The Impact of Transaction Costs and Differential BMP Adoption Rates on the Cost of Reducing Agricultural Nonpoint Source Pollution in Virginia

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Introduction

For over 30 years, federal and state governments have been engaged in a collective effort to improve the water quality and living resources in the Chesapeake Bay (CPB). To achieve these goals, the Chesapeake Bay states, the District of Columbia, and the federal government have focused their policy attention on reducing nitrogen and phosphorus loads delivered to the Bay. Despite substantial effort, achievement of water quality objectives remains elusive.

In Virginia, agriculture represents the single largest source of nutrient loads to the Chesapeake Bay. In 2013, agriculture contributed 31% and 59%, respectively, of the total nitrogen and phosphorus loads discharged to the Bay from all nutrient sources in Virginia (US EPA Chesapeake Bay Program 2014). Despite aggressive regulatory efforts in other nutrient source sectors, state authorities rely on educational programs and voluntary cost-share programs to induce landowners to adopt practices that reduce agricultural nutrient loads. While progress has been made in reducing nitrogen discharge, the Environmental Protection Agency (EPA) estimates that nitrogen and phosphorus loads will need to be reduced approximately 30% from 2013 levels to reach the reduction goals established for the agricultural sector (US EPA Chesapeake Bay Program 2014).

The cost estimates to meet agriculture reduction goals for the Bay run into the billions (Kaufman et al 2014; Schwartz 2010). Most cost models, however, are based on simplifying behavioral assumptions about public transaction costs, adoption rates, and implementation costs of agricultural nutrient-reducing practices (called best management practices or BMPs). Relatively little systematic research has been conducted on the transaction costs of implementing agricultural conservation programs (Rees and Stephenson 2014; Ribaudo and McCann 2012; McCann et al 2005). Consequently many cost models do not include any transaction costs (e.g. Ribaudo, Savage and Aillery 2014) or assume a constant (and frequently arbitrary) cost across all BMPs (Wainger et al 2013; Van Houtven et al 2012). Similarly, watershed scale cost models typically assume constant and uniform costs for different BMPs. Yet, observed BMP adoption rates vary across farmers and across BMP types, implying different opportunity costs of implementation. For instance, farmers often adopt some types of BMPs without any external financial inducements, implying low farmer opportunity costs (Claassen et al 2014). Adoption of BMPs across farms is also uneven with some farmers resistant to participating in any conservation programs (Fleming 2014; Benham et al 2007).

The objective of this paper is to examine the cost implications of including transaction costs and differential BMP costs and adoption rates associated with reducing nitrogen and phosphorus loads from agricultural sources in Virginia. The paper uses math programming to estimate the minimum cost of achieving agricultural nutrient reductions under a number of different cost scenarios. Reflecting standard modelling practice, a baseline model estimates the minimum costs to achieve a 20% reduction in nitrogen and phosphorous delivered to the Chesapeake Bay assuming no transaction costs or differentiation across adopters. The modelled scenarios allow implementation of 'BMP systems' that apply multiple BMPs to the same land use area, while recognizing diminished pollutant control effectiveness when BMPs are combined. The baseline model has three scenarios which vary unit implementation costs (low, medium and high). Next, transaction costs of implementing BMPs are introduced into the model. Transaction costs are based on estimated administration costs incurred administering federal cost-share programs and these costs vary by BMP type. Finally, we allow for three different types of adopters, distinguished by heterogeneous BMP implementations and transactions costs and maximum adoption rates for each type of adopter.

The total cost to achieve agricultural reduction goals under the transactions costs and adoption scenarios are compared to the baseline case to estimate the potential increase in costs associated with more plausible assumptions about transaction costs and differential adoption rates. Such information provides policy insight into the extent to which costs may be underestimated using conventional modelling assumptions and how the inclusion of transaction costs and heterogeneous adopters may affect the cost effective mix of best management practices.

BMP Adoption Rates and Transaction Costs

Economists have devoted considerable attention to estimating watershed scale costs to agriculture of meeting water quality objectives. In the Chesapeake Bay region, this literature includes estimating the total cost of implementing conventional voluntary programs with and without spatial targeting of financial incentives and estimating the cost-saving potential of trading nutrient control obligations with regulated sources (Schwartz 2010; Van Houtven et al. 2012; Wainger et al. 2013; Shortle et al 2014). These studies utilize cost estimation models that select among a suite of given agricultural BMPS. The cost coefficients for each BMPs are typically assumed constant and based on the average cost per individual BMP.

Studies on farmer behavior suggest considerable heterogeneity in BMP adoption rates and costs compared to what is typically reflected in cost models. Farmer adoption of agricultural conservation practices differ considerably by BMP type. In general, farmers voluntarily adopt management BMPs, conservation tillage and cover crops at a much higher rate than structural BMPs. Unassisted adoption rates for many structural practices in contrast range typically below 10% (Claassen et al 2014). For structural practices, Claassen et al (2014) report 16 percent voluntary adoption of buffer practices and an additional 6 percent with cost share; while for soil conservation practices such as terraces and water and sediment basins, 8.6 percent are adopted voluntarily and additional 4 percent with cost share. Farmers particularly avoid implementing practices that require taking land out of production, such as riparian buffers (Osmond et al 2012).

By comparison, many types of crop management practices face lower up-front implementation costs and research suggests that many farmers view these practices as low cost or net negative costs practices (Boyle 2006). However, with the exception of conservation tillage, voluntary adoption of the most common management BMPs is not particularly high. Fleming (2014) reports results for adoption of agricultural management practices from a 2010 survey by the University of Maryland. Estimates of voluntary (unassisted) adoption on a per acre basis ranged from 20 percent for cover crops to 46 percent for conservation tillage. Boyle (2006) estimates that 60% of all farm cropland acreage in the United States was managed under some form of conservation tillage in 2004, while USDA's Natural Resource Conservation Service (2011) found that nearly 90% of cropland in the Bay region utilized some form of reduce tillage, most of which was likely implemented without external financial assistance.

Public cost share or financial incentive payment programs aim to increase adoption rates by paying for a share of estimated implementation costs. Additional financial inducements are likely to be needed to increase adoption for structural practices with higher upfront costs and for farmers that have higher opportunity costs of adoption. While most research shows that the percentage of farmers adopting BMPs with state or federal financial assistance is relatively low, participation is thought to be limited by both the availability of technical assistance and funding (Claassen et al. 2014; Osmond et al 2012). For certain types of management and structural practices the current level of financial assistance may also limit adoption (Osmond et al 2012). Benham et al. (2006) report that while 81% of Virginia producers in the Chesapeake Bay adopted at least one best management practice, only 31% have implemented conservation practices with cost-share assistance.

Cost studies also typically assume zero or constant administrative transaction costs of implementing BMPs. Transaction costs include public agency costs associated with promotion, implementation, and verification of conservation practices as well private information and contracting costs. The public and private transaction costs associated agricultural conservation, however, is generally poorly understood (McCann et al 2005). Consequently, authors that look at the cost effectiveness of point-nonpoint trading programs may apply an arbitrary and/or constant value to every nonpoint source BMP applied. For example, Wainger et al (2013) apply transactions costs equal to 10 percent of implementation costs for agricultural BMPs while Van Houtven et al (2012) use a 38 percent "adjustment factor" when estimating costs of nutrient trading involving agricultural nonpoint sources. Recent work shows that transaction costs can represent a considerable share of total implementation costs (McCann et al 2005; Rees and Stephenson 2014). Public agency costs may differ across different types of conservation practices and impacted significantly by program rules and procedures. Further, as additional levels of reductions are pursued, the incremental transaction costs of gaining the participation of reluctant or high cost farmers would be expected to increase.

Estimating Costs to Achieve Agricultural Nutrient Control Objectives in Virginia

Three cost minimization models are developed to examine the cost implications of adoption rates and transaction costs on meeting the agricultural nutrient control. The models estimate the minimum costs to achieve a 20% load reduction for delivered total nitrogen and delivered total phosphorous from crop and pastureland without confined animals for the study area, which comprises approximately the southern half of the CPB, and includes the James, Potomac, Rappahannock and York watersheds (Figure 1). The models were formulated as linear programming problems in GAMS.[1] Model specification follows Schwartz (2010), adapted as required.

Data

Hydrogeomorphic regions

The study region is divided based on hydrogeomorphic region. Hydrogeomorphic characteristics of the land to which a BMP is to be applied affect the nutrient load reduction effectiveness of the BMP. For example, riparian buffers have highest efficiencies if applied in the *Coastal Plain Dissected Upland* region. Data for hydrogeomorphic regions obtained from the

[1] General Algebraic Modelling Software. CONOPT solver used.

Chesapeake Bay Watershed Model (CBWM) divides the CPB into 11 hydrogeomorphic regions (HGMR), based on land physiography and rock type (Figure 2), 8 of which intersect the study area.

