

A Meta-Analytical Approach for Determining the Effectiveness of Agricultural Best Management Practices (BMPs) for Reducing Nutrient Pollution in Florida

Phase 2: Cow/Calf Operations, Vegetable Crops, and Agronomic Crops

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CONTENTS

1	Executive Summary.....	7
1.1	Background	7
1.2	Methods.....	7
1.3	Key Results	7
1.4	Conclusions	8
2	Background	9
2.1	Regulatory history.....	9
2.2	Nutrient Pollution	9
2.3	Best Management Practices	10
2.3.1	Cow/calf Operations Nutrient BMPs.....	10
2.3.2	Agronomic and Vegetable Crop Nutrient BMPs	11
2.4	Basis for Meta-Analysis.....	12
3	Objectives.....	13
3.1	Primary Objectives of This Analysis	13
3.1.1	Population.....	13
3.1.2	Interventions.....	13
3.1.3	Comparator	13
3.1.4	Outcome	14
4	Methods.....	14
4.1	Question Formulation	14
4.2	Search Strategy	14
4.2.1	Search Terms.....	14
4.2.2	Databases.....	14
4.2.3	Websites.....	14
4.3	Study Inclusion Criteria	15
4.3.1	Eligibility Criteria	15
4.4	Study Quality Assessment.....	15
4.5	Data Extraction.....	16
4.6	Data Synthesis.....	18
4.6.1	Ratio of Means Effect Size.....	18
4.6.2	Heterogeneity and Publication Bias Analysis.....	20

4.6.3	Random-Effects Model	20
4.6.4	Inverse-Variance Weighting for Random Effects Models	21
5	Results	22
5.1	Studies Found	22
5.2	Study Quality	26
5.3	Descriptive statistics of articles	26
5.3.1	Outcomes Measured	26
5.3.2	Intervention Types	26
5.4	Quantitative Synthesis and Meta-Analysis	27
5.4.1	Cow-calf BMP Effectiveness	27
5.4.2	Agronomic Crops	30
5.4.3	Vegetable Crops	35
6	Discussion	41
6.1	Evidence of Effectiveness	41
6.2	Review Limitations	42
6.2.1	Limitations of Meta-Analysis in Ecology	42
7	Conclusions	43
7.1	Implications for Management / Policy / Conservation	43
7.2	Implications for Research	43
8	Sources of Support and Potential Conflicts of Interest	44
9	References	44
10	Appendix A	56
11	Appendix B	57
11.1	Cow/Calf BMP Study Quality Assessment	57
11.2	Agronomic Crop BMP Study Quality Assessment	58
11.3	Vegetable Crop BMP Study Quality Assessment	60
12	Appendix C	64
12.1	Summary of Extracted Information for meta-analysis	64
12.2	Cow/Calf BMPs	65
12.3	Agronomic Crop BMPs	67
12.4	Vegetable Crop BMPs	71
13	Appendix D	79
13.1	Cow/Calf General BMP Findings and Outcomes	79

13.1.1	Nutrient Management	81
13.1.2	Alternative Water Supply Sources	84
13.1.3	Prescribed Grazing	85
13.1.4	Water Resources Management	85
13.1.5	Wellhead Protection	85
13.2	General Vegetable/Agronomic Crop BMP Findings and Outcomes	85
13.2.1	Precision Agriculture	88
13.2.2	Irrigation System Maintenance and Evaluation.....	88
13.2.3	Tissue Testing.....	90
13.2.4	Soil Testing	90
13.2.5	Conservation Tillage	91
13.2.6	Field Borders	92
13.2.7	Contour Farming	92
13.2.8	Wetlands and Springs Protection.....	92
13.2.9	Water Supply Protection.....	92
13.2.10	Tailwater Recovery.....	92
13.2.11	Grassed Waterways	93
13.2.12	Integrated Pest Management	93
13.2.13	Nutrient Management	93
13.2.14	Irrigation Scheduling	93
13.2.15	Wetlands and Springs Protection.....	93
13.2.16	Irrigation System Maintenance and Evaluation.....	94
13.2.17	Wellhead Protection	94
13.2.18	Mowing Management.....	94
13.2.19	Integrated Pest Management	94
14	Appendix E	95
15	Appendix F	98

Figures

Figure 1. Diagram of article and report screening and selection for the meta-analysis.	24
Figure 2. Location of studies by commodity and county.	25
Figure 3. Forest plot of nitrogen effect size (log-transformed ratio of means) for cow/calf studies.	28
Figure 4. Funnel plot of cow/calf studies that measured a nitrogen response.	29
Figure 5. Forest plot of BMP effect size for cow/calf studies measuring a phosphorus response.	29
Figure 6. Funnel plot of cow/calf studies measuring a phosphorus response.	30
Figure 7. Forest plot of BMP effect size for agronomic crop studies measuring a nitrogen response.	31
Figure 8. Funnel plot of agronomic crop studies that measured a nitrogen response.	31
Figure 9. Forest plot of BMP effect size for non-aggregated agronomic crop studies measuring a nitrogen response.	33
Figure 10. Funnel plot of non-aggregated agronomic crop studies measuring a nitrogen response.	33
Figure 11. Forest plot of BMP effect size for agronomic crop studies measuring a phosphorus response.	34
Figure 12. Funnel plot of agronomic crop studies measuring a phosphorus response.	35
Figure 13. Forest plot of BMP effect size for aggregated vegetable crop studies measuring a nitrogen response.	36
Figure 14. Funnel plot of aggregated vegetable crop studies measuring a nitrogen response.	36
Figure 15. Forest plot of BMP effect size for non-aggregated vegetable crop studies measuring a nitrogen response.	37
Figure 16. Funnel plot of non-aggregated vegetable crop studies measuring a nitrogen response.	37
Figure 17. Forest plot of BMP effect size for aggregated vegetable crop studies measuring a phosphorus response.	39
Figure 18. Funnel plot of aggregated vegetable crop studies measuring a phosphorus response.	39
Figure 19. Forest plot of BMP effect size for non-aggregated vegetable crop studies measuring phosphorus as a response.	40
Figure 20. Funnel plot of non-aggregated vegetable crop studies measuring a phosphorus response. ...	40

Tables

Table 1. Summary of effect size and back-transformed meta-analytical results, showing statistically significant % reduction in nitrogen and phosphorus associated with BMPs, compared to no BMPs. NS= Not Significant at the 95% confidence interval.....	7
Table 2. Scoring system used to assess the study quality with a hierarchy of evidence approach.....	16
Table 3. Articles identified for meta-analysis.	23
Table 4. Type and number of BMP manipulations studied for reducing N and P.	26
Table 5. The number of study designs in each commodity grouping.	27
Table 6. Summary of meta-analytical results using the random-effects model.....	41

Equations

Equation 1. Effect size for each study was calculated by using the ratio of means method. For each study reporting a continuous outcome, the mean is denoted by mean_{exp} , standard deviation as sd_{exp} , and replication as n_{exp}	18
Equation 2. Variance calculation for the ratio of means effect size. From (Friedrich et al., 2008).	19
Equation 3. The ratio of the means is back transformed to obtain a pooled ratio and associated 95% confidence interval. From (Friedrich et al., 2008).	19
Equation 4. Log Ratio of Means Effect size = x . No effect = 0.....	19
Equation 5. Inverse-variance weighting for fixed effect models. From (Friedrich et al., 2008).	21
Equation 6. Inverse-variance weighting for random effects models. From (Friedrich et al., 2008).	21
Equation 7. Equation for the Q statistic. From (Friedrich et al., 2008).	21
Equation 8. Equation for the calculation of t^2 using the Q statistic. From (Friedrich et al., 2008).	21
Equation 9. Calculation of I^2	22

1 EXECUTIVE SUMMARY

1.1 BACKGROUND

The Florida Department of Agriculture and Consumer Services (FDACS), Office of Agricultural Water Policy (OAWP), has established a strategic objective to develop and implement Best Management Practices (BMPs), and to confirm BMP effectiveness. By early 2015, OAWP had screened over 1,000 technical articles, resulting in 267 publications that contained information, at least in part, on Florida-specific agricultural BMPs. Frydenborg EcoLogic evaluated these articles for relevant content, which was summarized in a Phase 1 report, and determined which articles were potentially appropriate for inclusion in a meta-analysis. Subsequently, OAWP contracted with Frydenborg EcoLogic to conduct a meta-analysis of the relevant literature. Meta-analysis is a method for systematically combining pertinent data from studies meeting pre-determined inclusion criteria, generating conclusions with greater statistical power than the individual studies.

1.2 METHODS

The objective of this meta-analysis was to synthesize empirical evidence associated with the effectiveness of agricultural BMPs, which are adopted by FDACS, for reducing nutrients from agricultural operations to off-site environmental media (soils, groundwater, and surface water) in Florida. Studies were systematically evaluated for set criteria, and measures of central tendency, replication, and variance extracted. Separate meta-analyses, at the request of FDACS, were performed on three priority commodity groups: cow/calf operations; agronomic crops (includes corn, peanuts, cotton, sugar cane, and sorghum); and vegetable crops (includes potato, strawberries, tomatoes, peppers, melons, cucumbers).

1.3 KEY RESULTS

Statistical analyses (using the log ratio of means, random-effects maximum likelihood model) were conducted to determine the pooled effect size of BMP implementation compared to no implementation. Variability was determined at the 95% confidence level (**Table 1** below). Effect sizes were back-transformed to percent reduction only when the 95% confidence interval did not overlap zero.

Table 1. Summary of effect size and back-transformed meta-analytical results, showing statistically significant % reduction in nitrogen and phosphorus associated with BMPs, compared to no BMPs. NS= Not Significant at the 95% confidence interval.

Commodity	Nitrogen			Phosphorus		
	Effect Size (Log-Ratio of means, Random-Effects Model)	Back-Transformed Natural Log of Effect Size	BMP % Reduction Compared to No BMP	Effect Size (Log-Ratio of Means, Random-Effects Model)	Back-Transformed Natural Log of Effect Size	BMP % Reduction Compared to No BMP
Cow/Calf	0.01	NS	NS	-0.08	NS	NS
Agronomic Crops	-0.91	0.40	60%	0.5	NS	NS
Vegetable Crops	-1.08	0.34	66%	-0.43	0.65	35%

1.4 CONCLUSIONS

This meta-analysis demonstrated the following:

- There were no statistically significant BMP effects for either nitrogen or phosphorus for the cow/calf operations, likely due to the small number of studies meeting inclusion criteria (four) and relatively low absolute value of nutrients associated with cow/calf operations.
- For agronomic crops, BMPs provided a statistically significant reduction in nitrogen (equivalent to an average of **60% reduction** compared to using no BMPs) but no significant reductions in phosphorus (there were only two agronomic studies that measured a phosphorus response).
- For vegetable crops, BMPs provided statistically significant reductions in both nitrogen and phosphorus (equivalent to average **reductions of 66% and 35%**, respectively), compared to using no BMPs.
- Despite the observed effectiveness of the agronomic and vegetable crop BMPs, further evaluation would be needed to determine if nutrient loads from operations implementing BMPs would be environmentally acceptable on a watershed or springshed scale.
- The results of this meta-analysis could be likely strengthened if data from additional robust studies on Florida agricultural BMPs could be obtained for further analysis.

2 BACKGROUND

2.1 REGULATORY HISTORY

Florida established a Nonpoint Source Management Program in 1978 to comply with the requirements of the Clean Water Act (CWA), which requires the State of Florida to assess and mitigate the impacts of nonpoint sources of pollution on waters of the state and US. In addition to typical regulation (*e.g.* Environmental Resource Permits), nonpoint sources of potential pollution are also addressed through voluntary measures, such as the implementation of Best Management Practices (BMPs). The identification of water bodies not meeting designated use, and establishment of a Total Maximum Daily Load (TMDL) for causative pollutants, is required by section 303(d) of the CWA. An implementation plan for a TMDL will establish specific allowable loadings for all point and nonpoint sources in the watershed of the impaired water. Agricultural practices occur on more than 10 million acres of Florida. Collectively, farmers operating within watersheds of TMDL impaired waterbodies could be subject to nutrient load reductions.

In 1999, the Florida legislature passed the Florida Watershed Restoration Act that charged FDACS with the responsibility and authority to develop interim measures aimed at reducing pollutant loading from agriculture operations. This law directs FDACS to identify, and adopt by rule, BMPs for agricultural nonpoint sources. The Florida Department of Environmental Protection (FDEP) is required to verify that these BMPs are effective at reducing pollutant loading to targeted waters. Currently under law, agricultural producers implementing the FDACS BMPs receive a “presumption of compliance” that they are meeting state water quality standards. In an effort to better quantify the effectiveness of the implemented BMPs, the Office of Agricultural Water Policy commissioned a meta-analysis on the efficacy of agricultural BMPs in Florida for three commodity groups.

