Payments by modelled results: a novel design for agri-environmental schemes

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Abstract

From a theoretical point of view, result-based agri-environmental payments are clearly preferable to action-based payments. However, they suffer from two major practical disadvantages: costs of measuring the results and payment uncertainty for the participating farmers. In this paper, we propose an alternative design to overcome these two disadvantages by means of modelling (instead of measuring) the results. We describe the concept of agri-environmental payments by modelled results (PAMR), including a hypothetical example of payments for the protection and enhancement of soil functions. We offer a comprehensive discussion of the relative advantages and disadvantages of PAMR, showing that it not only unites most of the different advantages of result-based and action-based schemes, but also adds two new advantages: the potential to address trade-offs among multiple policy objectives and management for long-term environmental effects. We argue that PAMR would be a valuable addition to the agri-environmental policy toolbox in the EU and beyond, while also reflecting recent advancements in agri-environmental modelling.

Keywords: Agriculture; Agri-environmental and climate measures; Environmental modelling; Governance; Incentives; Outcome; Payment-by-results; Performance; Policy implementation

JEL codes: Q18, Q24, Q52, Q58

1 Introduction

Agricultural production is entangled in several challenges that require appropriate design of institutional responses. Agriculture depends on an intact, functioning environment; but it also causes environmental damage. On the one hand, farmers are heavily affected by environmental change, e.g. climate change (Challinor et al., 2014; Peichl et al., 2019) and land degradation (Nkonya et al., 2016). On the other hand, agricultural production is a major source of multiple environmental pressures, including greenhouse gas emissions, soil erosion, ground and surface water pollution and landscape degradation (Campbell et al., 2017). Despite the recognition that agriculture is generating serious environmental problems, they persevere and in many cases are worsening (Springmann et al., 2018). This is often due to inadequate specification of property rights and the associated asymmetrical, inefficient and potentially unjust distribution of costs and benefits among farmers and other members of society (Bartkowski et al., 2018). From an economic point of view, agricultural produce and associated profits are private benefits, whereas the environmentally harmful impacts of agriculture are externalities (public bads to society and other stakeholders) that are not borne by farmers and hence in need of internalization in farmers' decisions. This includes the need to incentivize the provision of public goods (positive externalities such as carbon storage in soils), which risk being underprovided if there is no compensation for the farmer.

The most common policy instrument in this context is agri-environmental payments, a form of payments for ecosystem services (PES) (Engel, 2016): farmers voluntarily enter contracts under which they agree to change their management in a way that is assumed to benefit the environment. In exchange, they receive pre-defined payments. There are two general variants of agri-environmental payments – action-based and result-based schemes.[1] *Action-based schemes* offer farmers a uniform[2] payment within a specified area or region such as a watershed for adopting specific management practices or environmentally beneficial actions. *Result-based schemes*, on the other hand, offer payments conditional on achieving a result, i.e. a quantifiable environmental objective, while the choice of actions to achieve the result are up to the participating farmers. The defining characteristic of a result-based scheme is that the payment

[1] Note that different terms are used in the literature: action-based can be referred to as input- and measure-based or action-oriented payments/schemes, while result-based are referred to as performance-, outcome-, output-, success-based or -oriented payments/schemes, or objective-driven or payment-by-result schemes.

[2] Theoretically, non-uniform payment rates are conceivable for action-based schemes; however, current practice is uniform payments. Given the importance of fairness considerations in farmers' perceptions of different schemes, non-uniform action-based schemes may be problematic in terms of legitimacy (Vainio et al., 2019).

is based on a quantified result, and therefore implies the possibility of farmers receiving different payments for the same actions.

In what follows, we focus predominantly on agri-environmental payments within Pillar 2 of the European Union's (EU) Common Agricultural Policy (CAP). Most of the so-called agri-environment and climate measures within the CAP framework are action-based payment schemes (Burton and Schwarz, 2013). A growing body of literature indicates that these schemes perform poorly and there is a pressing need for more evidence-based governance systems (Dicks et al. 2014; Pe'er et al. 2019). According to Sutherland et al. (2004), the design of action-based schemes is in many cases only anecdotally based on scientific knowledge (see e.g. Finn et al. 2009; Prager and Freese 2009; European Court of Auditors 2011; ENRD 2016). While the CAP's agri-environmental schemes have been shown to slightly improve the state of European agroecosystems (e.g. Batáry et al., 2015), action-based schemes lack the important sensitivity to local conditions (Kleijn et al., 2011). Hence, they often fail in providing the ecological benefits they are presumed to bring about (Burton and Schwarz, 2013; Dupraz and Guyomard, 2019) and are cost-ineffective (Wätzold et al., 2016). Overall, the literature indicates that the lack of evidence-based links between the implementation of particular practices on particular farms is the root of the poor performance of action-based schemes.

A large body of literature exists on the relative strengths and weaknesses of action-based and result-based agri-environmental payments (Börner et al., 2017; Burton and Schwarz, 2013; Engel, 2016; Engel et al., 2008). This literature shows that result-based payments are clearly preferable from a theoretical point of view because they provide incentives to farmers to enrol their most suitable land, thus ascertaining goal attainment and preventing adverse selection; they have low informational requirements for the regulator (which, however, goes along with potentially high information rents for the farmers (White and Hanley, 2016)); they are cost-effective and dynamically efficient by providing incentives to innovate and drive down the costs of goal attainment over time. Furthermore, it has been pointed out that by being less prescriptive and by rewarding inventiveness, they may increase farmer engagement and lead to an internalization of the scheme's goals by the farmers (Burton and Schwarz, 2013). Why then are result-based schemes not more prevalent?

Result-based payments score significantly worse than action-based payments in terms of practicability, which explains their low prevalence: first, they require, ostensibly, sophisticated monitoring and measurement of results (Zabel and Roe, 2009); second, they are less attractive to farmers than action-based payments due to the associated uncertainty of payment, as "an individual's performance also depends on external environmental effects such as weather influences" (Zabel and Roe, 2009, p. 131; see also Drechsler, 2017; Derissen and Quaas, 2013). Accordingly, such schemes have only been applied in contexts where monitoring costs and payment uncertainty are acceptably low. Furthermore, conventional result-based payments provide incentives to enrol land where the required effect is already fulfilled or close to fulfilment (Uthes and Matzdorf, 2013), as usually the payments are not based on a change compared to the status quo, but rather on the absolute level of achievement.[3] Nonetheless, result-based agri-environmental payments are widely considered the way forward in Europe (e.g. Cullen et al., 2018; Mann, 2018). For instance, the European Commission has issued a handbook on designing and implementing result-based schemes within the CAP (Keenleyside et al., 2014).

