0.85***	0.69	0.219
w/i Farms Sprays (£/ha)	***3.00***	0.57	<.001
w/i Sprays.PYPeaBnGT0	***1.96***	1.18	0.097
w/i Farms Seed (£/ha)	***-1.45***	0.93	0.122
w/i Farms Other exp's (£/ha)	***2.44***	0.62	<.001
Constant	***7,543***	546	<.001

It could be postulated that the effects we observe here are associated with crop rotations, as with a first wheat (after a break crop) less fertiliser could be applied but yields could be higher (because, for example, first wheats after legumes that fix nitrogen require less fertilizer and give higher yields). This was tested by adding an interaction term for peas or beans in a previous year (somewhere on the farm). For fertilizers the coefficient was not significantly different from zero (Table 4), whereas rotations may be expected to lead to a lower response to the application of fertilizers in first wheats, i.e. a lower marginal physical product (MPP). However, most farms will have several fields of wheat (each possibly following a different crop) and so our observations are aggregated across several rotations on each farm in each year and also nitrogen fixing or heavily fertilised crops, such as field-scale vegetables or potatoes, amount to only 15% of the area of cereals in England. So the vast majority of wheat crops will not be following such break crops, making any possible effect of rotations difficult to identify with the available data. We do though, as noted above, identify the same loss-making marginal Gross Margins with near maximum yields for Winter Oilseed Rape which is not subject to this potential rotation effect, supporting the case that the that the results are not a consequence of crop rotation.

5. Discussion

Findings

In our results, yields appear to be nearly maximised. This is reflected in marginal yields (MPP) that are small, positive and significantly greater than zero in both oilseed rape and winter wheat. So farmers appear to be making systematic decisions on spending on crop inputs in England and Wales. This would not be the case if the losses observed at the margin were just an effect of prices. In that case we would expect that the MEOs and MPPs would not be significantly different from zero. Our results do suggest that farmers are consistently applying levels of inputs which, at the margin, cost more than they return in terms of increased financial product.

Limitations of the method

In the available data, prices and quantities of inputs are confounded in the observations and so we are not able to distinguish between contexts where farmers had to pay a higher price for their inputs and contexts in which they applied greater quantities of inputs or inputs of higher quality. However in both economic teaching and in practice (Blagburn 1961; Barnard and Nix 1979; Olson 2004; Warren 1998) farmers are expected to respond to changes in prices. So for example, if fertiliser prices fell (relative to grain) and farmers increased nutrient application rates to maximise returns, we do not adjust for this using separate indexes for prices of farm inputs and outputs because efficiency would in this context appear to decline unrealistically (Langton 2011).

Possible reasons for excessive application levels

We should emphasise that the results do not demonstrate that the application of inputs in total is not profitable. The focus of this analysis is on marginal returns. The results do not represent the average, or industry, profitability of variable input applications. Thus for instance, we calculate that the *average* profit per *kilogram of N* ("UBoN" as defined by Brink and van Grinsven 2011) to be £2.32. The application of N is clearly profitable. By comparison, across Northern Europe the *average* profits from N-application were estimated to be €0.4 to €2.7 per kilogram of N applied (Brink and van Grinsven 2011).

A first point to make is that the results do not appear to simply represent random errors. There is, of course, considerable uncertainty involved in making input decisions without knowledge of the production conditions or of future output prices. But the consistent significance of the estimated coefficients indicates something more systematic. One possible interpretation of this result might be that "*the decision to apply more than average* *to take advantage of the good years is appropriate since the cost of over-application is low compared to the cost of under-application*" (Rajsic and Weersink, 2008, p56). See also Rajsic, Weersink and Gandorfer (2009). However, in the analysis we find evidence of systematic over-application. If the large gains in a small number of good conditions were greater than the small losses in a larger number of poor conditions, we would expect to find that, overall, mean coefficients on gross margins were positive. This was not the case and so we do not accept this argument here.