Cow/calf BMPs are adopted in FDACS rule 5M-11, effective April 23, 2009. Vegetable and Agronomic BMPs are adopted in FDACS rule 5M-8, effective October 2005, and revised with an effective date of October, 2015.

In 2014, the FDEP adopted numeric nutrient criteria (NNC), which are expected to result in more listings of Florida waters, more TMDLs, and more responsibility of Florida farmers to demonstrate nutrient reductions through BMP implementation.

2.2 NUTRIENT POLLUTION

Excessive nutrient loading can be problematic to watersheds, and is often nonpoint source in origin (Carpenter et al., 1998). Unlike point source dischargers, there is no mandatory permit compliance program to enforce reductions in nutrient loading from agricultural operations. FDACS publishes guidelines for BMPs, which are frequently implemented by farmers. However, the effectiveness of these BMPs has yet to be quantified and examined for variation between studies. Understanding the effectiveness of BMP implementation is essential during the development of Basin Management Action

Plans (BMAPs) and Total Maximum Daily Loads (TMDLs), which are designed to restore water quality on a watershed scale.

2.3 BEST MANAGEMENT PRACTICES

BMPs are varied, but in general are a series of practices determined to be the most effective and practicable methods for improving water quality. They are based on research, field-testing, and expert review. Often, BMPs are implemented in combination with one another, in a “BMP treatment train”. BMPs can be both structural and nonstructural in nature, but they must always be technically feasible, economically viable, socially acceptable, and based on sound science.

2.3.1 Cow/calf Operations Nutrient BMPs

Nutrient management BMPs for livestock operations generally focus on fertilizer management, proper application of residuals or biosolids, proper animal nutrition, management of animal waste, and separation of cattle and aquatic systems. Some examples of BMPs relevant to nutrient reduction are listed below, taken from FDACS BMP manual for cow/calf operations (FDACS, Office of Agricultural Water Policy, 2008).

2.3.1.1 *Nutrient Management*

1. Use of a soil test to determine P fertilization rate needed to grow forage crops.
2. Use of Nutrient Budget Worksheet to determine if supplemental fertilizer is needed.
3. Following recommended rates of fertilizer for a particular forage crop.
4. Time fertilizer application with plant growth in order to maximize nutrient uptake and avoid leaching/runoff into the environment.
5. Prevent spreading fertilizer into streams, sinkholes, and wetlands by maintaining a minimum 50 foot buffer.
6. Following all applicable regulations in Rule 62-640 F.A.C. for residuals application.
7. Abide by all grazing restriction and setback requirements when applying residuals/septage.
8. Locate confined feeding areas away from watercourses, wetlands, sinkholes, or excessively sloped terrain. Ensure that filter strips or other conservation buffers are maintained between feeding areas and adjacent features.
9. Locate supplemental feeding and mineral stations at least 100 feet away from watercourses, streams, wetlands, wells, or sinkholes.
10. Manage livestock distribution to reduce any concentrated accumulation of wastes that could lead to nutrients contaminating ground or surface waters.
11. Use onsite manure sources as fertilizer supplement if needed in order to avoid adding inorganic fertilizer.

2.3.1.2 *Alternative Cattle Water Sources*

1. Construct ponds to be between 0.25 and 2 acres, and located at least 50 feet away from wetlands. Keep side slopes no steeper than one-to-one horizontal to vertical ratio.
2. Locate watering troughs and associated shade to keep cattle away from streams and watercourses.

2.3.1.3 Prescribed Grazing

1. Use rotational grazing to give areas time for re-growth and to evenly distribute manure from animals (which includes, in part, provisions for animal stocking rates).

2.3.1.4 Conservation Buffers

1. When creating new pastures adjacent to urban areas, install field borders around the perimeter or where runoff enters/leaves pasture.
2. Install a filter strip to treat runoff from concentrated livestock areas, such as feed areas, located directly adjacent to wetlands and sinkholes.
3. Design filter strip based on peak discharge from concentrated waste area. Construct treatment area wide enough for at least 15 minutes of flow-through time.
4. Install or maintain a riparian buffer or filter strip on pasture areas that exceed 1% slope and discharge directly to streams.

2.3.1.5 Fencing

1. Stabilize stream banks, and provide either adequate alternative water sources for cattle, or install and maintain exclusion fencing to keep cattle out of waters.

2.3.1.6 High-intensity Areas

1. Locate cowpens a minimum 200 feet away from watercourses, streams, wetlands, wells, and sinkholes. Construct a berm to prevent runoff.
2. Direct runoff from high-intensity areas away from watercourses, streams, wetlands, wells, and sinkholes using grassed waterways or swales.
3. Install filter strips, buffers, or berms to treat discharges into watercourses, streams, wetlands, wells, and sinkholes.

2.3.1.7 Wetlands and Springs Protection

1. Use a county soil survey map to identify wetland and hydric soil types, and use preservation, practical design alternatives.
2. Maintain a minimum 25 foot vegetative buffer exterior to the landward extent of all wetlands
3. Utilize pretreatments such as filter strips, swales, and holding sites.
4. Rotate livestock through wetland grazing systems at an accelerated pace when excessive rainfall is present.
5. Maintain a 100 foot vegetative buffer from springs, spring runs, and wet sinks.
6. Use split-applications for fertilizers on pasture areas that contribute surface water directly to springs, spring runs, and wet sinks.

2.3.2 Agronomic and Vegetable Crop Nutrient BMPs

The BMPs for agronomic and vegetable crops reside within the same manual published by FDACS (FDACS, Office of Agricultural Water Policy, 2015). In general, agronomic crops are grown in central and northern Florida, while vegetable crops are grown in southern Florida. Below are some examples of these BMPs.

2.3.2.1 Conservation practices and buffers, erosion control

1. Construct wells on higher ground and up-gradient from sources of possible contamination.
2. Use backflow prevention devices when fertigating.
3. Avoid mixing agrichemicals within 100 feet of any well or surface water body.

4. Screen shallow wells and case deep wells at least 10 feet deep.
5. All onsite wetlands and watercourses must contain a 25 -50 foot undisturbed upland buffer depending on size and type.
6. Use spreader swales to encourage sheetflow through upland buffer prior to discharge into wetlands.
7. Construct filter strips between farm lands and watercourses. Minimum 20 feet wide.
8. Construct strips of permanent vegetation around the perimeter of the farm (field border) and construct riparian buffers between farm and waterbody.
9. Preventing erosion through a variety of measures (vegetation cover, diversions, terracing, etc.).
10. Construct and maintain conveyance ditches to prevent degrading downstream water quality.
11. Utilize conservation tillage and cover crops to trap excess nutrients and prevent their transport into water following harvest.
12. Use conservation crop rotation to slowly add nutrients and organic matter to the soil and improve soil structure.
13. Conservation tillage (strip tillage).
14. Cover crops/legumes.

2.3.2.2 Nutrient and Irrigation Management

1. Use a soil test to determine if and to what amount fertilizer should be applied.
2. Conservation tillage (strip tillage).
3. Cover crops/legumes.
4. Banding of P fertilizer.
5. Precision application (GPS, guidance, light bars).
6. Use available tools (may include water table observation wells, on-site soil moisture sensors, crop water use information, or weather data) to assist in making irrigation decisions.
7. Use appropriate irrigation scheduling to minimize application losses due to evaporation and wind drift.
8. Properly monitor and maintain irrigation system and utilize Mobile Irrigation Lab if available.

2.3.2.3 Water Resources Management

1. Grassed waterways.
2. Furrow diking.
3. Terraces/diversions.
4. Center pivot irrigation systems (retrofitted with low pressure drop and nozzle packages).

2.4 BASIS FOR META-ANALYSIS

Meta-analysis is a method for systematically combining pertinent data from several selected studies to develop a single conclusion with greater statistical power than provided by the individual studies. Meta-analysis conclusions are statistically stronger than individual studies due to increased numbers and diversity of observations, or accumulated effects and results (Walker et al., 2008). By combining results from several studies, meta-analysis provides improved confidence that a particular set of BMPs achieves a desired beneficial environmental outcome.

Meta-analysis can be used to:

- Establish statistical significance with studies that have varying or conflicting results;
- Develop a more correct estimate of effect magnitude;
- Provide a more complete analysis of benefits as well as confirmation of benefits; and
- Provide a decision maker with greater ability to extrapolate to a variety of conditions.

Some disadvantages of meta-analysis are that it is difficult and time consuming to identify appropriate studies, and most studies do not provide adequate data for inclusion and analysis. Meta-analysis also requires heterogeneous study populations.

3 OBJECTIVES

3.1 PRIMARY OBJECTIVES OF THIS ANALYSIS

The Florida Department of Agriculture and Consumer Services, Office of Agricultural Water Policy, has established a strategic objective to develop and implement Best Management Practices, and to confirm BMP effectiveness.

The **primary objective** of this study was to answer the question:

What is the effectiveness of the FDACS agricultural BMPs for reducing nutrients from agricultural operations to off-site environmental media (groundwater and surface water) in Florida?

To answer this question, one must consider the population, interventions, comparators, and outcomes of the studies.

3.1.1 Population

Agricultural operations in Florida subject to FDACS regulation and Florida water quality rules. These are often grouped as follows: cow/calf, citrus, agronomic, vegetable, equine, nurseries, specialty fruit and nut crops, and sod operations. At the request of FDACS, this review examined cow/calf, agronomic, and vegetable operations.

3.1.2 Interventions

The potential interventions included any BMP recommended by FDACS and adopted into rule. These are outlined in documents available from their [website](#) (FDACS, Office of Agricultural Water Policy, 2008, 2015). BMPs vary between commodities, but are generally focused on nutrient and irrigation management.

3.1.3 Comparator

Absence of BMP intervention (*i.e.*, practices conducted by the farmer without BMPs) was compared to operations in which BMPs were included.

3.1.4 Outcome

Outcome involves the effect on water quality in terms of change to selected forms of N (nitrate, total nitrogen) or P (phosphate, total phosphorus). This was limited to actual environmental measures (*e.g.* no simulated data, no calculations based on crop nutrient content).

4 METHODS

4.1 QUESTION FORMULATION

FDACS contacted Frydenborg Ecologic initially for assistance in preparing a review of the literature in Florida associated with BMP implementation and outcomes. Through a series of meetings, it became clear that FDACS would benefit from a meta-analytical approach to more accurately characterize the effectiveness of their recommended BMPs. This would be particularly important when FDEP calculates allowable nutrient loadings from agricultural operations during the BMAP and TMDL process.

4.2 SEARCH STRATEGY

The FDACS Office of Water Policy conducted a literature review of agricultural BMP study results, emphasizing the potential effectiveness of BMPs that are prescribed in the adopted FDACS BMP manuals, especially those for nutrient and irrigation management. This literature search generated approximately 1,000 peer-reviewed scientific articles. Additionally, FDACS found 55 contract final reports and associated Section 319 (an FDEP grant program) BMP studies that were not published in journals. FDACS staff collected these reports and made them available to Frydenborg Ecologic for review and analysis.

4.2.1 Search Terms

Terms for additional searches by Frydenborg Ecologic were chosen to capture relevant information. They are separated into categories below. No terms for the outcome (*e.g.* concentration) were used as these are not always included in titles and abstracts, and studies utilize different methods of measurement. A "*" denotes wildcard. A detailed documentation is available in **Appendix A**.

- *population - ecological*: Florida, water, groundwater, leachate, soil, agriculture, farm, stream
- *population - commodity*: Agronomic, vegetable, corn, peanut, cotton, sugar cane, sorghum, potato*, strawberry*, tomato*, pepper, melon*, cucumber, cow, calf, citrus, vegetable, agronomic, dairy
- *intervention*: BMP, best management practice
- *measure*: nitr*, phosph*, nutrient

4.2.2 Databases

No additional database search was conducted, as it was not part of the contract.

4.2.3 Websites

An internet search was performed using the following search engines:

- <http://www.google.com>

- <http://scholar.google.com>

The top 50 hits from each search engine were examined for appropriate data, following Collaboration for Environmental Evidence (CEE) review guidelines.