Figure 1: Watersheds of the CPB

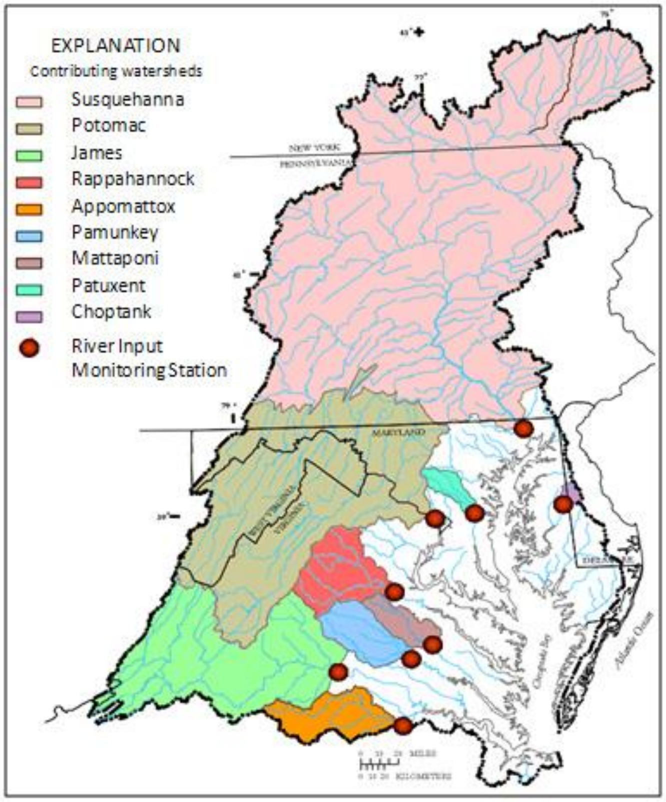
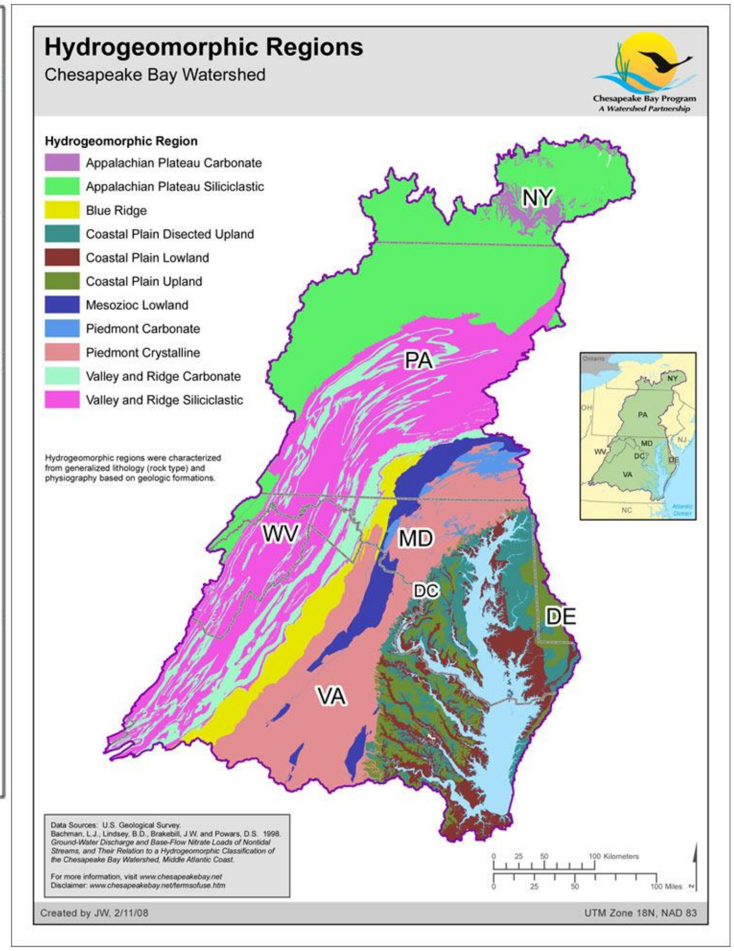


Figure 2: Hydrogeomorphic regions of the CPB



Sources: (Figure 1) US Dept. of Interior & USGS (2000);
(Figure 2) Chesapeake Bay Program (2008)

Landuses

Agricultural landuses as specified by the CBWM Phase 5.3.2 are available to be assigned a BMP system (forest and confined animal operations landuse areas are included in the model but are not available for BMP assignment). 'Landuses' are specified with reference to a particular 'land category' and land management practice, reflecting the significantly different nutrient loading characteristics associated with certain practices. Table 1 details the code and description for the 14 landuses available for BMP assignment in the model.[2]

[2] Note: although the model technically includes 14 landuses, in practice *nal* is not relevant because there is no acreage of this landuse in the study area.

Table 1: Landuses

Code	Description
hwm	High Tillage w/ Manure
nhi	Nutrient Management High Tillage w/ Manure
lwm	Low Tillage w/ Manure
nlo	Nutrient Management Low Tillage
hom	High Tillage w/o Manure
nho	Nutrient Management High Tillage w/o Manure
hyw	Hay w/ Nutrients
nhy	Nutrient Management Hay
hyo	Hay w/o Nutrients
alf	Alfalfa
nal	Nutrient Management Alfalfa
pas	Pasture
npa	Nutrient Management Pasture
trp	Degraded Riparian Pasture

BMP systems

All scenarios allow for the application of 13 BMPs: cover crops[3], continuous no-till, enhanced nutrient management, decision agriculture, riparian grass buffers, riparian forest buffers, offstream watering, livestock exclusion fencing, land retirement, tree planting, wetland restoration, upland prescribed grazing and upland intensive rotational grazing. Table A1 provides a short definition for each BMP type used in the model.

The BMPs may all be applied singularly, and certain BMPs may be stacked together to treat the same area of land. In total, a set of 56 BMP systems are available to be applied; 13 single BMPs and 43 systems involving two or more BMPs. Feasible BMP systems involving more than one BMP were specified given the following considerations, based on information from the CBWM:

- Some BMPs are mutually exclusive (e.g. forest and grass riparian buffers); therefore, multiple BMP systems can only include BMPs that are compatible.
- All BMPs have particular landuses that they can be applied to. For example, the BMP *LE* (livestock exclusion) can only be applied to the *trp* (trampled riparian pasture) landuse type, while, riparian buffers can be applied to any of the 14 eligible landuses. Therefore, systems of BMPs must be compatible in terms of the landuse they can be applied to.

[3] Although in practice a multitude of cover crops are available, the model includes only one – *early drilled rye* without fall application of nutrients.

- *CNT* (continuous no-till) is mutually exclusive to all other BMPs except riparian buffers.

Cross-indexing these BMP systems with the landuses they can feasibly be applied to yielded a set of 345 unique BMP 'treatments' (i.e. BMP system *j* applied feasibly to landuse *l*). The unit of analysis in the model is this set of BMP treatments in each hydrogeomorphic region. This specification allows nutrient reduction efficiencies of BMP systems to vary according to landuse and hydrogeomorphic region.

Implementation costs

Implementation costs for each single BMP are provided in Table 2. When two or more BMPs are stacked together in a system, implementation costs for each BMP are added. Reflecting the broad range of cost estimates available in the literature, for each BMP we specify low, medium and high unit implementation costs. Implementation cost estimates are annualized and include installation costs, annual maintenance costs over the BMP lifespan and annual land rental costs.

Table 2. Implementation costs (annualized $/acre)

BMPs	Low	Medium	High
Cover crops (early drilled rye)	27*	35	92*
Continuous no till	20	30	40
Decision Agriculture	13	21.5	30
Enhanced nutrient management	11.7*	19	37*
Land retirement	19	321.5	624
Livestock exclusion fencing	88	390.5	693
Offstream watering facilities	29.5*	32	32
Riparian forest buffer	98	500.5	903
Riparian grass buffer	44	338	632
Tree planting	56	448	840
Upland prescribed grazing	9	21	33
Upland intensive rotational grazing	53	73	93
Wetland restoration	318	602.5	887

*Implementation cost data from EPA BayFast and NRCS. All other implementation costs from Van Houtven et al (2012).

Transactions costs

The concept of transactions costs covers a range of different types of costs. In the context of conservation programs, costs that could be considered 'transactions costs' include at least the costs of developing environmental legislation and program rules, broad administration of environmental programs, communication and outreach, working with landowners to get conservation on the ground (e.g. project planning, technical assistance, contracting, etc.), and monitoring conservation projects ex-post, enforcement activity, program evaluation and reporting. Rees and Stephenson (2014) provide a comprehensive conceptual framework that can be applied to any conservation program to account for this broad range of costs using a "timeline" approach. Ideally, in a complete accounting one would assess the full range of transactions costs; unfortunately, such comprehensive data are not currently available.

To account for transactions costs in our model, we use estimates from Rees and Stephenson (2014) of the costs of contracting for specific agricultural conservation projects through cost share programs administered by the US Natural Resources Conservation Service (NRCS). The authors obtained, via extensive interviews with a NRCS District Conservationist, estimates of hours spent on each task in the NRCS contracting checklist for various projects.[4] It was identified that not all BMP projects require equal amount of time from NRCS staff; in fact, transactions costs (measured in public staff time) varies with the complexity of the contract to implement specific BMPs. Dimensions of complexity include the number of "items"[5] per project, and the level of technical expertise and planning required for each item. Staff provided low and high estimates of hours required for 3 types of contracts: "simple", "medium" and "complex". Note that transactions costs estimates are only for program staff: in reality, transactions costs are also incurred by private actors – most importantly the landowner, but also in some cases third parties such as legal advisors and other technical experts. Examples of each contract type are provided in Table 3. We transformed the hour estimates into dollars per acre by assuming an average project size of 100 acres and a unit cost of $75 per hour (includes wages and overhead); see Table 3.

[4] The transactions costs estimates cover the following activities (Rees and Stephenson 2014): *Inception*: initial meetings with landholders / farmers to discuss potential conservation activities and initial site visit; *Planning and application*: natural resource concerns on the site are identified and Conservation Plan and conservation activities are chosen (this may include interim sit visits by NRCS staff); cost estimates are made; application paperwork is submitted; *Approval*: NRCS staff review application, check eligibility, rank application processes and conduct approvals; *Contracting*: successful applicants are notified, large contracts (>$150,000) are sent for NRCS Regional approval, contracts are developed and signed, funding avenue (e.g. electronic banking) is determined; *Implementation*: pre-construction meeting / site visit; engineering designs developed (if needed), follow-up and spot checking of contracted item implementation; *Certification*: final "checkout" and signoff of practice installation for each contracted item.