The main obstacle posed by result-based schemes compared to action-based schemes is therefore practical: the measurement of the results of farmers' chosen measures. In the context of nonpoint-source pollution, Sidemo-Holm et al. (2018) have demonstrated that the practical shortcomings of result-based agri-environmental payment schemes can be alleviated by using models instead of direct measurement to determine the farmer's achieved result (see also Talberth et al., 2015). In this paper, we aim to develop further the idea of using modelling for solving the measurement problem and to demonstrate how uncertainties can be reduced on both sides of the transaction. To do this, we propose the design of an agri-environmental payments by modelled results (PAMR) scheme as a complementary option to conventional action-based and result-based payments, and discuss how it would combine some of the relative advantages of the two. Furthermore, we provide a framework of how modelling and smart infrastructure can be combined for possible applications in the context of sustainable land management, and demonstrate its applicability with an example in the area of soil function modelling and soil management.

The structure of the paper is as follows: in section 2 we elaborate on the relation of measurement and modelling in the context of result-based schemes. In section 3 we outline the general idea of a model-informed result-based payment scheme (i.e. PAMR) and illustrate it with a hypothetical application in the context of soil functions. In section 4 we offer a comprehensive

[3] According to Herzon et al. (2018), most result-based schemes provide payments on the basis of "the opportunity costs of the management that is considered most likely to be required to achieve the results" (p. 350). In fact, this is considered a legal requirement according to the WTO "Green Box" rules (Hasund and Johansson, 2016) and in line with EU's own Rural Development Regulation, Article 28 (Colombo and Rocamora-Montiel, 2018).

discussion of the relative advantages and disadvantages of our design proposal. In section 5 we conclude and suggest some areas for future research.

2 Measuring versus modelling results

Typically, result-based schemes are taken to mean schemes that are based on actual measurement of environmental results through monitoring. Consequently, in situations where it is infeasible to measure results directly due to either the lack of a perfect object of measure (e.g. P concentration in water) or high cost of measurements at the individual farm or field level (e.g. N concentrations in tile drains), it is also assumed that a result-based scheme is infeasible. However, if a suitable proxy for measuring the environmental result is available, then this can solve the measurement problem, and open the way for broader application of, in essence, result-based schemes.

So far, result-based agri-environmental schemes in the EU have adopted the first strategy for overcoming the measurement problem, by remunerating farmers based on an indicator as a proxy for the environmental result, usually biodiversity (Burton and Schwarz 2013; Herzon et al. 2018). Payments for biodiversity conservation are based on indicators of results rather than farmers' specific actions. The indicators include populations of particular species whose presence and abundance are known to correlate with a wider range of taxa. Other environmental public goods such as soil functions and regulating ecosystem services (e.g. water quality or run-off regulation) are only addressed by means of action-based schemes (if at all).

In cases where the feasibility or cost of measurement is the barrier to result-based schemes, modelling offers a solution. In a payments by modelled results scheme as described in detail in the following section, environmental results are predicted rather than measured. Models can synthesize knowledge about agroecosystems and process that knowledge to predict environmental benefits that cannot be easily measured on a large scale, e.g. the influence of agricultural management on the dynamics of soil functions (Vogel et al., 2018) and nonpoint-source pollution (Strauch et al., 2013). In order to do so, the model needs to describe the particular system's state and dynamics and its alteration by external factors (e.g. agricultural practices and climate), and thus provide predictions of the environmental effects of different management actions.

Models can of course never perfectly represent a complex system such as the interface between agriculture and the environment. There are always things going on in such a system that cannot be modelled because of data and resource shortages, and inherent stochasticity. How well a model resembles reality is revealed by the uncertainty of its predictions. It is therefore desirable that model predictions have low uncertainty (i.e. are reliable) when used for policy purposes, such as agri-environmental payment schemes. In contrast, measured results are ideally true values. The only uncertainty lies in the accuracy of the measurement methods – which may be large depending on the availability of measurement theory and technology. However, as discussed above, existing result-based payments are not based on measured results, but rather on indicators. Indicators imply high levels of uncertainty, just as modelled predictions, with respect to the reliability and stability of the relationship between the indicator and the desired result. Compared to measured indicators, models have the advantage that they can be used to estimate the uncertainty of the predictions.

To predict environmental benefits with the lowest possible uncertainty, models need, ideally, to include all relevant processes, functional relationships and dependencies – while at the same time striving for the maximum possible level of parsimony, in order to avoid propagation errors (Saltelli 2019). Otherwise, their predictive power will be limited (Evans et al., 2013). Model development requires expert knowledge in the process of indicator selection and interpretation. Data is required for model building, calibration, and evaluation. Still, measuring environmental benefits directly requires far more data in comparison. For instance, measurements to calibrate a model require fewer data points than making measurements in farmers' fields on a regular basis for monitoring purposes.

Before using model results for policy purposes, it has to be decided whether the predictions generated by the model are made with acceptably low uncertainty. A threshold for acceptable uncertainty can be decided upon initially, and as long as that threshold is exceeded, the model needs to be revised until the uncertainty is at an acceptable level, or otherwise abandoned. This process is similar to when evaluating the measurability of indicators in conventional result-based payments schemes. Instead of appraising the capacity of farmers, controllers and measurement tools, the modelling accuracy and precision are considered.

3 Agri-environmental payments by modelled results

From a theoretical point of view, result-based schemes are superior to action-based schemes (see section 1). However, from a practical perspective, result-based schemes suffer from two main shortcomings, both of which are broadly related to measurement: first, there is the general challenge to measure at acceptable cost the results whose realization is to be remunerated; and second, the result-based payment constitutes a source of financial uncertainty for participating farmers. The gist of the present article's argument is that both shortcomings can be overcome by means of modelling, though not in all cases and not for all schemes. In this section, we lay out a design of a payments by modelled results (PAMR) scheme. First, we present the conceptual idea in a general sense; subsequently, we illustrate it using the example of a hypothetical PAMR scheme targeting soil functions. The proposed scheme can be considered a hybrid scheme in the sense of Herzon et al. (2018), as the basis for payments is derived from farmers selecting from a set of specified actions (and payment is contingent upon performance of these actions), but the payment level is based on (modelled) results associated with the actions.