4.3 STUDY INCLUSION CRITERIA

All articles were first sorted to remove duplicates in Zotero version 4.0.28.3. The articles provided by FDACS were then subjected to a full text screen to identify articles suitable for a meta-analysis using eligibility criteria presented below. The intent at each stage was to remove articles that were not relevant or did not contain appropriate data. Reports utilizing the same data sets but titled differently were encountered during the final data extraction phase, and resulted in additional elimination of duplicates.

Records identified by Frydenborg Ecologic via web searches were subjected to a three tier screening process:

1. Titles of articles were assessed using inclusion criteria;
2. Abstracts of articles were assessed; and
3. Full articles were assessed.

4.3.1 Eligibility Criteria

The eligibility criteria consisted of:

- *Relevant population(s)*: Articles and reports that investigated the effectiveness of one or more mitigation measures (BMPs) aimed at improving water quality in Florida. Scale was not considered, but studies were limited to Florida;
- *Types of interventions*: Reports measuring any intervention aimed at improving water quality were included;
- *Types of comparators*: The absence of a BMP intervention;
- *Types of outcomes*: Water quality (irrespective of experimental scale) was measured by changes in N (total nitrogen or nitrate) and P (total phosphorus or phosphate). Studies that measured groundwater, soil below the root zone, and surface water were all included; and
- *Types of studies*: Only studies that reported primary research were included. Studies had to investigate the effect of an intervention on environmental nutrient levels (surface water quality, ground water quality, soil below root zone). Reviews and modelling studies were excluded, as well as studies measuring inferred impacts (*i.e.*, crop yield, plant biomass, denitrification rates, and mineralization of soil nutrients).

Two reviewers screened articles for inclusion criteria. When uncertainty existed regarding an article, the two reviewers examined the text and a consensus agreement was made.

4.4 STUDY QUALITY ASSESSMENT

An indication of the reliability of the evidence available for each commodity was calculated using a scoring system based on standard categories. Each article was given a value according to a hierarchy of evidence adapted from Pullin and Knight (2003), incorporating systematic review guidelines commonly used in conservation biology and public health. For example, in the study type category, a study is assigned two points for a manipulative study, one point for a correlative study, and studies that consisted of only

observational sampling receive no points. The scoring system employed in this review is presented in **Table 2**.

Values for each category were summed for each article for a total score. Article scores were then examined for mean and standard deviation within each commodity type. Detailed information for each study is available in **Appendix B**.

Table 2. Scoring system used to assess the study quality with a hierarchy of evidence approach

Category	Score	Hierarchy of evidence
Randomization	1	Yes – randomized
	0	Not randomized
Control type	3	Controlled BACI
	2	Control-Impact
	1	Before-After
	0	No control
Study length	2	Greater than 2 years
	1	Between 1 and 2 years
	0	Less than 1 year
Replication	2	Temporal and spatial replication
	1	Temporal or spatial replication
	0	No replication
Study type	2	Manipulative Study
	1	Correlative Study
	0	Sampling Study

4.5 DATA EXTRACTION

FDACS Office of Water Policy was interested in three priority commodities:

1. Vegetable crops;
2. Agronomic crops; and
3. Cow/calf operations.

Agronomic crops in Florida include sugarcane, corn, soybeans, cotton, peanuts, and forages grown for hay. With the exception of sugarcane, they are mostly grown in North Florida. Vegetable crops, which may be grown statewide, include potato, strawberries, tomatoes, peppers, melons, and cucumbers. Cow/calf operations, which account for the largest land use among all of the commodities, are present throughout the state, and do not include dairy operations.

An information extraction procedure was developed in order to consistently examine each article for relevant data required for a meta-analysis. Each article was examined for:

- Type of study;
- Location of study;
- Response variable and units;
- Replication;
- Commodity and crop;

- BMP implementation;
- Control mean;
- Treatment mean;
- Variance of control;
- Variance of treatment; and
- Sample size of control and treatment.

The publications were sorted alphabetically by author, and two investigators read the articles, one starting at “A”, and one starting at “Z”, systematically extracting the information available in the publication, until all the publications had been read and evaluated. Authors of studies which met most of the inclusion criteria, but failed to report key components (such as a variance measure) were contacted and asked to provide needed information via email.

Of the articles evaluated at full text level, 19 contained the information needed for inclusion in a meta-analysis. For the commodity groups requested by FDACS, there were:

- 10 agronomic studies;
- 5 vegetable studies; and
- 4 cow/calf studies.

Many publications could not be included in a meta-analysis for one or more of the following reasons:

- The content of the publication did not address an environmental response variable, and therefore, the information was not applicable for evaluating BMP effectiveness;
- No control treatments were used, therefore no comparison between a baseline condition and condition subject to a BMP was possible;
- Experimental treatments consisted of pseudo-replication and/or no replication, meaning variability associated with the treatment could not be properly characterized;
- There was no reporting of standard error, standard deviation, some other measure of variability associated with the mean. Without a measure of variability, the results from one study cannot be quantitatively compared to results of another study;
- Means were not provided, only a range of effects, with an inadequate explanation concerning the significance of the range;
- The experimental design of the study was not appropriate for evaluating BMP effectiveness; and
- The publication did not contain numeric endpoints associated with a BMP, instead, only a qualitative evaluation (fair, good, etc.) was provided.

Complete documentation for the studies included is available in **Appendix C**. If an article did not contain the information necessary for inclusion in a meta-analysis, a short summary of the most important findings relevant to BMP effectiveness was created and is presented in **Appendix D**. A brief explanation of the reasoning for rejecting several studies is available in **Appendix E**.

4.6 DATA SYNTHESIS

Data analysis was conducted using the statistical programming language “R” version 3.2.1 (R Core Team, 2014), with the following additional packages: metafor 1.9-7, MAd 0.8-2, dplyr 0.4.1, and tidyr 0.2.0.

Studies within the same commodity that reported the effects of BMPs on both phosphorus and nitrogen were split for analysis. This is because phosphorus is more likely to interact with and attach to particles, while nitrate, especially in groundwater, is highly mobile with little capacity for sorption (Almasri and Kaluarachchi, 2007). Therefore, it was hypothesized that nitrogen and phosphorus would respond to BMPs somewhat differently.

4.6.1 Ratio of Means Effect Size

As a meta-analysis calculates an overall effect size from a group of effect sizes, effect size for each individual study was first calculated. Effect size is a common statistical measure, with a standardized measure of uncertainty, which is shared among studies. Prior to effect size calculations, studies that had reported variability in the data as the standard error were recalculated to express variance in the form of standard deviation. Effect size was calculated as the response ratio (the natural log-transformed ratio of means). This method uses the natural logarithm of the ratio of the control and test means to create a dimensionless effect size that is capable of comparisons between studies reporting outcomes in different units (Friedrich et al., 2008) (**Equation 1**). This makes use of the natural logarithm scale, similar to statistical procedures for binary effect measures, due to its desirable statistical

properties. The log transformed response ratio represents the percentage change between the nutrients entering the environment from agricultural operations that use at least one BMP to non-BMP managed operations. The log-transformed response ratio describes the proportional change observed after implementing BMPs, and is commonly used in ecological meta-analyses due to its ability to provide more information on the magnitude of effects compared to an alternative method for creating dimensionless effect sizes, the standardized mean difference (SMD) (Hedges and Olkin, 1985). Variance (var) of the RoM is calculated using **Equation 2**.

Equation 1. Effect size for each study was calculated by using the ratio of means method. For each study reporting a continuous outcome, the mean is denoted by $mean_{exp}$, standard deviation as sd_{exp} , and replication as n_{exp} .

$$RoM = \frac{mean_{exp}}{mean_{contr}}$$

Effect size is a common statistical measure, with a standardized expression of uncertainty, which is shared among studies. For this analysis, effect size was calculated as the “response ratio” (the log-transformed ratio of means). Therefore, the effect size represents the percent change in nutrients entering the environment between agricultural operations that use at least one BMP and non-BMP managed operations.

Equation 2. Variance calculation for the ratio of means effect size. From (Friedrich et al., 2008).

$$\begin{aligned}
 \text{Var} \left[\ln \left(\frac{\text{mean}_{\text{exp}}}{\text{mean}_{\text{contr}}} \right) \right] &= \text{Var} \left[\ln(\text{mean}_{\text{exp}}) - \ln(\text{mean}_{\text{contr}}) \right] \\
 &= \text{Var} \left[\ln(\text{mean}_{\text{exp}}) \right] + \text{Var} \left[\ln(\text{mean}_{\text{contr}}) \right] \quad \left[\text{since the groups are independent} \right] \\
 &= \left(\frac{1}{\text{mean}_{\text{exp}}} \right)^2 \text{Var}(\text{mean}_{\text{exp}}) + \left(\frac{1}{\text{mean}_{\text{contr}}} \right)^2 \text{Var}(\text{mean}_{\text{contr}}) \\
 &= \frac{1}{n_{\text{exp}}} \left(\frac{\text{sd}_{\text{exp}}}{\text{mean}_{\text{exp}}} \right)^2 + \frac{1}{n_{\text{contr}}} \left(\frac{\text{sd}_{\text{contr}}}{\text{mean}_{\text{contr}}} \right)^2 \\
 &\quad \left[\text{since for random variable } X, \text{Var}(\text{mean}_X) = \frac{\text{Var}(X)}{n_X} = \frac{\text{sd}_X^2}{n_X} \right]
 \end{aligned}$$

The natural logarithm transformed ratios are combined across studies using the generalized inverse variance method (see section 4.6.4). The pooled transformed ratio is then back transformed to obtain a pooled ratio and 95% confidence interval (**Equation 3**).

Equation 3. The ratio of the means is back transformed to obtain a pooled ratio and associated 95% confidence interval. From (Friedrich et al., 2008).

$$95\% \text{ CI} = \exp \left\{ \left[\ln \left(\frac{\text{mean}_{\text{exp}}}{\text{mean}_{\text{contr}}} \right) \right] \pm 1.96 \sqrt{\text{Var} \left[\ln \left(\frac{\text{mean}_{\text{exp}}}{\text{mean}_{\text{contr}}} \right) \right]} \right\}$$

Log transforming the ratio of mean values allows for this non-normally distributed function to approximate a normal distribution, as well as for an approximation of the 95% confidence interval. A similar approach is used for other ratio methods such as the odds ratio and relative risk.

Due to the unitless nature of this method, the ratio of means can be used regardless of the units used in a study outcome measure.

The mean effect presented in the results section is a weighted mean effect calculated from the individual means of each included study, weighted by their inverse variance. Confidence intervals calculated for the mean effect can be interpreted as the interval in which there is 95% confidence that the true mean effect occurs. Prediction intervals are also calculated, and can be interpreted as the extent within which 95% of true effects are predicted to occur for future studies.

The mean effect sizes not overlapping zero at the 95% confidence interval were back transformed into percent reduction by **Equation 4**.

Equation 4. Log Ratio of Means Effect size = x. No effect = 0.

$$\text{Percent Reduction} = \frac{e^0 - e^x}{e^0} * 100$$

4.6.2 Heterogeneity and Publication Bias Analysis

Variability between studies in each group was examined using a heterogeneity measure (Q), calculated by weighting the sum of squared differences between individual effects and the pooled effect, which was tested against a chi-square distribution. While excessive heterogeneity is problematic for interpreting effect size properly, use of a random-effects model can help overcome the effects of heterogeneity (Eysenck, 1994). “Publication bias”, a phenomenon where only results of studies thought to be positive are actually printed and circulated, was examined through the use of funnel plots, and an inspection of the regression test for funnel plot asymmetry. QQ plots were also examined for approximate normality. Several modifiers were examined to determine their influence on any heterogeneity observed in each model, including crop type, BMP type, and response unit (*e.g.*, kg/ha vs. mg/L).

4.6.3 Random-Effects Model

The random-effects model was used to calculate overall effect size in this meta-analysis. This category of model is commonly accepted as appropriate for ecological meta-analyses, because ecological studies are typically not identical in their methods and site characteristics, and these sources of variability must be accounted for. In other words, ecological studies have variability across their effect sizes that derives from random difference across studies that cannot be readily identified or measured. The random-effects model allows for variability of effect sizes amongst studies, and treats heterogeneity between studies as random. Random effects model assumes that the variability between effect sizes is due to sampling error *and* the variability in the population of effects. An important characteristic of the random effects model is that there is not one single true effect size, but rather a range of possible effects. The random-effects estimate and its confidence interval addresses the question “what is the average intervention effect”? Random effects models are more conservative than fixed effects models, with larger confidence intervals. Unlike fixed effects models, random effects model weights each study by the inverse of the sampling variance *and* a constant that is representative of the variability across the population of effects. The specific model employed was the Restricted Maximum Likelihood (REML) estimator, which strikes a balance between unbiasedness and efficiency (Viechtbauer, 2005).