The fact that farmers do not operate simply as profit maximisers is well accepted (e.g. Schwarze, *et al*., 2014). Various explanations may be advanced in order to explain why farmers appear to be applying levels of inputs that exceed those that would maximise profits. Sheriff (2005) includes the following possible reasons: i) The perceived limited relevance of recommendations to ‘my farm’, to ‘my county’, and to ‘this year’, be they official, such as in the UK RB209 (Defra 2010), or commercial, such as IFIA (2007), where farmers believe that the recommendation is too conservative or pessimistic; ii) Substitutability of limiting factors (where a farmer might apply extra nutrients where yields are limited by rainfall, and the farmer is optimistic about rain); iii) Opportunity costs; and iv) Uncertainty (especially in the context of large potential losses and small costs).

Following from this, we consider various possible explanations for the apparent over application of inputs in the face of uncertainty, where yield, quality and prices are largely unknown at the time when the inputs are applied (*ex ante*). However, we accept that it is unlikely that any single factor represents a sole cause. Thus we consider: i) The possibility of unobserved costs; ii) The adoption of standard guidance; iii) Optimism; iv) Risk aversion; v) External advice; and vi) Agricultural subsidies.

i) Unobserved cost

It is not possible to observe the full range of costs facing farmers in making decisions about input levels. In this context there are opportunity costs and costs of information. Effort and time spent on increasing the precision of input applications has opportunity costs, such as in terms of work-hours available in autumn when farmers are under pressure to get other work completed. Farmers may save time and other costs by the convenience and low cost of ‘with seed’ applications of pesticides, or by the ease of application of standard mixes of fertiliser nutrients. To some extent this will depend on the skills and experience of the farmer. In this context then, some farmers may simply to follow standard input packages without reference to their own particular circumstances.

ii) Standard guidance

The standard recommendations for fertiliser applications in England, as provided in RB209 (Defra 2010), may also bias practices towards higher input rates. The recommended N level for England is set at the 98th percentile of the maximum yield on the response curve given in RB209 (because the ratio of grain prices to fertilizer prices is assumed to be 1/6 or 1/10). This corresponds very closely to the 5 year average application rate on winter wheat in Britain of 185 kgN/hectare (BSFP 2014). Given random variation, this means that many applications will be well in excess of the level required for maximum yield. The IFIA (2007) recommends applications at similar levels of the response curves, as do standard texts (e.g. Cooke 1982).

A further factor that may bias industry results towards negative returns from the last unit of input is that no response to varying input rates (e.g. to N) is seen in many site-by-year combinations. For example, 13 out of 30 (45%) site-by-year combinations in trials at 15 sites over 2005-2007 for the 2010 RB209 (Defra) gave no response to N (Sylvester-Bradley *et al* 2008). In such ‘site*years’ N-applications will, clearly, incur substantial losses.

iii) Optimism

Farmers may simply make systematic errors in assessing the levels of input to apply, where perhaps they anticipate a better growing season than generally eventuates. Kahneman (2011) has pointed to ‘optimistic bias’ as potentially the most significant of the cognitive biases. Farmers may apply levels of input that would be beneficial in the event of good growing conditions and prices but outcomes are not as good as anticipated and so the investments are not justified.

iv) Risk aversion

Attitudes to risk may also play an important role in the results that we observe here. Risk aversion may create an incentive for farmers to make prophylactic applications, applying extra inputs to reduce the risk of achieving low yields. A strong preference to avoid a yield-penalty may also be a factor leading to the observation of small marginal products and near maximum yields, perhaps influenced by negative self-image from having 'poor' looking crops or concerns about peer pressures when farmers continue to associate 'good farming' with high yields.

v) External Advice

Many farmers rely on external advice on the levels of inputs to apply. We have little evidence on the basis on which this advice is given but these results raise various issues. It is possible that advisors, as we have suggested might be the case with farmers, simply follow the standard recommendations with regard to fertiliser application rates. It could be that with training in agronomy rather than in economics, the emphasis is on yields rather than profits. Further, some advice is tied in with the sale of inputs. This context raises the further possibility that advisors whose incomes rely on the sales of inputs may consciously or unconsciously have an incentive to recommend higher levels of input use than would otherwise be the case. This is an issue that deserves further exploration.