3.1 Conceptual proposal

The core idea is that, instead of using ex-post indicator measurements to determine the achievement of results, a PAMR scheme would employ models to predict the results. These predicted environmental effects would then be the basis for determining payments. In what follows, we elaborate on how the information would flow between different inputs at different stages of a PAMR implementation, including modelling, farmer's choices, results, and payments. Furthermore, we employ the idea of an integrated model-software application to sketch out what an actual implementation may look like.

Firstly, models need to be fed with spatially explicit data describing agronomic, ecological and biophysical features of a farm's land, e.g. landscape structure, field size, soil type, hydrology and crop rotation, that are needed to predict the effects of management on environmental outcomes (Fig. 1, step 1). Secondly, the farmer can choose from the menu of potential management actions, e.g. reduced tillage, mowing dates, buffer strips and linear natural elements, and the model predicts environmental results, e.g. changes in the provision of soil functions or biodiversity, for a chosen combination and spatially explicit allocation of actions (Fig. 1, step 2). Thirdly, payment offers are calculated for each combination of management actions, based on their modelled environmental results (Fig. 1, step 3). This entails that farmers are presented with payment offers for any combination of actions (practices) they might wish to test; subsequently, the interface generates a suite of alternatives from which they can choose. Fourthly, the farmers can choose the alternative (combination of actions) that best satisfies their own preferences and knowledge about their fields, e.g. soil productivity, cost structures, profitability, and other types of motivation (Fig. 1, step 4). We suggest that this step can be facilitated with a software application that provides a graphical user interface (see e.g. Fales et al., 2016; Sturm et al., 2018). Such a software application, either web-based or mobile, could make the range of possible management choices under a particular scheme more accessible to the user (the farmer). Given the spatially explicit data input and the management choices by the farmer, the PAMR application would provide the farmers with predictions about environmental outcomes and entailed payments. Fifth and lastly, the scheme should be continually validated and (if necessary) updated to improve the accuracy of predicted results and effectiveness in terms of environmental outcomes (Fig. 1, step 5). This should include accounting for changes in land use which follow farmers' participation in the PAMR, e.g. effects on the local hydrology from planting a hedge, and validating with environmental monitoring at a larger scale.

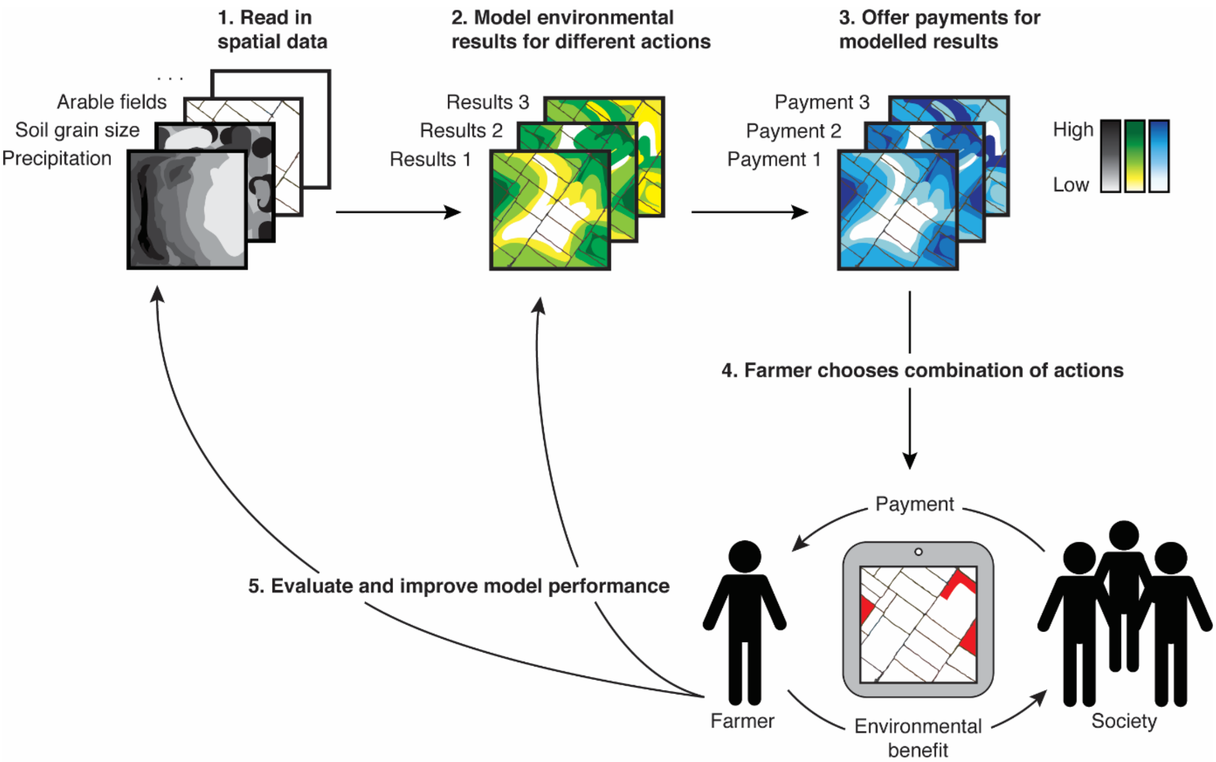

Figure 1: Schematic outline of an agri-environmental payments by modelled results (PAMR) scheme (Source: Bartkowski et al., 2019, slightly modified)

From a conceptual point of view, a PAMR scheme constitutes a form of contract between society and participating farmers (Hagedorn, 2008). Society can benefit from the provision of (public) ecosystem services by the farmers and the agroecosystems they manage. Taking the farmers' freedom of choice into account, society (and the regulator on society's behalf) make an "offer" for the provision of specified ecosystem services (in the widest sense). Within a safe virtual space of a smart application, farmers can experiment with different options and pick an action or a set of actions that they prefer, be it because of monetary pay-off, costs, environmental quality, or any other criteria such as intrinsic motivation. The software application would thereby become a decision-support tool to allow the farmers and regulators to make informed decisions under reduced uncertainty (for further discussion of the advantages and disadvantages, see section 4). In other words, the farmer implements the proposed actions and receives a predefined, certain payment contingent upon performing the chosen actions, based on ex-ante model prediction and subject to a potential control by the regulator. This entire scheme can be re-evaluated and improved over time with regard to four main elements: quality and resolution of the input data, model prediction accuracy and precision, the set of available measures, and the corresponding payment levels.