The random-effects model allows for variability of effect sizes amongst studies, and treats heterogeneity between studies as random. The random-effects estimate and its confidence interval addresses the question, “what is the average intervention effect”? The mean outcome presented is a mean effect calculated from the individual means of each included study, weighted by their inverse variance.

Prior to calculation of the overall effect size, effect sizes resulting from multiple comparisons made in a single study were aggregated to calculate one effect size per study. Aggregation of effect sizes from studies can be accomplished using the univariate procedure of Borenstein, Hedges, Higgins, and Rothstein (BHHR). This type of pre-aggregation step has been found to be the least biased and most precise for meta-analysis (Del Re, 2015). This aggregation was accomplished using the ‘MAd’ package.

A weighted mean effect, confidence interval, and prediction interval were calculated for cow/calf N response, cow/calf P response, agronomic N response, agronomic P response, vegetable N response, and vegetable P response.

4.6.4 Inverse-Variance Weighting for Random Effects Models

In fixed effects meta-analysis, the treatment effect measures are assumed to be distributed around the same value for each study. An estimation of this effect measure can be determined by taking a weighted average of each study's effect measures (Friedrich et al., 2008). Each study is weighted by the inverse of the variance of the effect measure (**Equation 5**).

Equation 5. Inverse-variance weighting for fixed effect models. From (Friedrich et al., 2008).

$$\Theta_{IV(FE)} = \frac{\sum_{i=1,k} w_i \times \Theta_i}{\sum_{i=1,k} w_i} \quad \text{with variance } (\Theta_{IV(FE)}) = 1 / \sum_{i=1,k} w_i$$

In **Equation 5**, $\Theta_{IV(FE)}$ is the inverse-variance weighted fixed effects pooled effect estimate. k designates the number of studies, i is the effect measure estimate for study i with a weighting of $w_i = 1/\text{variance}(\Theta_i)$.

In random effects meta-analysis, an individual study's effect measure is assumed to vary around an overall average treatment effect. Variance of this treatment effect, also known as between-study heterogeneity (t^2), is incorporated into the weights assigned to each individual study when producing an estimate (**Equation 6**).

Equation 6. Inverse-variance weighting for random effects models. From (Friedrich et al., 2008).

$$\Theta_{IV(RE)} = \frac{\sum_{i=1,k} w_i^* \times \Theta_i}{\sum_{i=1,k} w_i^*} \quad \text{with variance } (\Theta_{IV(RE)}) = 1 / \sum_{i=1,k} w_i^*$$

In **Equation 6**, $w_i^* = 1/(e_i^{-1} + t^2)$. An estimate of t^2 can be found by using the Q statistic (**Equation 7**), which has a chi-square distribution with $k-1$ degrees of freedom when heterogeneity is zero.

Equation 7. Equation for the Q statistic. From (Friedrich et al., 2008).

$$Q = \sum_{i=1,k} w_i \times (\Theta_i - \Theta_{IV(FE)})^2$$

An estimate of t^2 is calculated in **Equation 8**:

Equation 8. Equation for the calculation of t^2 using the Q statistic. From (Friedrich et al., 2008).

$$t^2 = \frac{Q - (k-1)}{\sum_{i=1,k} w_i - \frac{\sum_{i=1,k} (w_i)^2}{\sum_{i=1,k} w_i}} \quad \text{if } Q \geq k-1, \text{ and}$$

$$t^2 = 0 \quad \text{if } Q < k-1$$

If there is no between-trial heterogeneity ($t^2 = 0$), the Q-statistic has an expected value of $k-1$. In this case, the random effects model is equivalent to the fixed effects model. If heterogeneity is present ($t^2 > 0$, $Q/(k-1) > 1$), the proportion of variation in study level estimates of treatment effect due to the between-study heterogeneity can be expressed as a percentage, signified by I^2 (**Equation 9**). If the variance (and hence the weighting) of each study is identical, then variance of the effect measure reduces to the variance of a single trial. To conduct a random effects meta-analysis, it is required to calculate the effect measure and its associated variance for each study that will later be combined to determine a pooled estimate. First, the fixed effects pooled effect measure is determined. This is used to estimate Q and t^2 , and t^2 is then used to estimate the random effects pooled effect measure and its variance.

Equation 9. Calculation of I^2 .

$$I^2 = \frac{(Q - (k - 1))}{Q}$$

5 RESULTS

5.1 STUDIES FOUND

The search for additional data that was not provided and screened by FDACS was carried out between September 1 through 8, 2015. In total, the documents provided by FDACS resulted in 283 articles for review by Frydenborg Ecologic. Additional web searches and direct author contact by Frydenborg Ecologic identified 15 potential articles. All articles identified were reviewed at the full text level since the number was low relative to the typical meta-analysis. Additionally, the major findings of each article were summarized in a separate report for FDACS staff, and are included in **Appendix D**. A flowchart of the process used in this study is presented in **Figure 1**.

After careful screening, 43 articles met inclusion criteria for a meta-analysis, covering a wide array of commodities and BMPs. Of these 43 articles, 19 had been conducted on one of the three commodity groups of interest (**Table 3**). Studies were located throughout the state, and study the locations coincided with the commodity typically grown in different regions of the state of Florida (**Figure 2**).

Table 3. Articles identified for meta-analysis.

Citation	County	BMP Intervention	Commodity
(Bohlen and Villapando, 2011)	Okeechobee	Water retention/detention	Cow/calf
(Capece et al., 2007)	Highlands	Stocking rate (pasture management)	Cow/calf
(Shukla et al., 2011a)	Okeechobee	Waterway exclusion (culvert crossings and ditch fencing)	Cow/calf
(Shukla et al., 2014)	Okeechobee	Water retention/detention	Cow/calf
(Potter et al., 2005)	Miami-Dade	Cover crop use	Agronomic
(Zotarelli et al., 2008a)	Alachua	Irrigation BMP	Agronomic
(Woodard et al., 2002a)	Suwannee and Gilchrist	Organic, slow release fertilizer use	Agronomic
(Schaffer et al., 2001)	Miami-Dade	Efficient fertilizer application	Agronomic
(IFAS and SRWMD, 2008)	Suwannee and Lafayette	Irrigation and Efficient fertilizer application BMPs	Agronomic
(He et al., 2005)	St. Lucie	Efficient fertigation BMP	Vegetable
(Hendricks and Shukla, 2011)	Collier	Efficient fertilization and micro-irrigation BMPs	Vegetable
(Zotarelli et al., 2010)	Marion	Tensiometer-controlled irrigation, efficient fertilization BMP	Vegetable
(Zotarelli et al., 2009a)	Marion	Surface and subsurface drip irrigation, efficient fertilization	Vegetable
(Wang et al., 2005)	Miami-Dade	Cover crop use BMP	Vegetable
(Obern, 2011)	Hendry	Optimization of wetland treatment	Vegetable
(Pack et al., 2006)	St. Johns	Controlled release fertilizer use BMP	Vegetable
(Shukla et al., 2011b)	Hendry	Water management BMP	Vegetable
(Hendricks et al., 2014)	Collier	Efficient fertilization, drip irrigation	Vegetable
(Zotarelli et al., 2007)	Marion	Micro-drip irrigation, efficient fertilization	Vegetable

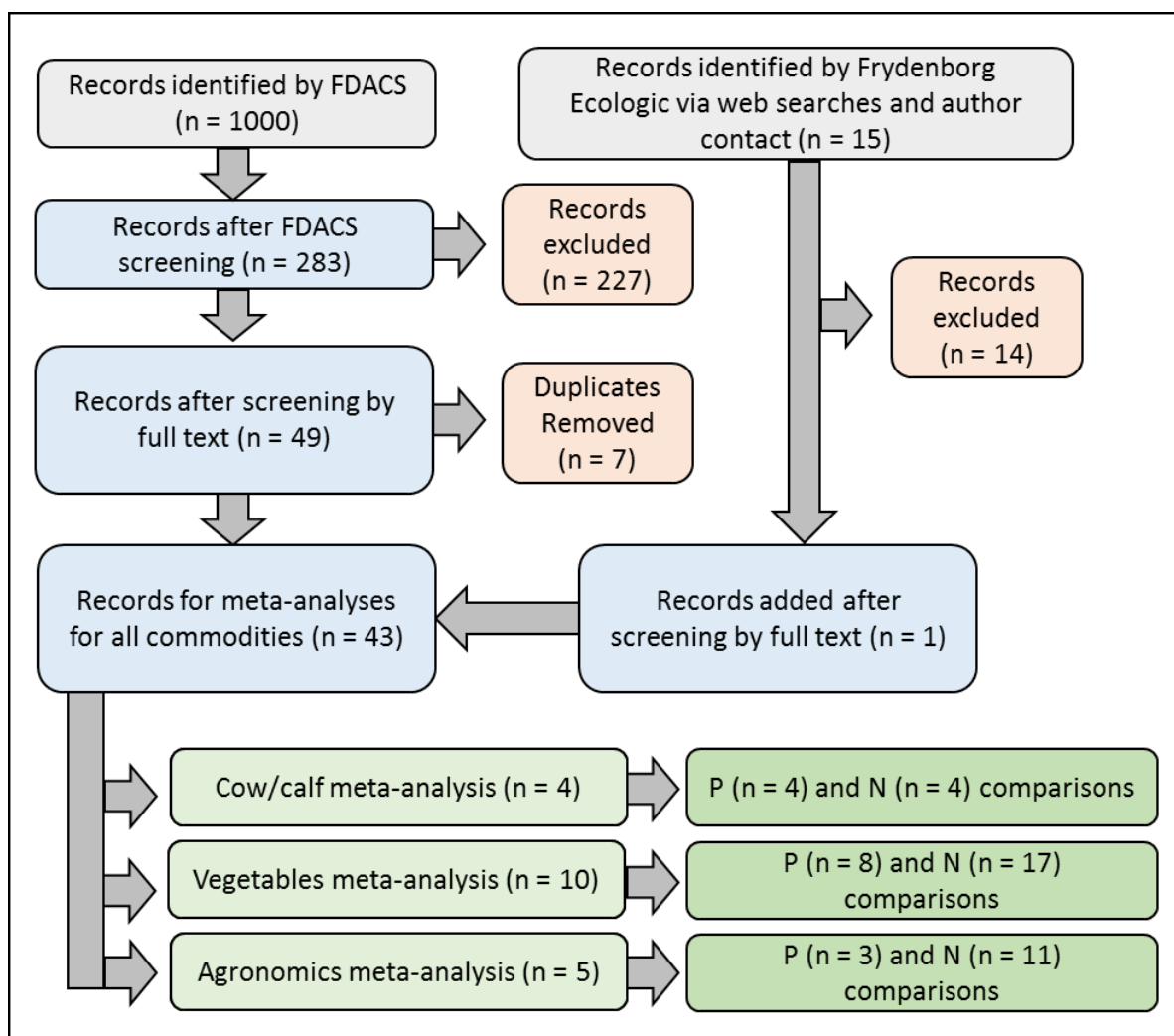


Figure 1. Diagram of article and report screening and selection for the meta-analysis.