vi) Agricultural subsidies

Direct payments to farmers in Europe are of the order of €230 per hectare, each year, under the EU Common Agricultural Policy (CAP). While input suppliers, and for tenant farmers landlords, may capture some of this support (e.g. O'Neill and Hanrahan, 2016), the increased income may affect farmer behaviour. The guaranteed income might reduce farmers' degree of risk aversion, offsetting the previous effect, or potentially reduce their marginal utility of income. In this context a farmer might opt for a simpler approach, applying standard levels of inputs rather than making the extra effort to maximise net profit. The net effect of CAP subsidies on input levels thus seems uncertain.

Further work is needed in order to assess the relevance and importance of these possible alternative explanations for the observed results.

6. Conclusions

The analysis has provided robust evidence that farmers are systematically applying rates of inputs that exceed the rates that would maximise their profits. In contrast, their decisions appear to enable them to come close to applying levels of inputs that maximise yields. The implication is that farmers could increase profits by applying lower levels of inputs. At the same time, the environmental impacts of input uses indicate that there can also be potential social benefits associated from lower rates of input use through reduced external costs borne by other actors, such as pollution. We have outlined possible explanations for the observed results. Some of these could indicate that the private gains might be hard to achieve, such as where 'over-applications' arise from costs that have not been identified in this analysis. Others could indicate ways in which profitability could be increased, such as if the results are explained by an excessive degree of optimism. Further work is required to sort through these various alternative explanations.

There is also a cautionary implication of the analysis for the adoption of price incentives as a means of shifting farmer decisions closer towards a social optimum. If farmers are not reacting accurately to the prices that they currently face in the market, there can be little expectation that they would react accurately to prices altered in order to promote social or environmental objectives. This is not to say that environmental taxes would not push farm level decisions in a desired direction, rather that we cannot expect such policies to deliver 'optimal' outcomes.

At this stage, we have not attempted to estimate the total losses associated with this apparent over-application of inputs. Aggregate losses, to farmers and to society, should be estimated from the areas under the whole of the production function. It will be interesting to derive the size of industry losses from these effects at the margin. Strip trials and 'field mosaics' which will provide clearer information on the production functions are being actively explored by NIABTAG, AHDB Cereals and ADAS (ADAS 2017). Vast and increasing quantities of data are being generated through precision farming, such as the field mosaics of Tru-Harvest/ ClimateCorp/ AgriData-Deere in the USA. Researchers need to clarify and disseminate the methods and algorithms for farm-level-optimisation using the big-data that is now available.

In conclusion, further analysis is required to understand better the ways in which farmers make decisions and the incentives that they and their advisors face. There are potential private and social benefits to be gained from better farm level decision making and this is an important goal for policy and research.

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Appendix I. Descriptive statistics for the Winter Wheat.