3.2 PAMR scheme example

We do not expect PAMR to be applicable in all contexts; in many cases, conventional agri-environmental schemes will remain the preferred choice. One potential field of application of PAMR is soil protection. Currently, agri-environmental policy instruments directly addressing soils and the functions they provide are scarce in the EU (Ronchi et al., 2019; Vrebos et al., 2017). As mentioned in section 2, virtually all existing result-based agri-environmental schemes in Europe are targeting biodiversity. Given the complexity and heterogeneity of soil systems, action-based schemes are likely to be quite ineffective in improving the provision of soil functions. At the same time, soil functions are difficult to measure on a large scale (e.g. Drobnik et al., 2018). Accordingly, PAMR schemes have a very large potential in the context of soils (Bartkowski et al., 2018; Vogel et al., 2018). In this section we present an example of a modelling approach that could (hypothetically) be the basis for a PAMR scheme in the context of soil functions. The example is based on a modelling framework currently under development within the German large-scale project BonaRes – Soil as a Resource for the Bioeconomy (see also Vogel et al., 2018; 2019). We explain and discuss the steps depicted in Figure 1 in this particular context, with an emphasis on Steps 1 and 2. We do not include Steps 4 and 5, as they only become relevant in an actual application of PAMR in the real world.

Step 1: Spatial data and modelling

In order to implement and evaluate the PAMR application, spatial data from various sources are required that can be used to make the model-based translation of management into soil functions spatially explicit and context specific. These essentially refer to meteorological, crop and soil data (compare Fig. 1). For the development of spatially continuous high-resolution geo-information from raw data from various sources (e.g. soil profile description, data from lab analysis, radar measurements), regionalization approaches are required that often rely on space-borne remote sensing and involve diverse modelling procedures. Models applied to generate spatially distributed rainfall and other climate data depend on the temporal and spatial scale, and include empirical statistical models as well as models of dynamic meteorology (see Srikanthan and Mcmahon, 2001 for a review). The EU's Sentinel satellite mission produces better temporal data continuity compared to previous satellite missions which may allow for the derivation of crop-specific land use classification and yield estimation, based on empirical modelling and complex data processing routines (Battude et al., 2016; Veloso et al., 2017).

Spatial soil information is often available as conventional polygon maps displaying the spatial extent of systematic units. However, as soil map development relies heavily on the individual soil surveyor's expertise, the methodology is not reproducible; spatial aggregation follows primarily optical criteria, soil types of different properties and genesis are merged. On the other hand, the state-of-the-art empirical modelling approach often relies on the same legacy soil databases (Arrouays et al., 2017), but translates expert knowledge on pedogenesis in predictor-response systems that are fitted by powerful algorithms from machine learning and spatial statistics. The approach is known as "digital soil mapping" and includes model performance evaluation and the provision of an uncertainty estimate per se. Geo raster data that approximate the soil forming factors (parent material, climate, topography, vegetation/land use) are used as predictors. They may originate from remote sensing data products and expert-based information; see Nussbaum et al. (2018) and Padarian et al. (2019) for recent applications.

Step 2: Linking management to soil functions

Within the PAMR framework, the above-mentioned geo raster data is used to feed into models linking management with environmental objectives. Within BonaRes, the process-based soil model called Bodium is currently under development. It attempts to integrate in a systemic approach (Vogel et al., 2018) the dominant processes in soils, and thus to facilitate the prediction of the multiple consequences of management practices for soil processes and, eventually, soil functions. Soil structure dynamics are an integral part of the modelled soil system. Plant roots and soil organisms build this structure, while agricultural practices (e.g. machine traffic) alter it. The dynamic soil structure influences water and air distribution and these in turn influence plant growth and organism activity. This biotic activity is the basis for nutrient cycling and organic matter decomposition, i.e. carbon sequestration and storage. All these processes are site-specific and depend on local conditions. These conditions comprise climatic and soil factors that cannot be influenced at a medium time scale – they are so-called "inherent soil properties" (Vogel et al., 2018; 2019). This input is provided by the georeferenced data and modelling synthesized in Step 1.

To facilitate the running of Bodium, scenarios are used. These scenarios reflect changes in management, which ideally involve bundles of practices rather than individual practices. For instance, a shift to conservation tillage may also imply an increase in mechanical weed control. Bodium translates management changes (crop rotation, tillage, fertilization and, to a more limited extent, pest control) into outcomes that are evaluated according to the major soil functions: biomass production, carbon storage, storage and filtering of water, soil biodiversity and nutrient cycling. Under the assumption that production and nutrient cycling are essentially private goods, they would not be used as objectives for a PAMR scheme; however, the modelling results with respect to these two have obvious relevance for the farmer's decision to participate in the scheme and, thus, in the sense of a decision support tool. Carbon storage, water buffering to mitigate flooding, groundwater recharge, nutrient retention and biodiversity are (expressions of) soil functions that have clear societal relevance in terms of regulating and supporting ecosystem services, and modelled changes in them could therefore be used to determine agri-environmental payments. The nature of Bodium, which models multiple soil functions simultaneously, would allow for a holistic approach that better takes into account the trade-offs involved than when single functions are targeted separately. For instance, there is a well-known trade-off between reduction of herbicide use and a corresponding increase in the need for mechanical weeding and thus compaction (Böcker et al., 2019). Accordingly, the PAMR interface would ideally offer the possibility to modify multiple management practices (or: bundles of practices); farmers would receive suggestions about which additional practices/parameters may require change following, for instance, a shift to conservation tillage. The selection of auxiliary practices to change would ultimately be up to the farmer (i.e., standardized yet adjustable bundles of practices or actions would be used). The implementation of the scheme would then refer to the bundle of chosen practices and the payments would be based on their modelled joint environmental effects.