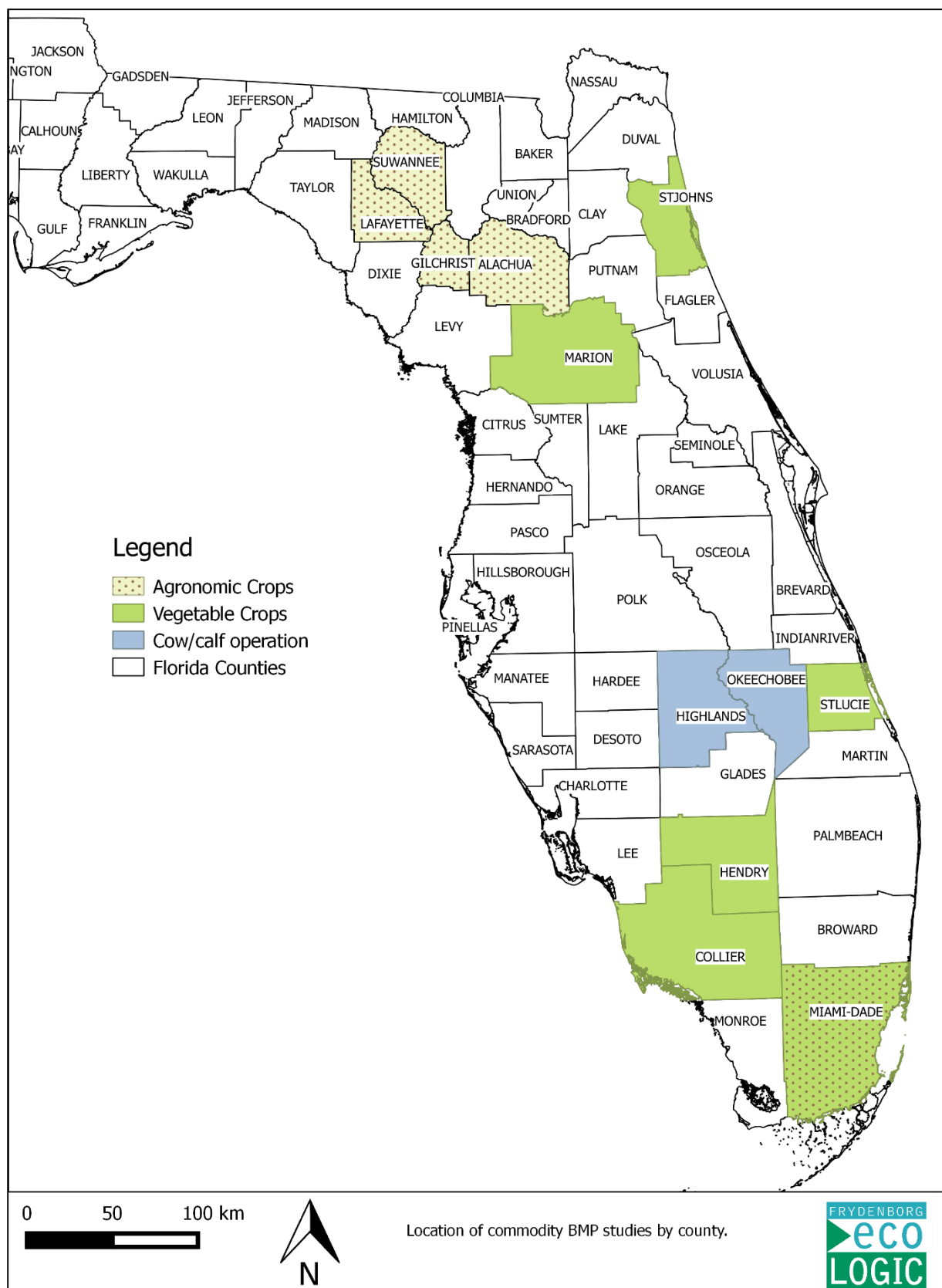


Figure 2. Location of studies by commodity and county.

5.2 STUDY QUALITY

Cow/calf studies had a mean score of 9 with a standard deviation of 1.6 (n = 4). Agronomic studies had a mean of 8.4 and a standard deviation of 0.89 (n = 5). Vegetable studies had a mean quality score of 8 with a standard deviation of 1.22 (n = 10). These results reflect that the majority of the studies in all categories were of a manipulative experimental design, well controlled and replicated, and were of longer duration.

5.3 DESCRIPTIVE STATISTICS OF ARTICLES

Studies often investigated multiple BMPs with multiple outcomes (TN, TP, nitrate, SRP, *etc.*), and sometimes occurred in multiple counties of the state. Because of this, there are discrepancies between the total number of articles reported, and the number of studies in each individual discussion (*i.e.*, an article measuring outcome of TN and TP from water retention, fertilizer management, and the combination of the two would be counted multiple times).

5.3.1 Outcomes Measured

For cow/calf operations, four studies assessed an N response, and the same four studies also assessed a P response. For agronomic crops, 5 studies assessed an N response, and 3 assessed a P response. For vegetable crops, 7 studies assessed an N response, and 5 studies assessed a P response.

5.3.2 Intervention Types

BMP interventions were varied and rarely repeated. Many studies examined the effect of BMPs in a randomized block design with multiple treatments and multiple levels (**Table 4**). Study design tended to be randomized block control impact (CI) studies (**Table 5**).

Table 4. Type and number of BMP manipulations studied for reducing N and P.

BMP manipulation	commodity	N (# of studies)	P (# of studies)
Water retention/detention	Cow/calf	2	2
Stocking rate (pasture management)	Cow/calf	1	1
Waterway exclusion (culvert crossings and ditch fencing)	Cow/calf	1	1
Cover crop use	Agronomic	1	1
Irrigation BMP	Agronomic	2	1
Organic, slow release fertilizer use	Agronomic	1	0
Efficient fertilizer application	Agronomic	2	2
Irrigation and Efficient fertilizer application BMPs	Agronomic	1	0
Efficient fertigation BMP	Vegetable	1	0
Efficient fertilization and micro-irrigation BMPs	Vegetable	1	0
Tensiometer-controlled irrigation, efficient fertilization BMP	Vegetable	1	0
Surface and subsurface drip irrigation, efficient fertilization	Vegetable	1	1
Cover crop use BMP	Vegetable	1	0
Optimization of wetland treatment	Vegetable	2	2
Controlled release fertilizer use BMP	Vegetable	1	1
Water management BMP	Vegetable	1	0
Efficient fertilization, drip irrigation	Vegetable	2	2
Micro-drip irrigation, efficient fertilization	Vegetable	2	2

Table 5. The number of study designs in each commodity grouping.

Study Design	Cow/calf (4 total)	Vegetable (10 total)	Agronomic (5 total)
BACI	2	0	0
CI	1	9	5
BA	1	1	0

5.4 QUANTITATIVE SYNTHESIS AND META-ANALYSIS

In the following forest plots, the log-transformed response ratio describes the proportional change observed in nutrients due to BMP implementation. The effect size mean of each study is indicated by a black square, which differs in size depending on the weight assigned to the study in the random effects model. Error bars represent the 95% confidence interval for each study. The overall effect size is indicated by a diamond. The width of the diamond corresponds to the 95% confidence interval. A 95% prediction interval is shown as a dotted line. In total, six models are presented. Studies were grouped by commodity (cow/calf, agronomic, vegetable), and again by measured nutrient (phosphorus and nitrogen). QQ-norm plots were examined for each model, and are presented in **Appendix F**.

Inter-study variation in each group is explored using the heterogeneity measure (Q), which is calculated by weighting the sum of squared differences between individual effects and the pooled effect, and tested against a chi-square distribution (Hedges and Olkin, 1985). The null hypothesis of this test is that variation between studies is zero, and therefore, the group is considered heterogeneous when $p > 0.05$. Heterogeneity can be visually observed by inspection of forest plots through the amount of overlap of the confidence intervals. The chi-squared test has low power when the sample size is low, which means that while a statistically significant result may indicate a problem with heterogeneity, a non-significant result is not necessarily evidence of no heterogeneity. A more useful method for quantifying the impact of heterogeneity on the analysis is through the I^2 statistic (Higgins and Thompson, 2002; Higgins et al., 2003). The I^2 describes the percentage of variability in the estimated effects due to heterogeneity rather than chance. The I^2 value can be roughly interpreted as:

- 0% to 40%: heterogeneity might not be important;
- 30% to 60%: may represent moderate heterogeneity;
- 50% to 90%: may represent substantial heterogeneity; and
- 75% to 100%: considerable heterogeneity.

In all cases, the importance given to the I^2 value depends on the magnitude and direction of effects, and the strength of evidence for heterogeneity (P value from chi-squared test, confidence interval for I^2) (after the Cochrane Handbook for Systematic Reviews, 2008).

Publication bias can be observed visually with the funnel plot of effect size by standard error, as well as through a regression test for plot asymmetry.

5.4.1 Cow-calf BMP Effectiveness

5.4.1.1 Nitrogen

The mean effect size for BMPs implemented on cow/calf commodities that measured a nitrogen response was 0.01 (with a 95% confidence interval of -0.12 to 0.14) (**Figure 3**). The cow/calf comparison

was restricted by the limited number of studies available that met inclusion criteria. The BMPs represented by each study is presented in **Table 3**.

No singular study found a significant effect in reduction of nitrogen as a result of BMP implementation, and there was no overall effect observed in the model.

Heterogeneity was not statistically significant ($Q = 2.86$, $df = 3$, $p = 0.41$), and the $I^2 = 0\%$.

A funnel plot did not show asymmetry of data, and a regression test for funnel plot asymmetry was not significant ($z = -0.91$, $p = 0.36$), meaning there was no publication bias (**Figure 4**).

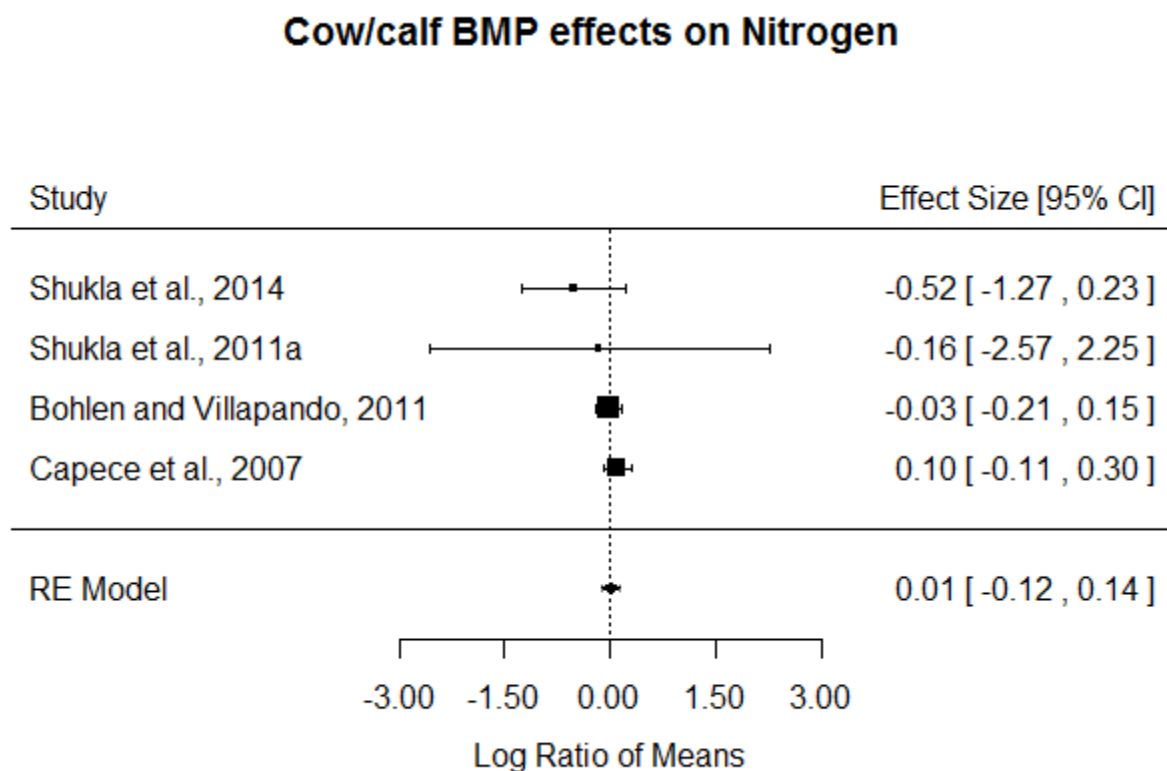


Figure 3. Forest plot of nitrogen effect size (log-transformed ratio of means) for cow/calf studies.

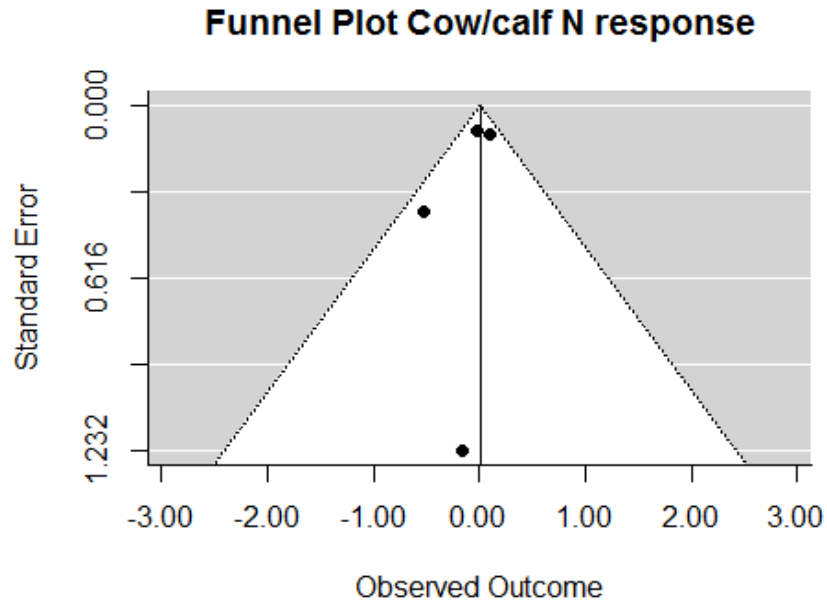


Figure 4. Funnel plot of cow/calf studies that measured a nitrogen response.