[5] Items are discrete components of a contract that are individually identified by NRCS staff.

Table 3: Transactions costs by contract type ($/acre)

Contract type	Transactions costs			Examples
	Low	Average	High	
Simple contract	$14	$16	$19	Land retirement, livestock exclusion fencing, riparian grass buffers, cover crops, continuous no-till
Moderate contract	$27	$33	$38	Decision agriculture, Offstream watering, riparian forest buffer, tree planting, upland prescribed grazing, *combinations of 2 simple BMPs*
Complex contract	$45	$53	$61	Upland intensive rotational grazing, wetland restoration, enhanced nutrient management, *combinations of 2 or more moderately complex BMPs*

Given that implementation costs used in our model are annualized, there is a need to also annualize transactions costs. We worked with NRCS to identify, for each of the 56 BMP systems included our model, which contract type (simple, medium or complex) should be assigned. Then, using project lifespans and a discount rate of 7 percent obtained from Van Houtven et al (2012) – which was the source of the majority of implementation cost data – we obtained annualized transactions costs. Where a BMP system included two practices that had different time horizons, the longer time horizon was used. Annualized transactions costs for each BMP system included in the model are provided at Appendix, Table A2.

BMP nutrient reduction efficiencies

BMP efficiency data was taken from the Chesapeake Bay Commission (2012, Appendix B), with supplemental information taken from the Chesapeake Bay Phase 5.3 Community Watershed Model documentation (Date NA: Section 6) and Simpson and Weammert (2009). These sources specify, for each of the 13 BMPs, whether the BMP involves landuse change and / or an 'efficiency factor', the specific nature of landuse changes and nutrient reduction factors.

The methodology for calculating total load reduction factors is adapted from Chesapeake Bay Commission (2012, Appendix B).

In generalized form, the total load reduction factor is calculated as the sum of efficiencies generated and reductions associated with landuse change, as follows:

$$Total\ reduction\ factor \equiv r_{j,h,l}^{p} \tag{1}$$

$$= \%land\ converted \times \Delta land\ load + \%land\ treated \times efficiency\ factor \times load\ of\ land\ treated$$

Where:

- *%land converted* is the ratio of land converted to a new landuse relative to the total area treated and/or converted;
- Δ*land load* is the change in load that occurs when landuse is converted;
- *%land treated* is the ratio of land treated by the BMP relative to the total area treated and/or converted;
- *efficiency factor* is the improvement (lowering) in delivered nutrient loads associated with a BMP that involves load reduction, application reduction or efficiency change (all BMPs other than those that directly change landuse); and
- *load of land treated* is the baseline load of the landuse that the efficiency is being applied to, sourced from the CBWM (baseline loads as of 2009). Note that in cases where the area that the efficiency is applied to also has a change in landuse, the *load of treated land* is the baseline load of the new landuse.

Most of the BMP systems specified involve multiple BMPs being applied to the same land. In this case, the above formula needs to be adapted to account for the "stacked" BMPs.
For a BMP system that involves changing the riparian area to a different landuse than for the rest of the area, the first term in the above formula is broken into two terms: one for the riparian area and another for the rest of the area. Note that riparian BMPs are assumed to treat 4 times their area (Chesapeake Bay Commission: 2012, pB-11).[6]

For a BMP system that involves multiple efficiency factors being applied to the same land, the second term in equation (1) is adapted to account for the efficiencies in a *multiplicative* manner. The BMP with the highest efficiency is accounted for first, and then subsequent efficiencies are accounted for, following Simpson & Weammert (2009). For example, the BMP system *CDR+DEC* (cover crop, early drilled rye + decision agriculture) involves the landuse for the *total* area being changed to the nutrient management alternative (e.g. if applied to landuse *hwm*, landuse changes to *nhi*) and the application of two efficiency factors. In this case, for total nitrogen, the efficiency associated with *CDR* is higher than that of *DEC*. Equation (1) is in this case adapted to:

[6] A valuable possible extension (discussed below) would be to incorporate specific data on riparian area within each land-river segment.

$$r^{N}_{CDR+DEC,h,hwm} = 1 \times \left(load_h{}^{hwm} - load_h{}^{nhi}\right) + 1 \times (efficiency_h{}^{CDR} + efficiency_h{}^{CDR} \times efficiency_h{}^{DEC})\ load_h{}^{nhi} \quad (2)$$

We drew on estimates from the literature to specify average efficiency factors for each of the 13 individual BMPs for each hydrogeomorphic region in the study area (See Appendix, Table A2). Equations (1) and (2) were then used as required to estimate total reduction factors for each of the 56 specific BMP systems, applied to a particular landuse *l* in hydrogeomorphic region *h*, for use in the cost minimization model.

Cost Minimization Models and Scenarios

Baseline model

For the baseline model three scenarios were specified: **low**, **medium** and **high** implementation costs, and each was run separately (see Table 4). Model specification is as follows:

Notation

Indices:

J Set of systems of BMPs, applied to landuse *l* (345 BMP-landuse systems)
H Set of hydrogeomorphic regions (8 regions)
L Set of landuses (20 landuses; 14 eligible for BMP application)
F Set of landuses that are eligible to have BMPs applied to them (14 landuses)
J^R Subset of BMPs that include a riparian BMP (riparian BMPs are *RGB*, *RFB* and *LE*)
J^L Subset of BMPs that is feasible to apply to landuse *l*
J^{LRC} Subset of BMPs that apply the *LR, WR* or *RFB* BMPs to cropland landuses (crop landuses are *HWM*, *NHI*, *LWM*, *NLO*, *HOM* and *NHO*)

Parameters:

c_j	cost of implementing BMP system *j* (differs with scenario – low, medium or high cost)
$r_{h,j}{}^p$	reduction factor for BMP system *j* implemented on landuse *l* in hydrogeomorphic region *h* for pollutant *p* (two pollutants are analyzed: delivered Total Nitrogen and delivered Total Phosphorous)
α	target percentage reduction (the model specifies α = 0.2, i.e. 20% reduction target for both nitrogen and phosphorous)
$Baseline\ Load_{l,h}{}^p$	baseline load of pollutant *p* for landuse *l* in hydrogeomorphic region *h*
AREAl,h	area of landuse *l* in hydrogeomorphic region *h*
CROPAREAl,h	areas that are cropland
PASAREAl,h	areas pastureland

Decision-making variables:

$x_{j,h,l}$ acres of feasible BMP system *j* applied to landuse *l* in hydrogeomorphic region *h*

Model specification

Objective function:

$$\min_{x_{j,k,l}} \sum_{j} \sum_{h} \sum_{l \in F} x_{j,h,l} c_j \qquad where\ l \in F\ if\ BMP\ system\ is\ feasible\ on\ landuse\ l \quad (3)$$

st

$$\sum_{j} \sum_{h} \sum_{l \in F} x_{j,h,l} r_{j,h,l}^{p} \quad \geq \alpha \sum_{h} \sum_{l} Baseline\ Load_{l,h}^{p} \quad \forall\, p \quad (4)$$

$$\sum_{j\, \in\, J^L} x_{j,h,l} \quad = AREA_{l,h} \qquad \forall\, l \in F, h, J^L \qquad (5)$$

$$\sum_{j\, \in\, J^R} x_{j,h,l} \leq 0.05 AREA_{l,h} \qquad \forall\, l \in F, h \quad (6)$$

$$\sum_{j\, \in\, J^{LRC}} x_{j,h,l} \leq 0.25 CROPAREA_{l,h} \quad \forall\, l \in F, h\ (7)$$

$$\sum_{j\, \in\, J^{LRP}} x_{j,h,l} \leq 0.25 PASAREA_{l,h} \quad \forall\, l \in F, h\ (8)$$

$$x_{j,h,l} \geq 0 \qquad \forall\, j, h, l$$

The objective function (3) minimizes the cost of assigning BMP systems to all agricultural landuses in the study area. Equation (4) is the key constraint of the model, requiring reductions in delivered total nitrogen and total phosphorous to be at least 30 per cent of baseline loads for all 20 agricultural landuses. Equation (5) requires the assignment of BMP systems to the entire study area, for the 14 landuses that are eligible to receive BMPs. Following Schwartz (2010), (5) holds with equality because a '*status quo*' BMP (*SQ*) was added to the suite of BMP systems that can be applied. There are no costs or nutrient load reductions associated with *SQ*, so this addition does not affect the model solution. The *SQ* addition directly provides an estimate for the area that is *not* treated for each HGMR-landuse combination (which would otherwise need to be calculated after each scenario is run). Equation (6) requires that BMP systems involving one or more riparian BMPs are applied to no more than 5% of applicable land. This assumption follows Palone and Todd (1998) and is used as a proxy for riparian area because data on the precise area of riparian land in each land-river segment and landuse is not available.

The *land retirement (LR)*, *wetland restoration (WR)* and tree planting *(TR)* BMPs each retire land from agricultural production. Equations (7) and (8) restrict the total amount of land that is available to be retired under these BMPs to no more than 25 percent each of crop lands and pasture lands, respectively. Due to the effects on farm production possibilities that agricultural land retirement entails, it is considered unlikely that the bulk of working lands would be retired even if there is a high benefit-cost ratio in terms of nutrient load reduction. Thus these constraints help ensure the model gives realistic results. Inclusion of such constraints is standard practice for such models in the literature, although exact parameters differ (e.g. Shortle et al (2014) constrain land retirement BMPs, including riparian buffers, to 25% of applicable areas; Wainger et al model various scenarios which include restriction of "land conversion" to 10% of farmland per land-river segment).