Within a PAMR scheme, the data and modelling from Steps 1 and 2 would be the basis for an online application available to the farmers, also being the source of combined spatial data describing a farmer's land eligible to participate in the agri-environmental payment scheme. Optionally, it is thinkable to allow the farmers to correct the data on the basis of standardized data input, e.g. from proximate sensors attached to the farmers' machines. These input data would then underlie the Bodium-based modelling. Changes in the soil production function would mainly inform the farmer about opportunity costs of the available actions. Changes in the other, public soil functions though would be the basis for offering payments to the farmer.

Step 3: Payments

For each soil function, payment rates per unit increase would be specified, according to which the farmers would receive remuneration. Generally, it is an important question for PAMR and any other result-based scheme how the payment rate per unit of the objective is to be determined. From a welfare economic point of view, it would be efficient to remunerate farmers for the realization of environmental benefits on the basis of the latter's marginal social value (i.e. shadow price) (Hasund, 2013). Otherwise, there is the risk of underprovision of the environmental public good in question.[4] On the other hand, however, if the payments are significantly higher than the opportunity costs (overcompensation), underprovision may result because the scheme funds are limited and more farmers could be enrolled if payments were lower (Börner et al., 2017). In the end, "the payment level determines the distribution of net gains between [ecosystem service] providers and [ecosystem service] beneficiaries" (Engel, 2016, p. 139). Of course, shadow prices of environmental public goods (ecosystem services, biodiversity etc.) can only be roughly approximated by means of economic valuation, and there is a general paucity of high-quality valuation studies (e.g. Bartkowski et al., 2015; Förster et al., 2019). This also holds in the specific context of soil valuation studies (Bartkowski et al., 2020; Jónsson and Davíðsdóttir, 2016). As a first step, a PAMR scheme targeting soil functions may thus rather use payment levels derived from a stakeholder-based negotiation process between the farmers and representatives of the wider society or set on the basis of the opportunity costs of a typical relevant management action. Eventually, valuation estimates from specifically conducted studies could be used to inform the adaptation of payment levels.

4 Discussion

We have presented the concept of an agri-environmental payments scheme based on modelled results (PAMR), both in a generalized form and in a specific context using an example related to soil functions. It should be noted that a pilot scheme was implemented in the United States that is consistent with the PAMR principles as described above. It was developed by The Nature Conservancy within a Strategic Agricultural Conservation programme in the Saginaw Bay

[4] Also, because non-economic factors also determine the participation in agri-environmental schemes, payments alone need not necessarily guarantee socially efficient levels of participation (and, thus, provision of the public good) (Bartkowski and Bartke, 2018).

watershed, Michigan, USA (Fales et al., 2016), complementing a model-based online decision support tool, the Great Lakes Watershed Management System (GLWMS). Among other uses, the GLWMS was the basis for a pay-for-performance (i.e. result-based) pilot programme, with payments provided for various management practices on the basis of their model-estimated effects on water quality. In this section, we would like to go beyond the quantitative results and scarce discussion provided by Fales et al. (2016), and discuss the relative advantages and disadvantages of PAMR by comparing it to conventional action-based and result-based schemes. There is no agreed upon set of criteria to evaluate agri-environmental schemes, but we use some widely found policy evaluation criteria to organize our discussion. Specifically, we use the general distinction between effectiveness (environmental outcomes, spatial targeting, additionality), efficiency (cost-effectiveness, dynamic efficiency) and acceptance by farmers (Hanley et al. 1999; Engel et al. 2008; Burton and Schwarz 2013). Within these general categories, we also discuss some more specific criteria, especially payment certainty, which is related to Burton and Schwarz's (2013) assessment that a major downside of result-based schemes is "increasing risk for suppliers". Of course, further criteria would also be possible, such as leakage, permanence, spatial coordination, coherence (Engel et al. 2008), distributional effects, and implementation feasibility (Hasund 2013). We touch upon the latter by briefly discussing the transaction costs associated with implementation and administration of the scheme as well as monitoring. Table 1 summarizes the comparison of PAMR with conventional action-based schemes, using conventional result-based schemes as baseline (given that it is the theoretical "gold standard"). The evaluation is based on the authors' assessment and expertise from their diverse disciplines. Note that we use a purely relative scale of the relative performance with respect to each criterion and assuming that the PAMR is based on a reliable model.

Table 1: Relative performance of action-based schemes and PAMR against the baseline of result-based schemes.

Note: This is a purely relative scale; + is a relatively positive (desirable) score, - is negative, = indicates performance comparable to result-based schemes.

Criterion	**Action-based**	**PAMR**
Effectiveness		
Spatial targeting	-	=
Environmental outcome certainty	-	-/=
Additionality	-	=
Efficiency		
Cost-effectiveness	-	=
Dynamic efficiency	-	-/=
Transaction costs		
Implementation and administration costs	+	-
Monitoring costs	+	+
Acceptance by farmers		
Payment certainty	+	+
Farmer autonomy	-	-/=

4.1 Effectiveness

Regarding the common criterion of (environmental) effectiveness, we discuss the advantages and disadvantages of PAMR with respect to three relevant sub-criteria: spatial targeting (i.e. the ability to account for spatial heterogeneity), environmental outcome certainty and additionality.

4.1.1. Spatial targeting

PAMR has an obvious advantage over conventional action-based payments; it is context-specific. By using spatially explicit data and modelling, PAMR responds to the challenges of the inherent spatial heterogeneity of agroecosystems and farming systems, while action-based schemes are based on an implicit 'one-size-fits-all' assumption and do not offer options to account for heterogeneity among farms (though there are exceptions, see ENRD, 2016). The same sensitivity to spatial heterogeneity holds for conventional result-based payments, which leverage farmers' local knowledge rather than spatially explicit data and models to account for heterogeneity. Accordingly, PAMR is similar to conventional result-based schemes in terms of its potential for spatial targeting, while action-based schemes are at a disadvantage.