Winter wheat crop variable	Mean	Median	Standard deviation	Standard error of mean	Skewness	Kurtosis
Yield (t/ha)	7.811	7.887	1.611	0.0193	-0.441	0.691
Area	82.92	47.23	118.7	1.424	4.958	42.04
Gross Margin (£/ha)	724	691.5	316.9	3.801	0.451	0.312
Economic output (/ha)	1,056	1,026	324.7	3.896	0.317	-0.169
Bye-products (£/ha)	74.68	51.13	95.38	1.144	4.809	65.11
log10 Economic output (/ha)	3.009	3.02	0.141	0.00191	-0.745	1.562
Fertilizers (£/ha)	160.7	146.1	75.74	0.909	0.927	1.562
Crop protection (£/ha)	153.9	150.6	52.79	0.633	0.767	5.347
Seeds (£/ha)	59.9	55.75	26.79	0.321	3.447	47.9
Other crop costs (£/ha)	26.5	11.36	42.05	0.504	3.051	12.69
Contract costs (£/ha)	89.94	36.13	124.8	1.498	2.407	10.58
log10 Ferts	2.148	2.173	0.353	0.00479	-6.097	51.7
log10 Protects	2.165	2.183	0.211	0.00286	-7.792	110.8
log10 Seeds	1.74	1.747	0.197	0.00267	-2.919	35.39
log10 Other costs	0.774	1.069	1.015	0.0137	-0.748	-0.644
Betw farms: Ferts	160.7	157.9	52.98	0.636	0.351	2.443
Betw: Crop protection	153.9	152	40.43	0.485	0.0291	1.367
Betw farms: Seeds	59.9	57.63	18.94	0.227	6.142	160.1
Betw: Other costs	26.5	14.58	34.3	0.412	2.408	6.554
Betw: Contract costs	89.94	42.38	111.7	1.341	2.106	9.618
w/i farms: Ferts	0	-1.475	54.13	0.649	0.751	2.153
w/i farms: Protects	0	0	33.94	0.407	1.3	17.92
w/i farms: Seeds	0	-0.15	18.95	0.227	1.691	17.06
w/i farms: Other crop costs	0	-0.152	24.31	0.292	2.408	28.81
w/I farm: Contract costs	0	-0.308	55.66	0.668	1.17	18.65
Weight all	32.9	29.38	20.91	0.251	1.771	6.8

Source: Farm Business Survey (Defra 2015) Notes: Production is in tonnes per hectare sown, others in £/hectare (or base 10 logarithms - where specified). n=6,948. Inputs are per hectare figures, for all variation. "Betw" are between farms variation in mean farm spending. "w/i" are individual farms' deviations from individual farm means ("within farm" variation).

Appendix II. Descriptive statistics for the Winter Oilseed Rape (WOSR).

Oilseed rape crop variable	Mean	Median	Standard deviation	Standard error of mean	Skewness	Kurtosis
Yield (t/ha)	3.415	3.48	0.847	0.0144	-0.232	1.517
Area	51.05	33.15	55.84	0.951	3.174	14.24
Gross Margin (£/ha)	620.2	570.4	368.1	6.268	0.514	0.626
Economic output (/ha)	1019	965	398.9	6.793	0.536	-0.0902
Bye-products (£/ha)	4.495	0	18.71	0.318	5.607	38.47
Fertilizers (£/ha)	178.5	161.3	79.39	1.352	1.558	8.539
Crop protection (£/ha)	151.5	143.6	58.05	0.988	0.93	2.507
Seeds (£/ha)	49.04	46.29	28.31	0.482	6.585	125
Other crop costs (£/ha)	21.58	13.14	28.23	0.481	4.003	41.32
Betw farms: Ferts	178.4	175.2	54.18	0.922	0.915	4.944
Betw: Crop protection	151.4	146.4	44.15	0.751	0.761	2.12
Betw farms: Seeds	49.03	47.21	20.94	0.356	11.48	368.3
Betw: Other crop costs	21.59	15.75	21.99	0.374	2.234	8.442
w/i farms: Ferts	0.05	-0.773	58.06	0.989	1.45	13.53
w/i farms: Protects	0.0	0	37.72	0.642	0.239	3.123
w/i farms: Seeds	0.0	-0.311	19.06	0.325	3.022	31.29
w/i farms: Other costs	0.0	-0.081	17.67	0.301	2.672	60.81
Weight all	33.15	30.14	19.5	0.351	2.03	8.516

Source: Farm Business Survey (Defra 2015). Notes: Production is in tonnes per hectare sown (t/ha), Area is in hectares (ha), others in £/hectare. n=3,449. Inputs are per hectare figures, for all variation. "Betw" are between farms variation in mean farm spending. "w/i" are individual farms' deviations from individual farm means ("within farms" variation).