Transactions Costs Model

To explore the effects of including transactions costs on the least cost solution, we added the estimated unit transactions cost estimates for each BMP system (see Table 3 in previous section), and re-ran the baseline scenarios using a modified objective function:

$$\min_{x_{j,k,l}} \sum_{j} \sum_{h} \sum_{l \in F} x_{j,h,l}(c_j + tc_j) \quad \textit{where } l \in F \textit{ if BMP system is feasible on landuse } l \qquad (3a)$$

where tc_j is the unit transactions cost associated with BMP system *j.* All constraints remain the same as in the base scenarios. Because there are three levels of implementation costs (low, medium and high), and three levels of transactions costs (low, average, high), we ran 9 scenarios to examine all possible combinations of implementation costs and transactions costs (see Table 4).

Table 4: Modelled scenarios

	Scenario number	Implementation costs assumption	Transactions costs assumption
Baseline model	1	Low	*Not included*
	6	Medium	*Not included*
	9	High	*Not included*
Transactions costs model	2	Low	Low
	3	Low	Average
	4	Low	High
	5	Medium	Low
	7	Medium	Average
	8	Medium	High
	10	High	Low
	11	High	Average
	12	High	High
Differential adoption rates model	13	Low cost adopters = Low Medium cost adopters = Medium High cost adopters = High	*Not included*
	14	Low cost adopters = Low	Low cost adopters = No TCs

	Medium cost adopters = Medium High cost adopters = High	Medium cost adopters = Average High cost adopters = High

Differential Adoption Rates Model

Many studies note heterogeneities among farmer attitudes toward adopting conservation practices (e.g. Claassen et al 2008, Ducos and Dupraz 2006, Lichtenberg 2004, Osmond et al 2012). Osmond et al (2012, p124A) comment that "conservation practice adoption is a multi-dimensional choice", depending not only on economic factors but also on social factors such as family dynamics. In order to account for heterogeneous adopters, we conceive of three different 'types' of adopters who face different costs of BMP implementation:

- *low cost adopters*: this type is assumed to adopt BMPs without the aid of cost share programs or other financial incentive programs. The decision to adopt without external financial incentives indicates that this type has a relatively low opportunity cost of adoption. This could occur for several reasons: for example, this type may be able to implement a practice at a lower cost than other individuals (for example because they own equipment or have expertise necessary for BMP implementation, or have a lower opportunity cost of time (Lichtenberg 2004)). Alternatively, this type may have a lower *net* cost of adoption because they have environmental preferences such that they derive utility from implementing conservation practices.

- *medium cost adopters*: this type is assumed to adopt conservation practices with the aid of cost share incentives. This indicates that they either face higher implementation costs than the low type, and/or derive less benefit from conservation. This type is therefore assumed to have medium implementation costs. Further, this type is assumed to incur average transactions costs of participating in cost share programs (which serves as a benchmark against which the high-cost type can be distinguished).

- *high cost adopters*: this type is assumed to be reluctant to participate in conservation activities. For example, this type may perceive a higher risk of adopting management practices relative to other types, and may be resistant to taking land out of production (for buffers, land retirement, or wetland restoration). Nevertheless, this type is assumed to adopt when sufficient public subsidies are provided. This type is therefore assumed to have both high implementation costs and high transactions costs of participating in public programs. This latter assumption reflects the notion that program staff need to invest more resources to encourage this type to participate, conduct more site visits to check the progress of implementation and provide a greater degree of technical assistance.

In addition to the three types, we also restrict the sum of available land across all types to model the reality that there are some landowners who simply will not adopt, or, alternatively, some acreage which will not have BMPs applied. This is achieved by making the sum of the maximum adoption rates for all types equal less than 100 percent of available land. Reflecting results from Benham (2010), which found that most famers had adopted at least one BMP, for most practices non-adoption is specified as 20 percent of the relevant available area. However, for certain practices such as enhanced nutrient management and those involving land retirement, a higher amount of non-adoption is specified, to better reflect a greater reluctance of farmers to adopt practices which take land out of production or which are perceived to increase yield risk (Claassen et al 2008).

Adoption rates are allowed to vary by BMP type (Table 5). This reflects the reality that some BMPs are more readily adopted without cost share than others. For example, cover crops are often perceived to have additional benefits such as preventing topsoil erosion, whereas enhanced nutrient management (which reduced fertilizer applications) are generally perceived to increase yield risk and as such is more likely to be avoided by voluntary adopters.

Table 5: Assumptions for adoption model: BMP Implementation costs, transactions costs† (annualized $/ac), and maximum adoption rates‡ (%)

	Low cost type	Medium cost type	High cost type	Non adopters
Implementation cost (IC) & Transactions cost (TC) categories	*Low IC, No TC*	*Medium IC, Average TC*	*High IC, High TC*	*NA*
Cover Crops	$27*, $0 (12%)	$35, $16 (34%)	$92*, $19 (34%)	(20%)
Continuous No Till	$20, $0 (20%)	$30, $16 (30%)	$40, $19 (40%)	(20%)
Decision Agriculture	$13, $0 (10%)	$21.5, $33 (20%)	$30, $38 (20%)	(50%)
Enhanced Nutrient Management	$11.70*, $0 (0.1%)	$19, $53 (13%)	$37*, $61 (13%)	(75%)
Land Retirement	$19, $0 (1%)	$321.5, $2 (5%)	$624, $3 (5%)	(90%)
Livestock Exclusion Fencing	$88, $0 (4%)	$390.5, $2 (86%)	$693, $3 (0%)	(10%)
Off-stream Watering Facilities	$29.5*, $ (20%)	$32, $4 (30%)	$32, $5 (30%)	(20%)
Riparian Forest Buffer	$98, $0 (7%)	$500.5, $3 (37%)	$903, $4 (37%)	(20%)
Riparian Grass Buffer	$44, $0 (14%)	$338, $2 (33%)	$632, $2 (33%)	(20%)
Tree Planting	$56, $0 (1%)	$448, $3 (4.5%)	$840, $4 (5%)	(90%)
Upland Prescribed Grazing	$9, $0 (10%)	$21, $33 (35%)	$33, $38 (35%)	(20%)
Upland Intensive Rotational Grazing	$53, $0 (0.1%)	$73, $53 (25%)	$93, $61 (25%)	(50%)
Wetland Restoration	$318, $0 (0.1%)	$602.5, $5 (1%)	$887, $6 (1%)	(98%)

*Implementation cost data from EPA BayFast and NRCS. All other implementation costs from Van Houtven et al (2012). †Transactions costs from Rees & Stephenson (2014), annualized using a 7% discount rate and assumed practice life of: 1 year (CDR, CNT, DEC, EN, UGZ, UIGZ), 10 years (LR, OW, LE), and 15 years (RFB, RGB, WR, TR). ‡Adoption rate totals may not add to 100% due to rounding.

The differential adoption rates model ("adoption model") allows for the three adopter types by replacing the decision variable x_j with three separate variables; one for each adopter type. Accordingly, the objective function (3) becomes:

$$\min_{x_{j,k,l}} \sum_{j}\sum_{h}\sum_{l\in F}\left(lag_{j,h,l}\left(c_j^{high} + tc_j^{high}\right) + reg_{j,h,l}\left(c_j^{med} + tc_j^{avg}\right) + good_{j,h,l}\left(c_j^{low}\right)\right) \quad (3b)$$

where decision-making variables are:

$lag_{j,h,l}$ is acres of BMP j assigned to landuse l for high cost type adopters in region h;

$reg_{j,h,l}$ is acres of BMP j assigned to landuse l for medium cost type adopters in region h; and

$good_{j,h,l}$ is acres of BMP j assigned to landuse l for low cost type adopters in region .

Equations (4) through (6) are retained, *mutatis mutandis*. Equations (7) and (8) are replaced by the set of maximum adoption constraints, an example of which is given below. This further set of constraints restricts BMP application according to the type of adopter and BMP type. Equation (9) shows an example of this constraint for the *high cost* adoption type and BMP systems that contain the BMP continuous no-till (j=CNT). The parameter $AREA^{CNT}{}_{l,h}$ is calculated within the model as the sum of areas where it is feasible to apply CNT, either as a single BMP or stacked together with other permissible BMPs. The constraint requires that the sum of acreage containing the BMP CNT be at most $\beta_{j,lag}$ percent of the applicable area. Table 5 provides the maximum adoption constraint percentages for each adopter and BMP type.

$$\sum_{j\,\in\, J^{CNT}} lag_{j,h,l} \le \beta_{j,lag} AREA^{CNT}{}_{l,h} \quad \forall\, l \in F, h \qquad (9)$$

Results

Costs of achieving nutrient reduction objectives

Least cost achievement of the nutrient objectives in the baseline model (without transaction costs and unlimited adoption) ranges from $34.7 million (scenario 1, low implementation costs (ICs)) to $294 million annually (scenario 9, high ICs). The wide range between these results demonstrate the uncertainty inherent in the underlying exercise of identifying implementation costs required, let alone trying to account for transactions costs and behavioral assumptions.

Adding transaction costs results in substantive increases in the cost of achieving the nutrient reduction objective. Analysis of these scenarios indicates that total costs of achieving objectives increases by between 15 and 60 percent when transactions costs are accounted for.

Table 6 compares the changes in both implementation costs and total costs for each scenario that includes transactions costs, relative to the appropriate baseline scenario which exclude transactions costs.