4.1.2 Environmental outcome certainty

From the point of view of society and the regulator (but also the intrinsically motivated farmer) the environmental effectiveness of applied measures, i.e. environmental outcome certainty, is crucial. In this context, we mean epistemic certainty, i.e. the reliability of the involved theories, models, measurement techniques etc. to reflect “true values”. Action-based schemes can be reliable in this sense when they are based on established theories and/or expert knowledge and/or models (e.g. Wätzold et al. 2016; Rodríguez-Ortega et al. 2018) and when spatial heterogeneity does not play a large role (see above). Comparing PAMR with conventional result-based payments offers mixed results. Modelling has some advantages over measuring. Models make it possible to anticipate environmental benefits before they are generated (ex-ante evaluation). Policy makers can therefore be informed about future environmental benefits on a field level. For this, it is necessary that models predict at an adequate temporal and spatial resolution to allow policy makers to evaluate the contribution of local actions to the probability of reaching environmental goals, and use such information to plan future commitments.

However, one must say that a PAMR scheme is only as good as the model(s) underlying it. The epistemic uncertainty of model predictions will vary between different environmental benefits. For example, models with good precision and accuracy have been used to predict the impact of agricultural practices on greenhouse gas emissions (Weiske et al., 2006), buffer strips in preventing downstream eutrophication (White and Arnold, 2009) and the impact of various agricultural practices on water quality (Fales et al., 2016) or the provision of soil functions (see section 3.2). Other environmental benefits are more difficult to model. For example, the extinction rate of species is inherently stochastic and can hardly be modelled without a discouragingly wide range of possible outcomes (Ludwig, 1999).

Whether the model-baseed scheme leads to attainment of society’s environmental goals in the long-run will depend on the accuracy of the predictions. Each model is calibrated and evaluated based on measurements; however, a model can be applied to an area for which measurement is impractical (assuming that other conditions for model application are met). Furthermore, since models required for both Step 1 and Step 2 of a PAMR scheme are likely to be complex and data-intensive, possible errors propagate throughout the modelling chain (cf. Saltelli 2019). They comprise uncertainties of the original input data, the models involved in spatially continuous data generation, the applied process models simulating the system dynamics, and the assessment scheme of the model outputs. Therefore, uncertainties in the obtained predictions have to be quantified. By quantifying uncertainty, models also make possible the integration of uncertainty in decision-making. Policy makers can adjust the payment so that it is higher when the uncertainty is low, and vice versa, to account for the risk that the envisaged outcome is not reached despite payments being made. In comparison, the correlative uncertainty between measured indicators and desired results in conventional result-based schemes is not quantified and thus cannot be used to improve decision making. Consequently, action-based schemes have clear disadvantages regarding outcome certainty, while PAMR has both advantages and disadvantages.

4.1.3 Additionality

The additionality of action-based payments is unknown since the results are not quantified. In a PAMR scheme, the model would compare the status quo with a change. Therefore, it is unlikely that payments will be provided for results that would have been achieved (or were already achieved) in the absence of the scheme. This could similarly be done in result-based schemes where the results are measured, by comparing the environmental outcomes before and after enrolling in a scheme, though it has not been done on a regular basis in practice. Using the status quo as a baseline in PAMR (and in measurement-based schemes) may however imply adverse selection – by creating an incentive to downgrade land before entering the scheme in order to achieve a higher increment (and thus higher payment). The alternative would be to use some general baseline, such as “good agricultural practice” for the land in question – here, the downside would be the potential inefficiency due to paying for non-additional effects (windfall gain), if the actual status quo is above the baseline. Furthermore, this approach would require the definition of a general standard to be used as a baseline – thus counteracting the context-specific nature of result-based payments that serves as reference for PAMR. Eventually, it is an empirical question which variant is likely to be less problematic and more practicable.

4.2 Efficiency

We consider two standard sub-criteria used to evaluate the efficiency of agri-environmental policy instruments: cost-effectiveness and dynamic efficiency.

4.2.1 Cost-effectiveness

From a theoretical point of view, result-based payments are generally considered more cost-effective than action-based payments, especially under the assumption that information asymmetries are limited and the regulator is able to perfectly monitor the results (Melkonyan and Taylor, 2013; White and Hanley, 2016). Spatial targeting can, principally, improve cost-effectiveness in both types of schemes with near-perfect information availability to the regulator (Drechsler et al., 2016; Engel, 2016). However, the regulator usually has limited knowledge of the cost structures of individual farms. Result-based payments are expected to solve this information asymmetry, because payments are only provided in exchange for the provision of environmental benefits (Burton and Schwarz, 2013). Since rational farmers will only implement measures that are profitable/utility-improving (i.e., do not generate a net loss/dis-utility) to them, they will implement measures until the Equi-marginal Principle for cost-effectiveness is satisfied across all farms. Preliminary assessments of existing result-based schemes have corroborated this theoretical prediction (Matzdorf and Lorenz, 2010; White and Sadler, 2012).

In contrast, action-based schemes are usually cost-ineffective, as the underlying uniform payments do not reflect spatial heterogeneity in costs and benefits, thereby making it impossible to achieve cost-effectiveness. In this context, PAMR is largely comparable with conventional result-based schemes, and for large-scale schemes, modelling may also offer a less-costly alternative to measurement for administrative bodies. The information asymmetries due to unknown costs remain, but the regulator can predict the results (outcomes) of different management actions implemented by farmers. Offered a payment per unit for the desired results, rational farmers will, as in a measured result-based scheme, be incentivized to equalize their marginal costs of implementing measures with the level of the payment, thereby guaranteeing cost-effectiveness of achieving the predicted results. In this way, PAMR achieves spatial targeting of measures without the regulator needing to know the costs for individual farms. Rather, by serving farmers with context-sensitive, spatially explicit modelling, the translation of management choices into environmental effects will ensure the choice of cost-effective measures (because accurately modelled results will incentivize the farmer to minimize their costs in the same way as measured results do).

The cost-effectiveness of agri-environmental policy instruments can be significantly lowered by their transaction costs (see DeBoe and Stephenson, 2016), though high transaction costs can be motivated by substantial improvement in effectiveness (Armsworth et al., 2012). Further below, we briefly discuss the transaction costs associated with the implementation and administration as well as monitoring of PAMR.