5.4.1.2 Phosphorus

The mean effect size for BMPs implemented on cow/calf commodities measuring a phosphorus response was -0.08 (with a 95% confidence interval from -0.40 to 0.23) (**Figure 5**). The studies included in the phosphorus model for cow/calf BMPs did not differ from studies included in the nitrogen model. Similar to the nitrogen model, conclusions are limited due to the low number of studies included.

Cow/calf BMP effects on Phosphorus

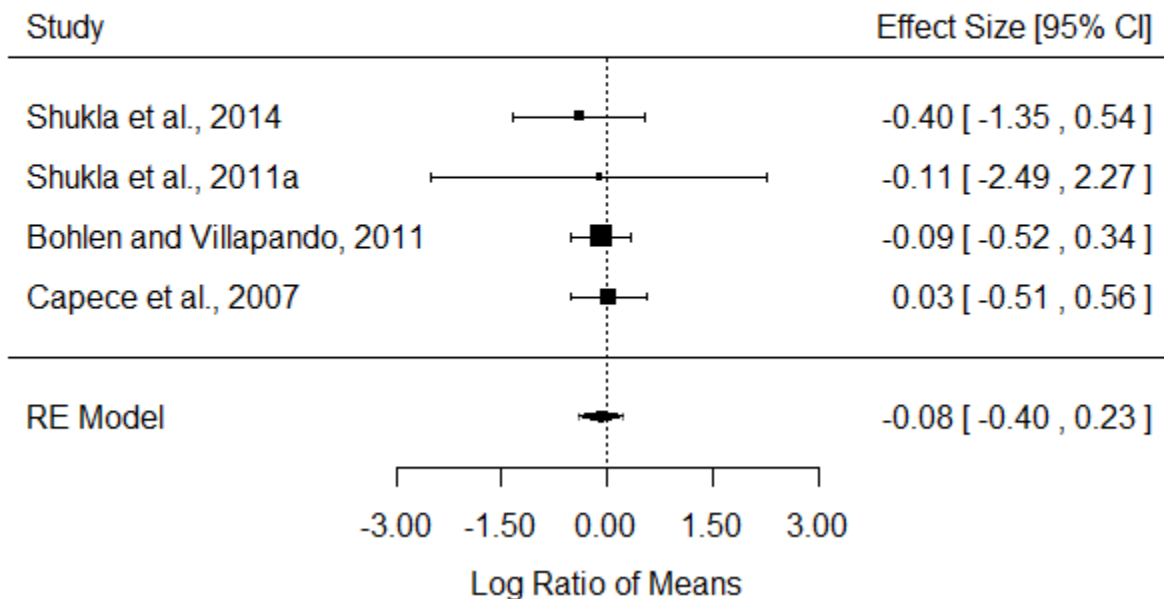


Figure 5. Forest plot of BMP effect size for cow/calf studies measuring a phosphorus response.

Heterogeneity was not statistically significant ($Q = 0.59$, $df = 3$, $p = 0.90$), and the $I^2 = 0\%$. A funnel plot did not show asymmetry of data, and a regression test for funnel plot asymmetry was not significant ($z = -0.33$, $p = 0.75$) (**Figure 6**).

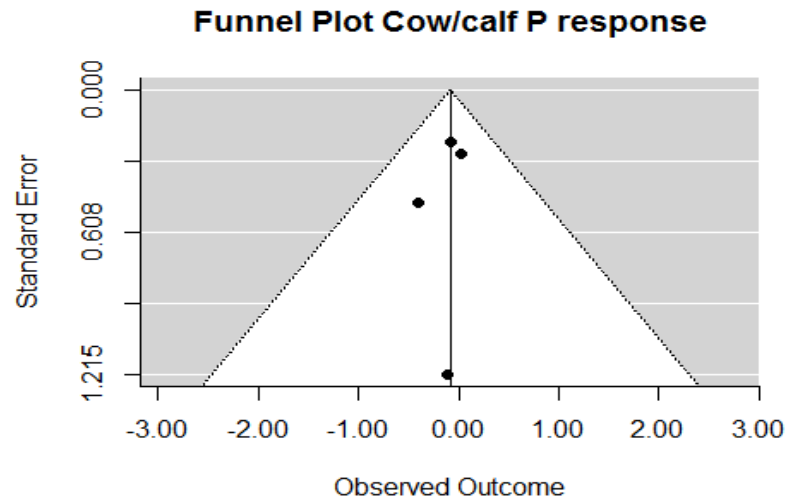


Figure 6. Funnel plot of cow/calf studies measuring a phosphorus response.

5.4.2 Agronomic Crops

5.4.2.1 Nitrogen

The mean effect size for BMPs implemented on agronomic commodities that measured a nitrogen response was significant (-0.91 , with a 95% confidence interval from -1.72 to -0.10) (**Figure 7**). A funnel plot showed no asymmetry of the data, and a regression test for funnel plot asymmetry was not significant ($z = 0.23$, $p = 0.82$) (**Figure 8**). Heterogeneity was statistically significant ($Q = 137.02$, $df = 4$, $p < 0.0001$), and the $I^2 = 94.9\%$. While the random effects model is used to incorporate unknown sources of heterogeneity among studies when calculating an overall effect size, heterogeneity should still be investigated (see below). Additionally, estimates of heterogeneity are known to be biased in small meta-analyses, and it is recommended that I^2 be interpreted cautiously when the meta-analysis is small and the null hypothesis of homogeneity ($I^2 = 0$) has been rejected (von Hippel, 2014).

Agronomic BMP effects on Nitrogen

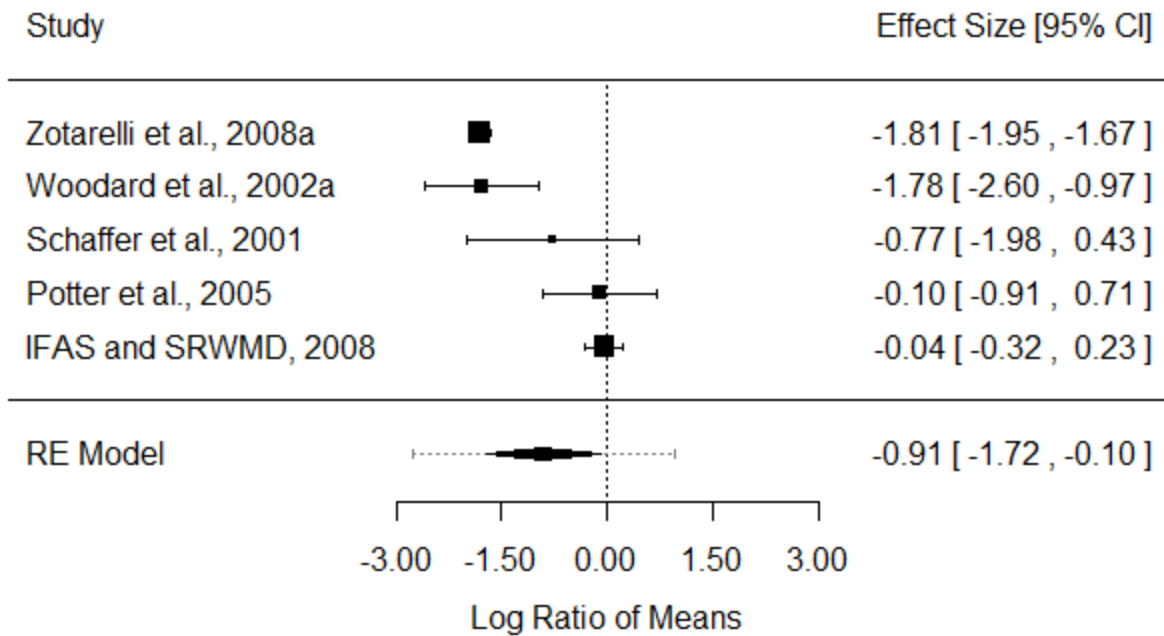


Figure 7. Forest plot of BMP effect size for agronomic crop studies measuring a nitrogen response.

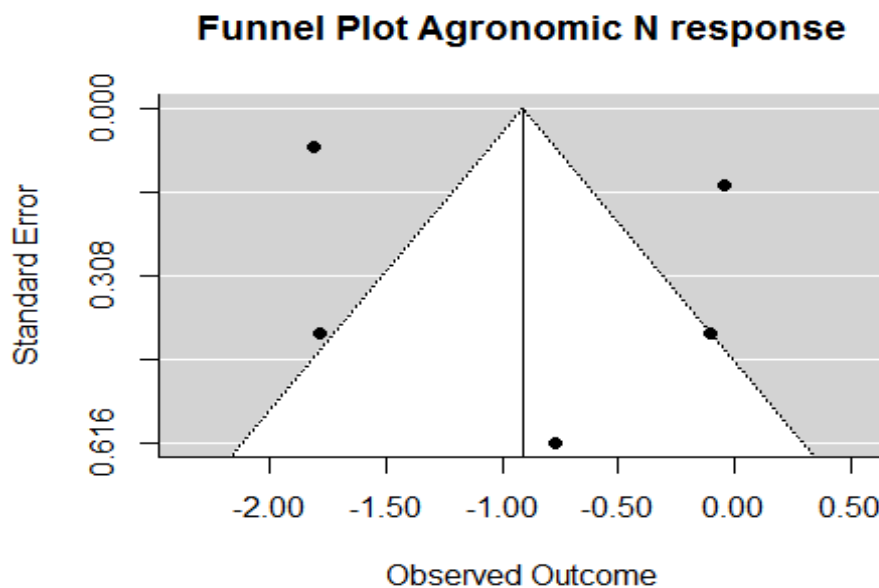


Figure 8. Funnel plot of agronomic crop studies that measured a nitrogen response.

From visual inspection of the forest plot, heterogeneity appears to be due to the amount of reduction and differences in variance associated with each study, and not the direction of the effect (*i.e.*, the effect size mean for each study demonstrates a reduction in nitrogen). The random effects model assigns weights to studies based on their size. The forest plot does not demonstrate a difference in effect size due to study size, which if present would be indicative of a systematic difference between studies, such as a result of publication bias. The existence of heterogeneity is suggestive that factors other than the implementation of a BMP are influencing the effect estimate. In this meta-analysis, it is likely that methodological diversity (*i.e.*, no studies utilized the exact same methods, study area, and crop type for reducing nutrients) accounts for the heterogeneity, and has influenced the results of the different studies.

Potential moderators that could explain the observed heterogeneity are crop type, specific BMP implemented, and the response units of the measurement. A mixed effects model that included these moderators was run on the non-aggregated means. The I^2 was 85.7% for this model, and the remaining heterogeneity was still significant ($QE = 40.5$, $df = 7$, $p < 0.0001$), despite the moderator effect also being found to be significant ($QM = 8.2$, $df = 3$, $p = 0.04$). Of the three moderators examined, BMP type was the only one found to be significant ($z = 2.2$, $p = 0.03$, effect size = 0.19 [0.03, 0.35]).

A forest plot of the random effects model was constructed without aggregation of intra-study comparisons (**Figure 9**), with accompanying funnel plot (**Figure 10**). This figure suggests that BMPs involving irrigation and fertilization rates were not as effective as the controlled release fertilizer BMP, and that the most effective treatment was a combination of controlled release fertilizer applied at a low rate. Comparisons of specific BMPs should be cautiously interpreted as only one study (Woodard et al., 2002a) measured controlled release fertilizer.