Table 6: Aggregate annual costs and costs changes when transactions costs are included*

Implementation cost (IC) assumption	Transactions Cost (TC) assumption	Scenario No.	IC ($m)	TC ($m)	% Δ in IC compared to No TC alternative	% Δ in Total Cost compared to No TC alternative	TC as % of Total Costs
Low IC	No TC	1	35	-	-	-	-
	Low TC	2	41	10	19%	47%	19%
	Avg TC	3	41	11	19%	52%	22%
	High TC	4	42	13	20%	58%	24%
Medium IC	No TC	5	156	-	-	-	-
	Low TC	6	156	42	1%	27%	21%
	Avg TC	7	157	49	1%	33%	24%
	High TC	8	157	58	1%	38%	27%
High IC	No TC	9	294	-	-	-	-
	Low TC	10	294	42	0.2%	15%	13%
	Avg TC	11	294	51	0.2%	17%	15%
	High TC	12	294	59	0.2%	20%	17%
Adoption models	No TC	13	248	-	-	-	-
	TC	14	249	42	0.3%	17%	14%

* percentages are compared to the scenario with the same implementation costs assumptions, e.g. Implementation costs for scenario 4 (Low IC, High TC) were 20% higher compared to scenario 1 (Low IC, No TC).

Inclusion of transactions costs potentially affects total costs in two ways: firstly, total costs are directly increased because a new cost category is being accounted for. The contribution of transactions costs to total costs, shown in the final column of Table x, ranges from 13% (scenario 10) to 27% (scenario 8). Unsurprisingly, transactions costs have the highest contribution when transactions costs are assumed to be high and implementation costs are low. The direct contribution of transactions costs was estimated to range between $42 to nearly $60 million per year for the medium and high cost implementation cost scenarios (see Table 6). Transaction costs were only about a quarter of this amount for the low implementation cost scenarios because for these scenarios the majority of BMPs applied were low transaction cost practices (i.e. requiring “simple” contracts). These estimates only include transaction costs of getting BMPs implemented and do not include any monitoring or contract enforcement costs.

Secondly, total costs may be indirectly affected via higher implementation costs if including transactions costs alters the least cost allocation of BMPs, which could occur if transaction costs change the relative cost of nutrient removal across BMPs. It is apparent from the changes in implementation costs displayed in Table 6 that this *does* occur when *low* implementation costs are assumed; implementation costs rise by around 20% when transactions costs are included. In these cases, the magnitude of transactions is sufficiently high relative to implementation costs that the ranking of BMP cost-effectiveness changes substantially when transactions costs are included. In contrast, when starting from a base of assumed medium or high implementation costs, transactions costs are generally not large enough to cause significant changes to BMP cost-effectiveness rankings. Changes in the distribution of BMPs due to the addition of transactions costs are discussed in more detail below. These results suggest that overall for scenarios assuming medium or high implementation costs, changes to total costs are largely the result of adding a new cost, rather than due to a different distribution of BMPs.

The inclusion of differential adoption rates also substantially impacted costs. The total costs for the adoption model scenarios 13 ($248 million) and 14 ($291 million) fall only a little below the high implementation cost scenarios estimated (Scenarios 9 through 12), and are considerably higher than the scenarios which assume medium implementation costs. These findings suggest that cost estimates based on plausible adoption rates across different types of farmers can be substantially higher than mean estimates that are typically reported. Transactions costs constitute 14 percent of total costs in scenario 14 (adoption model with transactions costs); one of the lowest contributions across all scenarios. This result arises because the *low cost adopter* type is assigned zero transactions costs (and relatively generous low-cost adoption rates are specified for some BMPs (e.g. no till)), and therefore any BMP assignment to this type contributes solely to implementation costs. Nevertheless, due to transactions costs and a reassignment of BMPs causing a change in implementation costs, total costs in scenario 14 are 17 percent higher than the no-transactions costs alternative (scenario 13). The distribution of costs across types in the adoption model is examined in further detail below.

Distribution of Treatment Acres and Costs

The total area assigned a BMP system was relatively constant across most scenarios at around 2 million acres (Table 7), with the highest area of 2.1 million acres occurring in the adoption scenarios. The notable exception to this is scenarios 2, 3 and 4, for which implementation costs are *low* and transactions costs are included. For transactions costs scenarios assuming medium and high implementation costs, as well as for the adoption scenarios, inclusion of transactions costs did not significantly alter the mix of BMP systems between BMPs applied singularly versus those which stacked multiple BMPs together. The proportion of assigned acreage allocated to stacked BMP systems ranged from 3 percent (scenario 1) to 7 per cent (adoption scenarios 13 and 14).

Table 7: Change in area assignment when transactions costs are included in model *

	Scenario No.	**Area assigned a BMP system (acres)**	**% Δ in total area assigned cf No TC alternative**	**% Δ in single BMP area cf No TC alternative**	**% Δ in multiple BMP area cf No TC alternative**
Low IC	1	2,057,526	-	-	-
	2	1,205,715	-41%	-43%	24%
	3	1,205,715	-41%	-43%	24%
	4	1,190,624	-42%	-44%	24%
Medium IC	5	2,042,324	-	-	-
	6	2,042,324	0.0%	-0.1%	1%
	7	2,042,324	0.0%	0.1%	-2%
	8	2,041,035	-0.1%	0.0%	-2%
High IC	9	2,078,218	-	-	-
	10	2,033,571	-2%	-2%	1%
	11	2,033,571	-2%	-2%	1%
	12	2,033,571	-2%	-2%	1%
Adoption models	13	2,116,744	-	-	-
	14	2,117,646	0.0%	0.1%	-0.3%

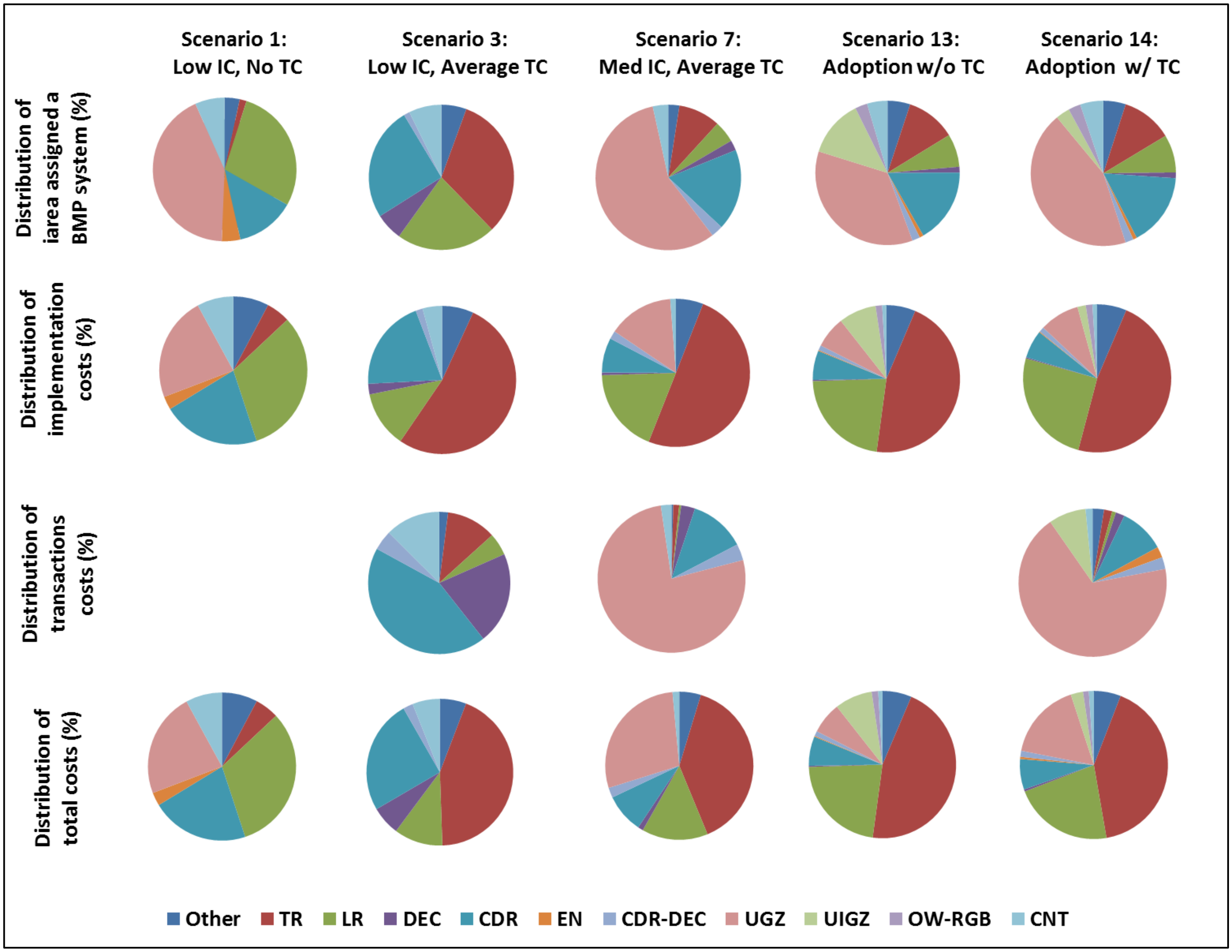
* percentages are compared to the scenario with the same implementation costs assumptions, e.g. Area of single BMP implemented for scenario 4 (Low IC, High TC) was 42% lower compared to scenario 1 (Low IC, No TC).

Upland prescribed grazing accounts for the majority of area assigned a BMP system in all scenarios except scenarios 2, 3 and 4, ranging from 43% of area assigned a BMP in scenario 1 to 57% in scenarios 10-12. However, the total number of acres assigned to this BMP in the medium and high implementation cost scenarios (5 through 12) is around 30% higher compared to the low cost baseline scenario (1), indicating a relative increase in the cost-effectiveness of this BMP compared to alternatives as underlying cost assumptions are varied from low to high.