4.2.2 Dynamic efficiency

An obvious downside of action-based payments is that they offer little or no incentive to innovate – since the payment is tied to a specific management action, it is rational for the participating farmer to stick to this action. Conversely, since the farmer is rewarded on an annually recurring basis for (measured or predicted) results, result-based payments and PAMR alike create an incentive to consider ways of improving the effectiveness of environmentally beneficial management practices in the future, because the more effective a given practice or the lower the cost of implementing it, the higher the farmer's future profits. There is broad evidence that environmental taxes and payments in other sectors that are based on results, e.g. air-pollution taxes, are a catalyst for technical change that has substantially reduced the costs of environmental improvements, while action-based schemes have the least potential to promote dynamic efficiency (Requate, 2005). Given that a PAMR scheme creates a link between environmental effectiveness and livelihoods, one can expect the scheme to promote the desire for learning (through, e.g., experimenting with the model) and harness their innovative capacity for resolving environmental problems.

Nevertheless, PAMR scores less well in terms of dynamic efficiency than conventional result-based schemes that rely on measurement. Farmers cannot benefit from innovation if the environmental benefits from such innovation cannot be modelled. Innovation is only theoretically possible if a farmer suggests something that can be modelled easily.[5] However, in general it takes several years of research to develop a model to predict effects of practices with acceptable uncertainty. More realistically, farmers can instead be engaged in the model-building process and contribute before the scheme is launched. It has been shown that stakeholders who participate in model building for environmental decision-making contribute with information, novel ideas and solutions (Beierle, 2002), increased acceptance and uptake of modelled results (Wassen et al., 2011) and improved environmental outcomes (Brody, 2003). This can also help the modellers understand the context and management practices for which they model the outcomes, while also helping the policy makers and farmers understand what is feasible to model and under what uncertainty (Addison et al., 2013). Moreover, environmental management, as well as agricultural management are annually recurring processes. If farmers are provided with a mechanism to feed into model improvement, so that they can expect innovations to be included in the model over time, then the system would promote dynamic efficiency, though with a time lag.

Time lags are characteristic of the diffusion of technological developments in agriculture generally, hence the inability for immediate introduction of environmental innovations should

[5] Note that we suggest involving farmers in updating the set of modelled practices (model extension); due to incentive problems, we do not consider model validation by farmers a feasible option beyond in the initial phase of scheme development.

not pose a significant disadvantage, if the long-term advantages can be perceived by farmers. A mechanism to involve farmers in continual model development (see step 5 in Figure 1) could also promote farmer collaboration and the sharing of ideas, which is known to be important for innovation (Darnhofer et al., 2010; Mills et al., 2019). For example, if the introduction of a proposal for model improvement requires a minimum level of consensus among farmers, it should encourage dialogue amongst farmers and modellers through e.g. facilitation activities. Conversely, it is an open question how willing farmers would be to "play around" with the PAMR tool and to participate in its further development (e.g. adding new practices to the modelled portfolio). The challenge here is mainly how to best create opportunities for farmers and other stakeholders to provide input into continual model development. This may also include provision of spatially explicit data needed to feed the model (Finger et al., 2019; Weersink et al., 2018). For this, standards would be needed to ensure valid model results.

4.3 Transaction costs

As noted above, transaction costs are a difficult-to-assess yet important factor influencing the practicability, feasibility and cost-effectiveness of agri-environmental policy instruments, including payment schemes (DeBoe and Stephenson, 2016). We focus on two sub-criteria in this context: implementation and administration costs as well as monitoring costs.

4.3.1 Implementation and administration costs

The implementation and administration of conventional action-based and result-based schemes is relatively simple. Especially for the former, it only requires the definition of actions to be incentivized within the scheme; for the latter, it may also entail first measurements of indicators to determine the baseline against which improvements are to be remunerated. Furthermore, result-based schemes usually go along with education and advisory services, which create additional costs (Keenleyside et al., 2014). In both cases, the enrolment of farmers and administration of contracts (including payments) adds to the transaction costs. For PAMR, the enrolment and contract administration costs are likely to be of similar magnitude. However, since the proposed scheme is based on a model and requires a custom web interface and/or mobile application, the implementation costs associated with developing those may be quite high. Even if an existing model is used (such as Bodium), it still has to be coupled to an interface which allows farmers to easily interact and experiment with the scheme. Furthermore, data needed to run the model needs to be stored somewhere, which also implies costs.

4.3.2 Monitoring costs

Monitoring costs of conventional action-based schemes are relatively low, as payments are based on pre-defined actions, which are usually easily observable (such as the creation of landscape elements or reduced tillage). For conventional result-based schemes, much depends on who does the monitoring – in some pilot schemes, it is done by the farmers themselves, which is a low-cost option (Keenleyside et al., 2014). If monitoring and measurement is to be done by the administrating agency, the costs are likely to be high. As for PAMR, since the payment is contingent on actions (with the payment level based on model predictions), the monitoring costs are similar to those of conventional action-based schemes.

4.4 Acceptance by farmers

For social–cultural or "long-term behavioural" change (Burton and Schwarz 2013: 632), a necessary precondition is acceptance of a PAMR scheme by farmers, and thereby contributing to its political acceptability. In what follows, we focus on two sub-criteria in this context: payment certainty and farmer autonomy (the latter including the consideration of non-pecuniary motives).

4.4.1 Payment certainty

One of the main advantages of action-based payment schemes over result-based payments is, from the perspective of the participating farmers, that they offer the certainty of payment – if farmers sign up for a scheme and apply the agreed-upon management actions, they will be paid. Meanwhile, in a result-based scheme, the payment is conditional on achieving the result – which, however, is not only influenced by the actions of the farmer, but also by various external factors such as extreme weather events, unexpected pest infestations, the actions of neighbours etc. There are only few contexts in which the uncertainty of receiving payment is acceptably low. Payment uncertainty is a criterion in which PAMR scores better than conventional result-based payments; since payments are based on ex-ante results of modelling, payment is as certain as in the case of action-based schemes. In this sense, PAMR combines two main advantages of result-based and action-based schemes, respectively: while offering greater outcome certainty to society than action-based payments (though less than is the case in a conventional result-based scheme), it also provides similar payment certainty for the farmer.