Agronomic BMP non-aggregated effects on Nitrogen

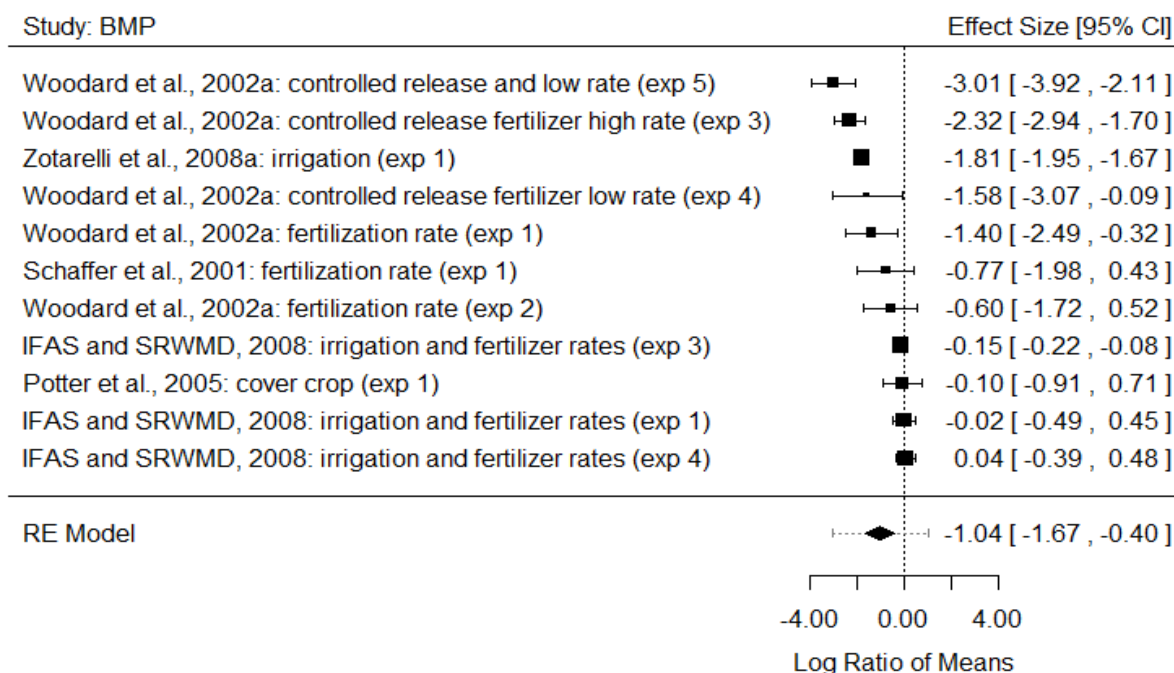


Figure 9. Forest plot of BMP effect size for non-aggregated agronomic crop studies measuring a nitrogen response.

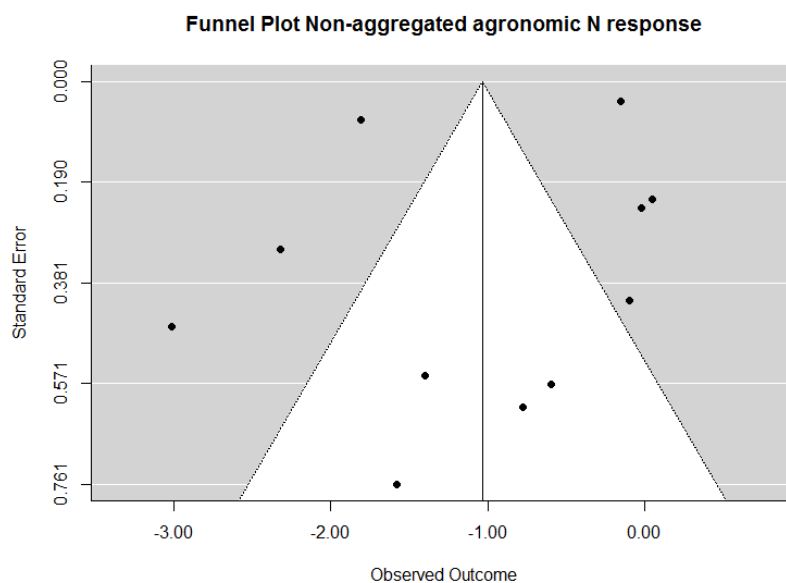


Figure 10. Funnel plot of non-aggregated agronomic crop studies measuring a nitrogen response.

5.4.2.2 Phosphorus

The mean effect size for BMPs implemented on agronomic commodities that measured a phosphorus response was not significant (0.50, with a 95% confidence interval from 0.00 to 1.01) (**Figure 11**). As this model only contains two studies, it is of limited use in evaluating BMP effectiveness.

Heterogeneity was not statistically significant ($Q = 0.02$, $df = 1$, $p = 0.89$), and $I^2 = 0\%$.

A funnel plot did not show asymmetry of data, and a regression test for funnel plot asymmetry was not conducted due to lack of data (**Figure 12**).

Agronomic BMP effects on Phosphorus

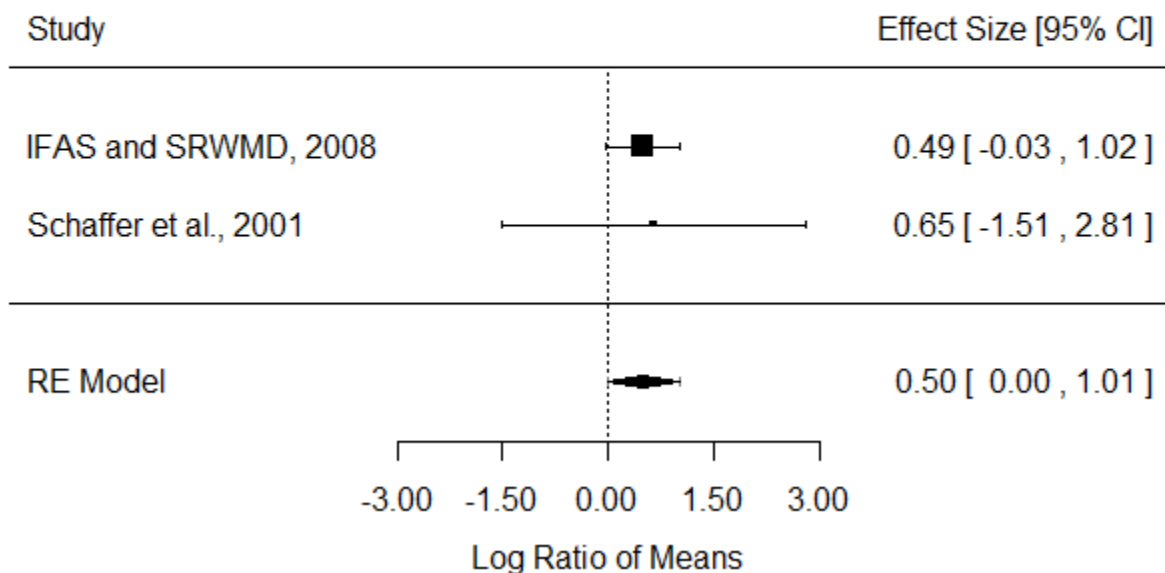


Figure 11. Forest plot of BMP effect size for agronomic crop studies measuring a phosphorus response.

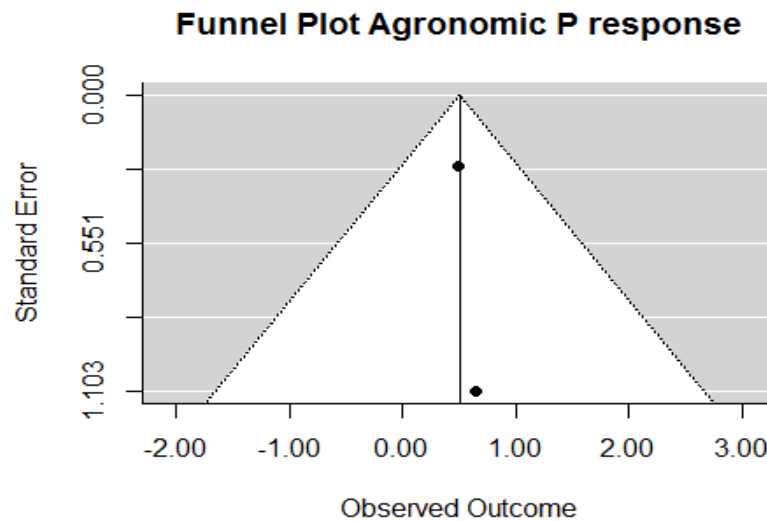


Figure 12. Funnel plot of agronomic crop studies measuring a phosphorus response.

5.4.3 Vegetable Crops

5.4.3.1 Nitrogen

The mean effect size for BMPs implemented on vegetable commodities that measured a nitrogen response was significant (-1.08, with a 95% confidence interval from -1.65 to -0.50) (**Figure 13**). A funnel plot did not show asymmetry of data, and a regression test for funnel plot asymmetry was not significant ($z = -0.21$, $p = 0.84$) (**Figure 14**). Similar to the agronomic crops, the heterogeneity for this model was statistically significant ($Q = 90.95$, $df = 6$, $p < 0.0001$), and $I^2 = 94.1\%$.

From visual inspection of the forest plot, heterogeneity appears to be due to the amount of reduction and differences in variance associated with each study, and not the direction of the effect (*i.e.*, the effect size mean for each study demonstrates a reduction in nitrogen). The random effects model assigns weights to studies based in part on their size and variation. The forest plot does not demonstrate a difference in effect size due to study size or effect size variation, which if present, would be indicative of a systematic difference in effect observed between studies potentially due to factors such as sample size.

The existence of heterogeneity is suggestive that factors other than solely the implementation of BMPs are influencing the effect estimate. In this meta-analysis, it is likely that methodological diversity accounts for the heterogeneity, and has effected the results of the different studies. Potential moderators that could explain the observed heterogeneity are crop type, specific BMP implemented, and the response units. A mixed effects model that included these moderators was constructed on the non-aggregated effect size means. The I^2 was 85.8% for this model, and the remaining heterogeneity was still significant ($QE = 82.1$, $df = 13$, $p < 0.0001$). The moderator effect was not found to be significant ($QM = 5.4$, $df = 3$, $p = 0.14$).

A forest plot of the random effects model was constructed without aggregation of within study comparisons (**Figure 15**), with accompanying funnel plot (**Figure 16**). This figure did not demonstrate clearly that a particular BMP was superior to others for reducing nitrogen export from vegetable

operations. Of all the individual effect sizes included, cover crop and subsurface drip BMPs had the largest effect size. Comparisons of specific BMPs should be cautiously interpreted as there are other covariates between BMP types, such as study design, crop, and location, and the overall number of studies is low.

Vegetable BMP effects on Nitrogen

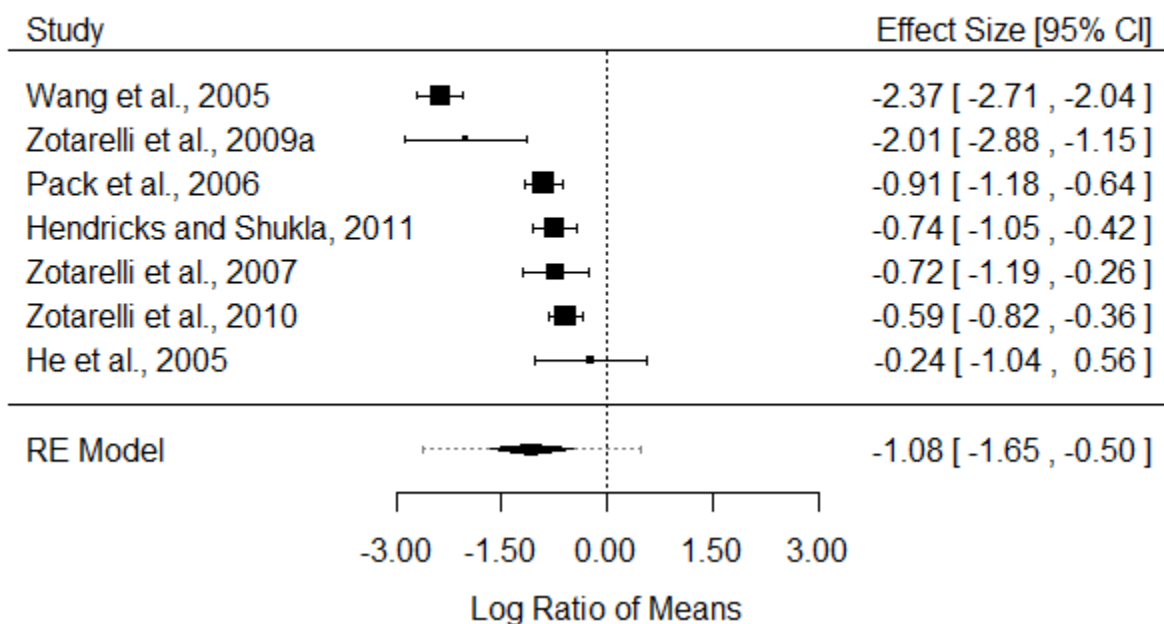


Figure 13. Forest plot of BMP effect size for aggregated vegetable crop studies measuring a nitrogen response.