For scenarios 2, 3, and 4, upland prescribed grazing (administered singly) did not feature in the least cost solution; the area assigned to UGZ in scenario 1 is entirely re-allocated in scenarios 2, 3 and 4, meaning that with the addition of transactions costs the least-cost allocation has moved away from prescribed grazing (which has very low implementation costs in these scenarios) and towards practices such as tree planting, cover crops and decision agriculture. This accounts for both the lower total area assigned and the lower transactions costs estimates for these scenarios. Given that this BMP has relatively low nutrient reductions per acre (refer Table Ax), switching from this BMP to alternatives which have higher per acre reductions meant that the objectives could be achieved with around 40 percent less acreage assigned a BMP system compared to the relevant no-transactions costs alternative scenario (scenario 1). Further, since tree planting, which accounts for the majority of acreage assigned in these scenarios, has much lower transactions costs per acre than prescribed grazing, aggregate transactions costs are relatively low compared to other scenarios in the transactions costs model.   Figure 3 shows the distribution of area assigned a BMP system and costs across BMP types, for selected scenarios. Contribution of a particular BMP system to total area assigned, implementation costs, and transactions costs are different; thus, characterization of which BMPs are "most important" for achieving nutrient reduction objectives depends on whether area allocated or contribution to costs is considered. From an area perspective, upland prescribed grazing accounts for the largest amount of acreage assigned a BMP in all scenarios except scenarios 2, 3, and 4 (for which tree planting has the most acreage). However, this BMP has a low per acre implementation cost compared to other BMPs, and as such does not account for the majority of implementation costs. This picture changes when transactions costs are considered; upland prescribed grazing was identified by NRCS as being a "moderate" contract type, even though the time horizon for this BMP is only one year. This means that this BMP is among the most costly in terms of public transactions costs incurred. As is evident in the third row of Figure 3, transactions costs associated with this BMP system far outstrip those of any other (for scenarios where UGZ is assigned positive area). Tree planting and land retirement display an opposite pattern to upland prescribed grazing. Due to the fact that these BMPs have a high implementation cost per acre relative to most other BMPs but a relatively low transactions cost per acre, their share of implementation costs is much higher than either their share of assigned acreage or transactions costs.

These results suggest that approximating transactions costs as a fixed proportion of implementation costs may not be appropriate. Currently implementation costs and technical assistance are often viewed as varying according to the specific practices being implemented; these results suggest that the transactions costs of administering financial incentive programs should be treated in the same manner.

Figure 3. Distribution of area, implementation costs, transactions costs and total costs, by BMP system for selected scenarios.



Adoption scenarios: results by adoption type

The adoption scenarios differ from the baseline and transactions costs scenarios in several ways: not only are implementation costs and transactions costs allowed to vary across types (meaning that the adoption scenarios effectively mix elements of several earlier scenarios), but additional constraints on areas available for BMP placement vary both across types and BMP systems.

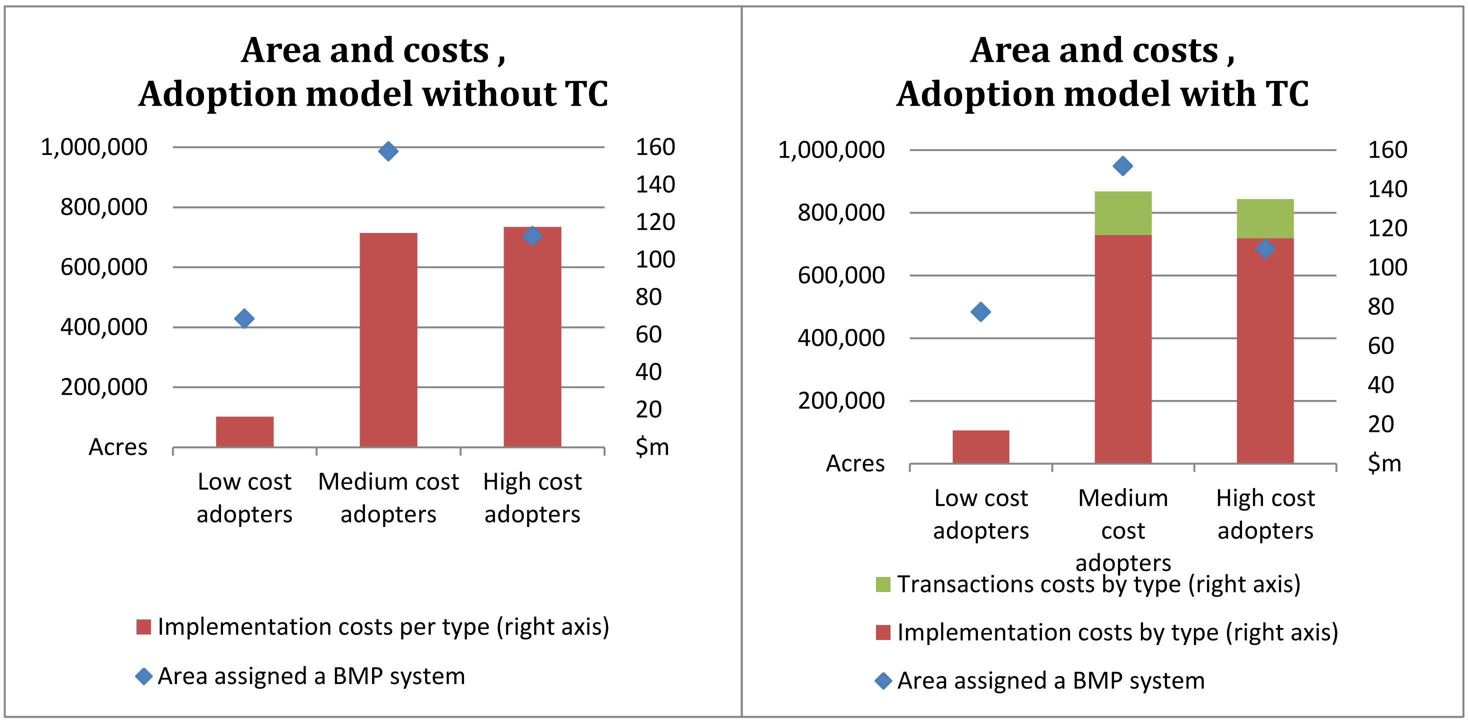
This makes decomposing changes in aggregate cost and area estimates into their constituent parts to determine what causes the changes a difficult task. One important dimension is how BMP systems – and therefore costs – are allocated across types. The low-cost adopter has an obvious cost advantage, but on the other hand has the most restricted available area (refer Table x in previous section). Table 8 shows the proportion of area assigned a BMP system and costs attributable to each type for the adoption scenarios (Appendix Table A4 area allocated to specific BMPs by adoption type). Several comparisons are noteworthy here. First is that the aggregate area that is assigned a BMP system is largely unchanged, at around 2.1 million acres. Secondly, both scenarios show a preference for assigning BMPs to the low-cost adopter type: although constraints for the low-cost type allow at most 20 percent of the relevant available area to be assigned to that type (and usually less than this for most BMPs), the proportion of assigned acreage for this type is at least this in the least cost solutions (20% and 23% in scenarios 13 and 14, respectively). Moreover, this preference grows more marked when transactions costs are included. Third, assignment of BMP systems involving two or more "stacked" BMPs, while only accounting for around 7% of the overall acres assigned, is concentrated on the low-cost type: 60 percent of the stacked BMP systems occurring in the solution are assigned to the low-cost type. Conversely, high-cost types are almost exclusively assigned single BMP systems.

Table 8: Area results for adoption model scenarios

	Scenario 13 Adoption without TC				**Scenario 14 Adoption with TC**			
	Low cost type	Medium cost type	High cost type	Total	Low cost type	Medium cost type	High cost type	Total
Area assigned a BMP system (acres)	427,783	985,477	703,484	2,116,744	483,743	949,255	684,648	2,117,646
% of assigned area by type	*20%*	*47%*	*33%*	*100%*	*23%*	*45%*	*32%*	*100%*
Area single BMP system (acres)	333,973	946,038	681,293	1,961,304	390,953	908,599	663,166	1,962,717
Area "stacked" BMP system (acres)	93,809	39,439	22,191	155,440	92,790	40,656	21,483	154,928
% of single BMP area by type	*17%*	*48%*	*35%*	*100%*	*20%*	*46%*	*34%*	*100%*
% of stacked BMP area by type	*60%*	*25%*	*14%*	*100%*	*60%*	*26%*	*14%*	*100%*

A key result from the adoption models is the disproportionate contribution of high-cost adopters to both implementation and transaction costs. As shown in Figure 4, despite accounting for considerably less area than the medium-cost type, implementation and transactions costs are roughly equal for these two types, reflecting higher marginal implementation and transaction costs for the high-cost type. This result occurs because, due to the restrictions on the low- and medium-cost types, the model is forced to turn to the high-cost adopters to meet the targets despite the significant costs of doing so. However, adoption constraints are not necessarily static: in formulating this model specification we acknowledge that additional education and extension could facilitate lowering perceived opportunity costs of BMP adoption, thereby changing the distribution of types. For example, if investments in education or extension required to change types from high-cost to medium-cost are less than the marginal cost of securing nutrient reductions via high-cost type adopters, such investment could serve to lower the total costs of achieving nutrient obligations.

Figure 4: area and costs by adopter type, Adoption model: scenarios 13 and 14.