4.4.2 Farmer autonomy

It is a general advantage of result-based schemes that they are consistent with farmers' preference for making their own decisions about how to manage their land, including management for environmental objectives. Thus, result-based schemes not only increase room for immaterial benefits of a feeling of agency and autonomy, but also allow for using relevant local knowledge (e.g. Riley, 2016; Stupak et al., 2019). In this respect, PAMR has both a relative advantage and disadvantage compared to result-based schemes (see below). However, it is important to note that especially here, empirical research and pilot PAMR schemes would be necessary to reach reliable insights.

First, the PAMR interface or app is not only useful in the context of the payment scheme itself – but also has the character of a decision support tool, though one focusing strongly on environmental effects of agricultural management practices (cf. Fales et al., 2016). In this sense, PAMR has the appeal of combining a policy instrument with a decision support tool that would support farmers in their pursuit of both private and public goals. Furthermore, by linking management choices to their environmental effects, PAMR may facilitate the consideration of non-pecuniary motives by farmers, who may make decisions not only on the basis of profit maximization (Bartkowski and Bartke, 2018). This is a significant advantage compared to action-based payment schemes, in which knowledge about the effects of practices by individual farmers is not usually available to them, so it is rational for the farmer to focus on pecuniary rewards (in some cases, they may know that the scheme is ineffective, and thus participate solely for pecuniary reasons). Having access to the model would enable the farmer to experiment and thereby learn from the predicted results of different actions. Normally, farmers are not provided with individual feedback on the environmental consequences of their management choices in an action-based scheme, which deadens engagement.

However, for reasons already discussed with respect to dynamic efficiency, PAMR is still more restrictive than a conventional result-based scheme because it only allows for management changes that are and can be modelled. Therefore, the autonomy of the participating farmers is not as high, though higher than in the case of action-based schemes.

4.5 Additional benefits of PAMR

In addition to a first assessment of PAMR in terms of common evaluation criteria, we would like to stress two additional advantages that it offers: the ability to integrate multiple objectives and long-term effects. There is an increasing number of models that allow taking into account multiple environmental effects (e.g. ecosystem service bundles), thus supporting the analysis of trade-offs between different objectives. Using such multi-objective models to support a PAMR scheme (see also section 3.2) would allow regulators to provide more "holistic" incentives, focusing on the interactions between different environmental objectives rather than treating each of them separately (or some of them not at all, e.g. due to prohibitive costs of measurement). Furthermore, it would enable and support farmers in choosing management approaches that improve multiple ecosystem services simultaneously – while also making them aware of the trade-offs involved. Relatedly, the PAMR framework offers an option for targeting long-term processes, for which measurement would imply long time lags, as well as for taking into account the effects of external drivers (such as climate change) on the targeted environmental objectives. Given the usual contract length of five to seven years in the EU, no management practices are currently incentivized whose positive environmental impacts take longer. For instance, the effects of practices changing the structural development of soils to improve water infiltration and storage or the consequences of crop diversification as a substitute for pesticides on soil biology may be detectable only after longer periods. Modelling allows predicting the far-into-the-future effects of various practices and provide remuneration to farmers accordingly, thus also giving them incentives for longer-term investments in changing practices. Also, incorporating expected developments of external drivers (such as temperature rise due to climate change) may allow for a more realistic remuneration in longer-term contracts. This would further increase the range of applications and their societal relevance in agri-environmental policy. Of course, it would also require longer contract lengths to ensure that the changes are not reversed before taking effect.

5 Conclusions

In this paper, we introduced a novel conceptual idea for the design of agri-environmental payment schemes – agri-environmental payments by modelled results (PAMR). PAMR is a combination of design elements, but also of many advantages of conventional result-based payments and the payment certainty of action-based schemes. On the one hand, the prime advantages of the former would be retained – high environmental effectiveness, cost-effectiveness, (more limitedly) dynamic efficiency and possibly also facilitation of farmers' autonomy. Given high quality models, it can be assumed that on average, the predicted results will be realized (with some random variation due to factors such as weather conditions). Importantly, the two main practical downsides of result-based schemes (vis-à-vis action-based), namely costs of measurement and payment uncertainty for farmers, can be resolved with the proposed modelling approach. In the first instance, the need to visit all fields and carry out costly measurements and analysis is replaced by modelling results, with measurements restricted to a sample of fields for either continual model validation and improvement, or regulatory control. Furthermore, since the model would predict the environmental effects ex ante and the payments to the farmer would be based on these predictions, there would be no payment uncertainty for the farmer. In this sense, PAMR has the potential to reduce outcome uncertainty as compared with action-based schemes (from the regulator's perspective), while also reducing payment uncertainty as compared with conventional result-based schemes (from the farmer's perspective). Overall, the PAMR scheme would thus improve social welfare. The payment would be tied to modelled environmental outcomes and thus would be cost-effective since society would only provide payments based on site-specific model predictions of actual environmental outcomes and farmers would seek the least costly measures to obtain the payments. The downside from society's perspective is that if actual results are lower than predicted by the model, the real effectiveness of the scheme is reduced. This downside is minimized over time in our framework through the design element of continual model validation and development.

Two major improvements that go beyond conventional action-based or result-based schemes are the possibility to address multiple objectives and long-term objectives. As illustrated by referring to the modelling framework under development in the BonaRes project, PAMR would increase the policy relevance of more complex, multi-objective models, e.g. in the generally rather neglected context of soil functions. Furthermore, using models also allows to take on a longer-term perspective and base payments today on effects that are expected farther in the future.

Our paper offers the conceptual outline of PAMR. For it to become a viable option for policy, there is a need for further research. First, farmers' acceptance of and willingness to participate in a PAMR scheme should be studied – the experience reported by Fales et al. (2016) provides first tentative reasons for optimism. Second, the relevance of various models and modelling frameworks for PAMR should be tested in more detail – the framework has the largest potential where measurement is difficult or the achievement of the scheme's goal is highly uncertain for farmers. Third, there is a need for new ways of increasing model robustness and flexibility, so as to allow uptake of innovations (to spur dynamic efficiency). Fourth, interface solutions should be developed to maximize the usability and attractiveness of PAMR in practice. This should be informed by farmers' preferences. Above all, however, there is a need for a pilot study applying the PAMR principles in a real-world context.

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