Further information from the models about which adoption constraints are binding in scenario 14 (adoption model with transactions costs) sheds light on the role that these constraints have on the least cost solutions. For *upland prescribed grazing*, constraints were binding in all cases, indicating that this practice is relatively cost-effective even for high-cost adopters, and that the assumed maximum adoption rates *do* alter the least cost solution.

For BMP systems that retire working lands (*tree planting* and *land retirement*), constraints are binding for the low-cost type adopter in all cases, but for the medium-cost and high-cost types, these constraints bind in successively fewer cases. Where these constraints *are* binding, the marginal value of the constraint – interpretable as the shadow price of relaxing the constraint by 1 unit – is considerably higher than corresponding values for constraints on other BMP systems (e.g. management BMPs), indicating that retirement of working lands is in many cases still more "desirable" in terms of cost-effectiveness than other available BMPs.

Adoption constraints for the cropping management practices *decision agriculture* and *enhanced nutrient management* were generally not binding on any type, despite the fact that these constraints were relatively more strict (a greater proportion of non-adoption was assumed for these practices). This indicates that these practices are simply not cost-effective in these scenarios, rather than being constrained by adoption rate assumptions.

Interestingly, constraints for BMP systems involving *continuous no-till* were binding for the low- and medium-cost types in the upland hydrogeomorphic regions (across all relevant landuses) but not in the coastal plain. This is the only case of a clear distinction in results between hydrogeomorphic regions and likely is caused by significant differences in nutrient reduction efficiencies between upland and coastal plain regions for this practice.

Conclusion

Results from the modelled scenarios help shed light on the role of transactions costs and differential adoption types on the distribution and magnitude of costs to achieve the specified nutrient targets. The simplest and perhaps most important result is that inclusion of transactions costs *does* substantially affect estimates of total costs by a non-trivial amount; total costs could increase anywhere between 13 and 27 percent depending on the scenario analyzed. Given that the estimates of transactions costs included in the model covered only the *public* costs of implementing conservation contracts and omitted other important costs such as those accruing to private actors and the public costs of administering programs, as well as ex-post costs such as monitoring, evaluation and enforcement, the contribution of transactions costs as presented here should be conceived of as a lower bound.

Additionally, we showed that generally the magnitude of transactions costs is not sufficiently high to cause substantial changes in the cost-effective combinations of BMPs relative to the no-transactions costs baseline, except in the cases where low implementation costs are assumed. This suggests that the contribution of transactions costs to total costs is primarily related to “adding on” of another cost, rather than indirectly via changing the mix of practices in the least cost solution.

Analysis of the distribution of different costs across BMP systems shows that those BMPs which account for the most implementation costs do not necessarily account for the most transactions costs (and vice versa). In particular, it suggests that transactions costs should be acknowledged to vary with the type of practices being implemented, rather than being approximated as a fixed proportion of implementation costs.

Finally, allowing for different types of adopters allows for a more realistic assessment of potential costs. Acknowledging different opportunity costs of adoptions and the limits to adoption rates in voluntary programs can significantly drive up costs relative to conventional model estimates. In addition, this analysis highlights the disproportionate costs associated with achieving nutrient reductions via high-cost adopters, and suggests there may be a role for education or extension to assist landholders to lower opportunity costs of participating in conservation (i.e. to change to a lower cost type).

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APPENDIX

Table A1: Agricultural BMPs used in the model

Name & code	Definition
Riparian Forest Buffer (*RFB*)	Linear wooded areas along rivers, stream and shorelines. Forest buffers help filter nutrients, sediments and other pollutants from runoff as well as remove nutrients from groundwater.
Riparian Grass Buffer (*RGB*)	Agricultural riparian grass buffers are linear strips of grass or other non-woody vegetation maintained between the edge of fields and streams, rivers or tidal waters that help filter nutrients, sediment, and other pollutants from runoff.
Wetland restoration (*WR*)	Agricultural wetland restoration activities re-establish the natural hydraulic condition in a field that existed before the installation of subsurface or surface drainage. Projects can include restoration, creation and enhancement acreage. Restored wetlands can be any wetland classification including forested, scrub-shrub or emergent marsh.
Tree planting (*TR*)	*See land retirement*
Land Retirement (*LR*)	Agricultural land retirement takes marginal and highly erosive cropland out of production by planting permanent vegetative cover such as shrubs, grasses, and/or trees. Agricultural agencies have a program to assist farmers in land retirement procedures. Land retired and planted to trees is reported under *Tree Planting*.
Enhanced Nutrient Management (*EN*)	Based on research, the nutrient management rates of nitrogen application are set approximately 35% higher than what a crop needs to ensure nitrogen availability under optimal growing conditions. In a yield reserve program using enhanced nutrient management, the farmer would reduce the nitrogen application rate by 15%. An incentive or crop insurance is used to cover the risk of yield loss. This BMP effectiveness estimate is based on a reduction in nitrogen loss resulting from nutrient application to cropland 15% lower than the nutrient management recommendation.
Decision Agriculture (*DEC*)	A management system that is information and technology based, is site specific and uses one or more of the following sources of data: soils, crops, nutrients, pests, moisture, or yield for optimum profitability, sustainability, and protection of the environment.
Cover Crop (Early Drilled Rye) *CDR*	*The model uses one type of cover crop: Early-Drilled Rye* Cereal cover crops reduce erosion and the leaching of nutrients to groundwater by maintaining a vegetative cover on cropland and holding nutrients within the root zone. This practice involves the planting and growing of cereal crops (non-harvested) with minimal disturbance of the surface soil. The crop is seeded directly into vegetative cover or crop residue with little disturbance of the surface soil. These crops capture or "trap" nitrogen in their tissues as they grow. By timing the cover crop burn or plow-down in spring, the trapped nitrogen can be released and used by the following crop. Different species are accepted as well as, different times of planting (early, late and standard),

	and fertilizer application restrictions. There is a sliding scale of efficiencies based on crop type and time of planting. Commodity cover crops differ from cereal cover crops in that they can be harvested for grain, hay, or silage and they might receive nutrient applications, but only after March 1 of the spring following their establishment. The intent of the practice is to modify normal small grain production practices by eliminating fall and winter fertilization so that crops function similarly to cover crops by scavenging available soil nitrogen for part of their production cycle.
Continuous No-Till Agriculture (*CNT*)	The Continuous No-Till (*CNT*) BMP is a crop planting and management practice in which soil disturbance by plows, disk or other tillage equipment is eliminated. *CNT* involves no-till methods on all crops in a multi-crop, multi-year rotation. When an acre is reported under *CNT*, it will not be eligible for additional reductions from the implementation of other practices such as cover crops or nutrient management planning.
Livestock Exclusion (*LE*)	Livestock Exclusion involves excluding a strip of land with fencing along the stream corridor to provide protection from livestock. The fenced areas may be planted with trees or grass, or left to natural plant succession, and can be of various widths. To provide the modelled benefits of a functional riparian buffer, the width must be a minimum of 35 feet from top-of-bank to fence line. The implementation of stream fencing provides stream access control for livestock but does not necessarily exclude animals from entering the stream by incorporating limited and stabilized in-stream crossing or watering facilities.
Offstream Watering (*OW*)	Offstream watering typically involves the use of permanent or portable livestock water troughs placed away from the stream corridor. The source of water supplied to the facilities can be from any source including pipelines, spring developments, water wells, and ponds. In-stream watering facilities such as stream crossings or access points are not considered in this definition.
Upland Prescribed Grazing (*UGZ*)	This practice utilizes a range of pasture management and grazing to improve the quality and quantity of the forages grown on pastures and reduce the impact of animal travel lanes, animal concentration areas or other degraded areas. Prescribed grazing can be applied to pastures intersected by streams or upland pastures outside of the degraded stream corridor (35 feet width from top of bank). Pastures under the proscribed grazing systems are defined as having a vegetative cover of 60% or greater.
Upland Precision Intensive Rotational Grazing (*UIGZ*)	This practice utilizes more intensive forms pasture management and grazing techniques to improve the quality and quantity of the forages grown on pastures and reduce the impact of animal travel lanes, animal concentration areas or other degraded areas of the upland pastures. This practice requires intensive management of livestock rotation, also known as Managed Intensive Grazing systems (MIG), that have very short rotation schedules. Pastures are defined as having a vegetative cover of 60% or greater.

Source: Adapted from Chesapeake Bay Commission (Date NA), Appendix 6 – BMP.

Table A2: removal efficiencies (%) for individual BMPs and hydrogeomorphic region

	Nitrogen								Phosphorous							
Hydrogeomorphic region	BLUERIDGENT	CPDUPNT	CPLOWNT	CPUPNT	MESOLOWNT	PIEDCRYSNT	VRCARBNT	VRSILINT	BLUERIDGENT	CPDUPNT	CPLOWNT	CPUPNT	MESOLOWNT	PIEDCRYSNT	VRCARBNT	VRSILINT
RFB	34	65	56	31	34	56	34	46	30	42	39	45	30	42	30	39
RGB	24	46	39	21	24	39	24	32	30	42	39	45	30	42	30	39
WR	14	25	25	25	14	14	14	14	26	50	50	50	26	26	26	26
TR	*change from landuse to forest*								*change from landuse to forest*							
LR	*change from landuse to hay w/o nutrients*								*change from landuse to hay w/o nutrients*							
LE	25	25	25	25	25	25	25	25	30	30	30	30	30	30	30	30
CDR	34	45	45	45	34	45	45	34	15	15	15	15	15	15	15	15
CNT	15	10	10	10	15	15	15	15	40	20	20	20	40	40	40	40
EN	7	7	7	7	7	7	7	7	0	0	0	0	0	0	0	0
DEC	4	4	4	4	4	4	4	4	0	0	0	0	0	0	0	0
OW	5	5	5	5	5	5	5	5	8	8	8	8	8	8	8	8
UGZ	10	10	10	10	10	10	10	10	20	20	20	20	20	20	20	20
UIGZ	11	9	9	9	11	11	9	11	24	24	24	24	24	24	24	24

Sources: Chesapeake Bay Commission (2012, Appendix B), with supplemental information taken from the Chesapeake Bay Phase 5.3 Community Watershed Model documentation (Date NA: Section 6) and Simpson and Weammert (2009).

Table A3: Transactions costs by BMP system (annualized $/acre)

BMP system	BMP time horizon (years)	Low	Average	High	BMP system	BMP time horizon (years)	Low	Average	High
RFB	15	2.80	3.35	3.90	**LR-UGZ**	10	3.63	4.35	5.06
RGB	15	1.41	1.68	1.96	**LR-UIGZ**	10	5.95	7.05	8.15
WR	15	4.59	5.44	6.29	**LE-RFB**	15	2.80	3.35	3.90
TR	15	2.80	3.35	3.90	**LE-RGB**	15	2.80	3.35	3.90
LR	10	1.82	2.18	2.54	**LE-UGZ**	10	1.82	2.18	2.54
LE	10	1.82	2.18	2.54	**LE-UIGZ**	10	5.95	7.05	8.15
CDR	1	13.71	16.38	19.06	**OW-RFB**	15	2.80	3.35	3.90
CNT	1	13.71	16.38	19.06	**OW-RGB**	15	2.80	3.35	3.90
EN	1	44.74	53.00	61.26	**RFB-WR**	15	4.59	5.44	6.29
DEC	1	27.29	32.67	38.05	**RGB-TR**	15	1.41	1.68	1.96
OW	10	3.63	4.35	5.06	**RGB-WR**	15	4.59	5.44	6.29
UGZ	1	27.29	32.67	38.05	**CDR-DEC-EN**	1	44.74	53.00	61.26
UIGZ	1	44.74	53.00	61.26	**CDR-DEC-RFB**	15	2.80	3.35	3.90
CDR-DEC	1	27.29	32.67	38.05	**CDR-DEC-RGB**	15	2.80	3.35	3.90
CDR-EN	1	44.74	53.00	61.26	**CDR-EN-RFB**	15	4.59	5.44	6.29
CDR-RFB	15	2.80	3.35	3.90	**CDR-EN-RGB**	15	4.59	5.44	6.29
CDR-RGB	15	2.80	3.35	3.90	**DEC-EN-RFB**	15	4.59	5.44	6.29
CNT-RFB	15	2.80	3.35	3.90	**DEC-EN-RGB**	15	4.59	5.44	6.29
CNT-RGB	15	2.80	3.35	3.90	**LR-LE-RFB**	15	2.80	3.35	3.90
DEC-EN	1	44.74	53.00	61.26	**LR-LE-RGB**	15	2.80	3.35	3.90
DEC-RFB	15	2.80	3.35	3.90	**LR-OW-RFB**	15	2.80	3.35	3.90
DEC-RGB	15	2.80	3.35	3.90	**LR-OW-RGB**	15	2.80	3.35	3.90
EN-RFB	15	4.59	5.44	6.29	**LR-RFB-UGZ**	15	4.59	5.44	6.29
EN-RGB	15	4.59	5.44	6.29	**LR-RFB-UIGZ**	15	4.59	5.44	6.29
LR-LE	10	3.63	4.35	5.06	**LE-RFB-UGZ**	15	4.59	5.44	6.29
LR-OW	10	3.63	4.35	5.06	**LE-RFB-UIGZ**	15	4.59	5.44	6.29
LR-RFB	15	2.80	3.35	3.90	**LE-RGB-UGZ**	15	4.59	5.44	6.29
LR-RGB	10	1.82	2.18	2.54	**LE-RGB-UIGZ**	15	4.59	5.44	6.29

NB: 7% discount rate assumed.

Table A4: Percentage of area assigned a BMP system, by BMP system, all scenarios

	Low IC				Med IC				High IC				Adoption models	
Scenario No.	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**
Area assigned a BMP system (million acres)	2.06	1.20	1.20	1.19	2.04	2.04	2.04	2.04	2.08	2.03	2.03	2.03	2.12	2.12
						% of area assigned a BMP system								
TR	2%	32%	32%	34%	9%	9%	9%	9%	10%	10%	10%	10%	11%	11%
LR	28%	22%	22%	21%	5%	5%	5%	5%	3%	3%	3%	3%	7%	8%
DEC	-	6%	6%	6%	-	2%	2%	2%	-	-	-	-	1%	1%
CDR	13%	25%	25%	26%	18%	18%	18%	18%	18%	18%	18%	18%	17%	16%
EN	4%	-	-	-	2%	1%	-	-	4%	2%	2%	2%	1%	1%
DEC-EN	-	-	-	-	-	-	-	-	-	-	-	-	-	-
CDR-DEC	-	1%	1%	1%	-	3%	3%	3%	1%	3%	3%	3%	2%	2%
CDR-RGB	1%	2%	2%	2%	1%	1%	1%	1%	1%	1%	1%	1%	-	-
CDR-RFB	-	-	-	-	1%	1%	1%	1%	1%	1%	1%	1%	-	-
UGZ	43%	-	-	-	57%	57%	57%	57%	56%	57%	57%	57%	35%	44%
CDR-EN	1%	-	-	-	3%	-	-	-	2%	-	-	-	1%	1%
WR	-	-	-	-	-	-	-	-	-	-	-	-	-	-
UIGZ	-	-	-	-	-	-	-	-	-	-	-	-	13%	3%
RGB-WR	-	-	-	-	-	-	-	-	-	-	-	-	-	-
RGB-TR	-	-	-	-	-	-	-	-	-	-	-	-	-	-
RGB	1%	1%	1%	1%	-	-	-	-	-	-	-	-	-	-
RFB-WR	-	-	-	-	-	-	-	-	-	-	-	-	-	-
RFB	-	-	-	-	-	-	-	-	-	-	-	-	2%	2%
OW-RGB	-	-	-	-	-	-	-	-	-	-	-	-	3%	3%
OW-RFB	-	-	-	-	-	-	-	-	-	-	-	-	-	-
OW	-	-	-	-	-	-	-	-	-	-	-	-	-	-
LR-UIGZ	-	-	-	-	-	-	-	-	-	-	-	-	-	-
LR-UGZ	-	-	-	-	-	-	-	-	-	-	-	-	-	-
LR-RGB	-	-	-	-	-	-	-	-	-	-	-	-	-	-
LR-RFB-UIGZ	-	-	-	-	-	-	-	-	-	-	-	-	-	-

Scenario No.	Low IC 1	2	3	4	Med IC 5	6	7	8	High IC 9	10	11	12	Adoption models 13	14
LR-RFB-UGZ	-	-	-	-	-	-	-	-	-	-	-	-	-	-
LR-RFB	-	-	-	-	-	-	-	-	-	-	-	-	-	-
LR-OW-RGB	-	-	-	-	-	-	-	-	-	-	-	-	-	-
LR-OW-RFB	-	-	-	-	-	-	-	-	-	-	-	-	-	-
LR-OW	-	-	-	-	-	-	-	-	-	-	-	-	-	-
LR-LEX-RGB	-	-	-	-	-	-	-	-	-	-	-	-	-	-
LR-LEX-RFB	-	-	-	-	-	-	-	-	-	-	-	-	-	-
LR-LEX	-	-	-	-	-	-	-	-	-	-	-	-	-	-
LEX-UIGZ	-	-	-	-	-	-	-	-	-	-	-	-	-	-
LEX-UGZ	-	-	-	-	-	-	-	-	-	-	-	-	-	-
LEX-RGB-UIGZ	-	-	-	-	-	-	-	-	-	-	-	-	-	-
LEX-RGB-UGZ	-	-	-	-	-	-	-	-	-	-	-	-	-	-
LEX-RGB	-	-	-	-	-	-	-	-	-	-	-	-	-	-
LEX-RFB-UIGZ	-	-	-	-	-	-	-	-	-	-	-	-	-	-
LEX-RFB-UGZ	-	-	-	-	-	-	-	-	-	-	-	-	-	-
LEX-RFB	-	-	-	-	-	-	-	-	-	-	-	-	-	-
LEX	-	-	-	-	-	-	-	-	-	-	-	-	-	-
EN-RGB	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%
EN-RFB	-	-	-	-	-	-	-	-	-	-	-	-	-	-
DEC-RGB	-	-	-	-	-	-	-	-	-	-	-	-	-	-
DEC-RFB	-	-	-	-	-	-	-	-	-	-	-	-	-	-
DEC-EN-RGB	-	-	-	-	-	-	-	-	-	-	-	-	-	-
DEC-EN-RFB	-	-	-	-	-	-	-	-	-	-	-	-	-	-
CNT-RGB	-	-	-	-	-	-	-	-	-	-	-	-	-	-
CNT-RFB	-	1%	1%	1%	-	-	-	-	-	-	-	-	1%	1%
CNT	7%	7%	7%	6%	3%	3%	3%	3%	3%	3%	3%	3%	5%	5%
CDR-EN-RGB	-	-	-	-	-	-	-	-	-	-	-	-	-	-
CDR-EN-RFB	-	-	-	-	-	-	-	-	-	-	-	-	-	-
CDR-DEC-RGB	-	-	-	-	-	-	-	-	-	-	-	-	-	-
CDR-DEC-RFB	-	-	-	-	-	-	-	-	-	-	-	-	-	-
CDR-DEC-EN	-	-	-	-	-	-	-	-	-	-	-	-	-	-