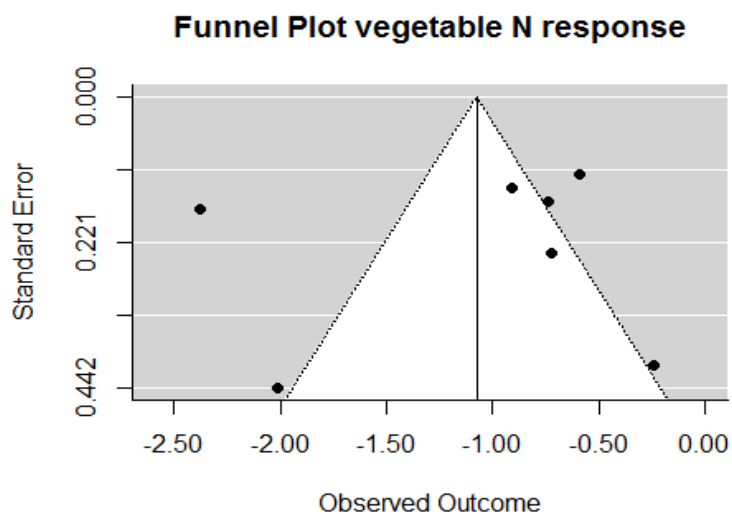


Figure 14. Funnel plot of aggregated vegetable crop studies measuring a nitrogen response.

Vegetable BMP non-aggregated effects on Nitrogen

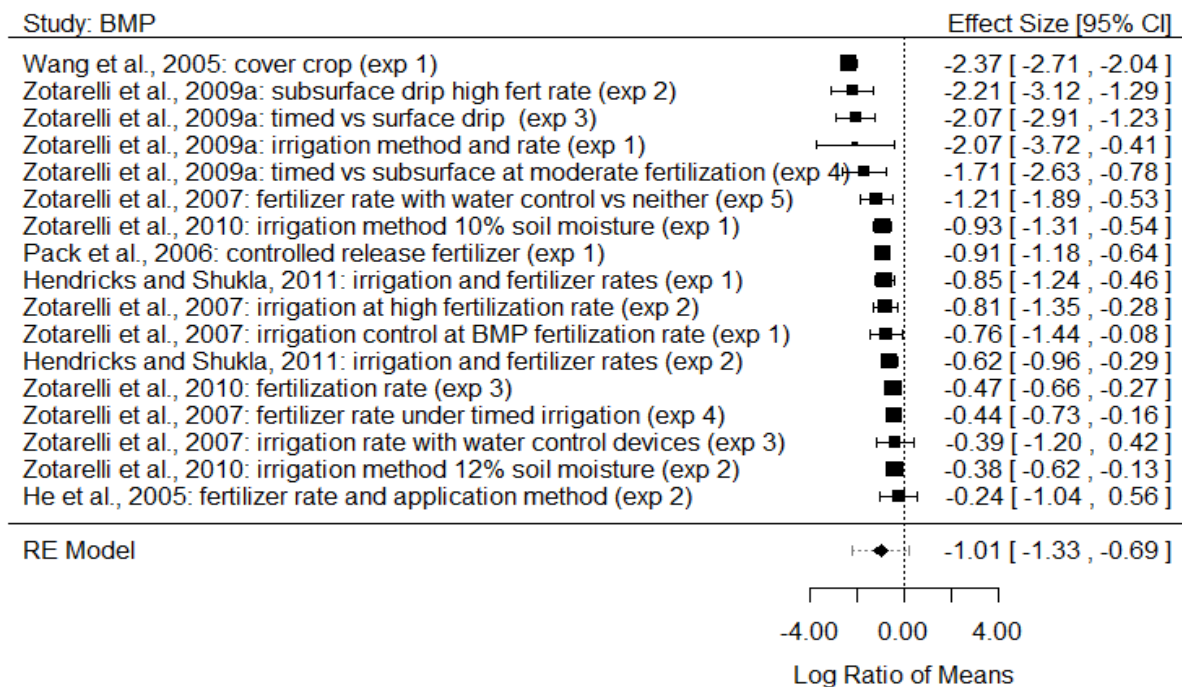


Figure 15. Forest plot of BMP effect size for non-aggregated vegetable crop studies measuring a nitrogen response.

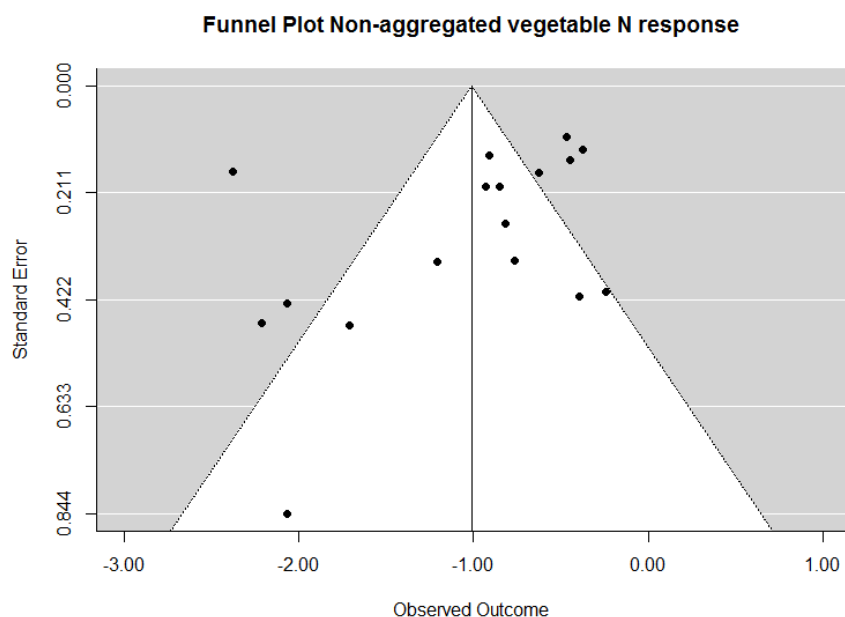


Figure 16. Funnel plot of non-aggregated vegetable crop studies measuring a nitrogen response.

5.4.3.2 Phosphorus

The mean effect size for BMPs implemented on vegetable commodities that measured a phosphorus response was significant (-0.43, with a 95% confidence interval from -0.70 to -0.16) (**Figure 17**). A funnel plot did not show asymmetry of data, and a regression test for funnel plot asymmetry was not significant ($z = -0.27$, $p = 0.79$) (**Figure 18**).

Heterogeneity was not statistically significant ($Q = 8.5$, $df = 4$, $p = 0.08$), but $I^2 = 94.1\%$. Potential moderators that could explain the observed heterogeneity were explored further.

From visual inspection of the forest plot, heterogeneity appears to be due to the degree of BMP effect and differences in effect size confidence intervals, and not the direction of the effect (*i.e.*, the effect size mean for each study demonstrates a reduction in phosphorus). The random effects model assigns weights to studies based on their size. The forest plot does not demonstrate a difference in effect size due to study size, which if present would be indicative of a systematic difference between studies, such as a result of publication bias.

The existence of heterogeneity is suggestive that factors other than solely the implementation of a BMP are influencing the effect estimate. In this meta-analysis, it is likely that methodological diversity accounts for the heterogeneity, and has affected the results of the different studies. Potential moderators that could explain the observed heterogeneity are crop type, specific BMP implemented, and the response units. A mixed effects model that included these moderators was constructed on the non-aggregated means. The I^2 equaled 47.1% for this model, and remaining heterogeneity was not significant ($QE = 7.7$, $df = 4$, $p = 0.10$). A moderator effect was not found to be significant ($QM = 3.99$, $df = 3$, $p = 0.26$).

A forest plot of the random effects model was conducted without aggregation of intra-study comparisons (**Figure 19**) along with an accompanying funnel plot (**Figure 20**). This figure did not specifically demonstrate that one particular BMP was superior to others for reducing phosphorus export from vegetable operations. Of all the individual effect sizes included, wetland treatment and cover crop BMPs had the largest effect size. The variability of the wetland treatment study was very large, however. Comparisons of specific BMPs should be cautiously interpreted as there are other covariates between BMP types, such as study design, crop, and location, and further, the overall number of studies implementing the same BMP in this analysis is low.

Vegetable BMP effects on Phosphorus

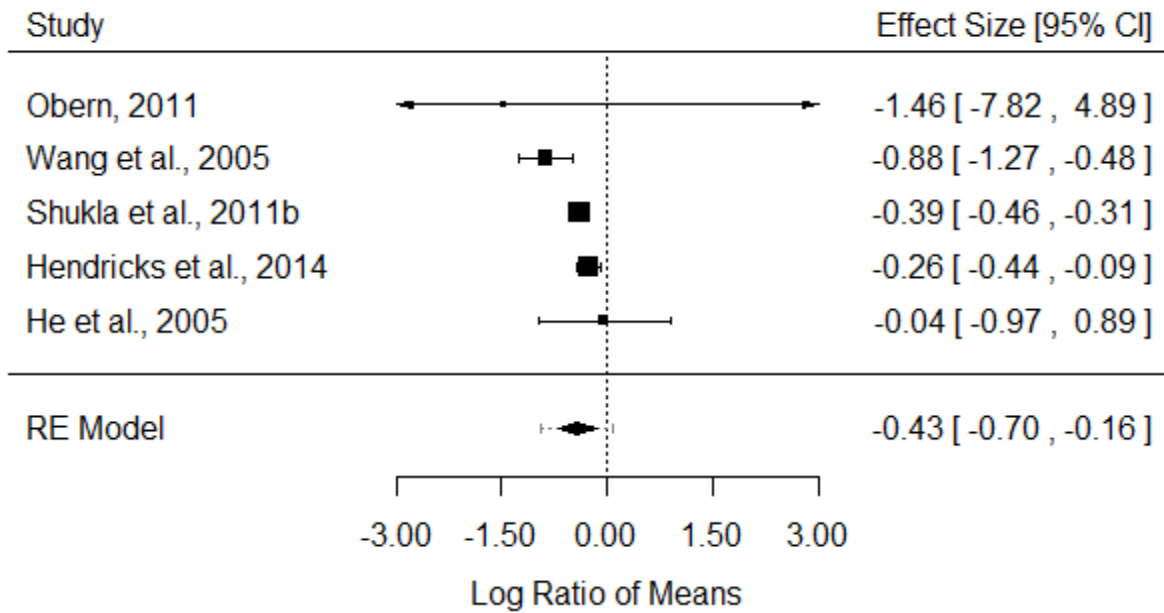


Figure 17. Forest plot of BMP effect size for aggregated vegetable crop studies measuring a phosphorus response.

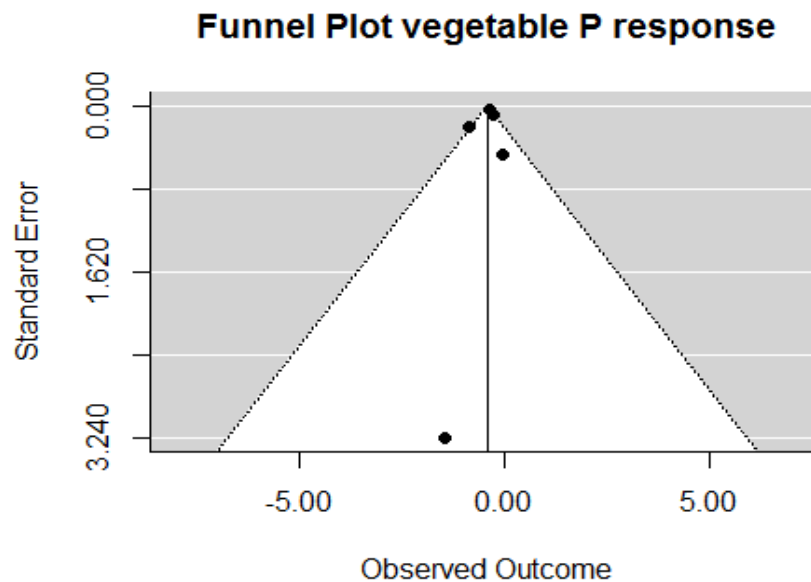


Figure 18. Funnel plot of aggregated vegetable crop studies measuring a phosphorus response.

Vegetable BMP non-aggregated effects on Phosphorus

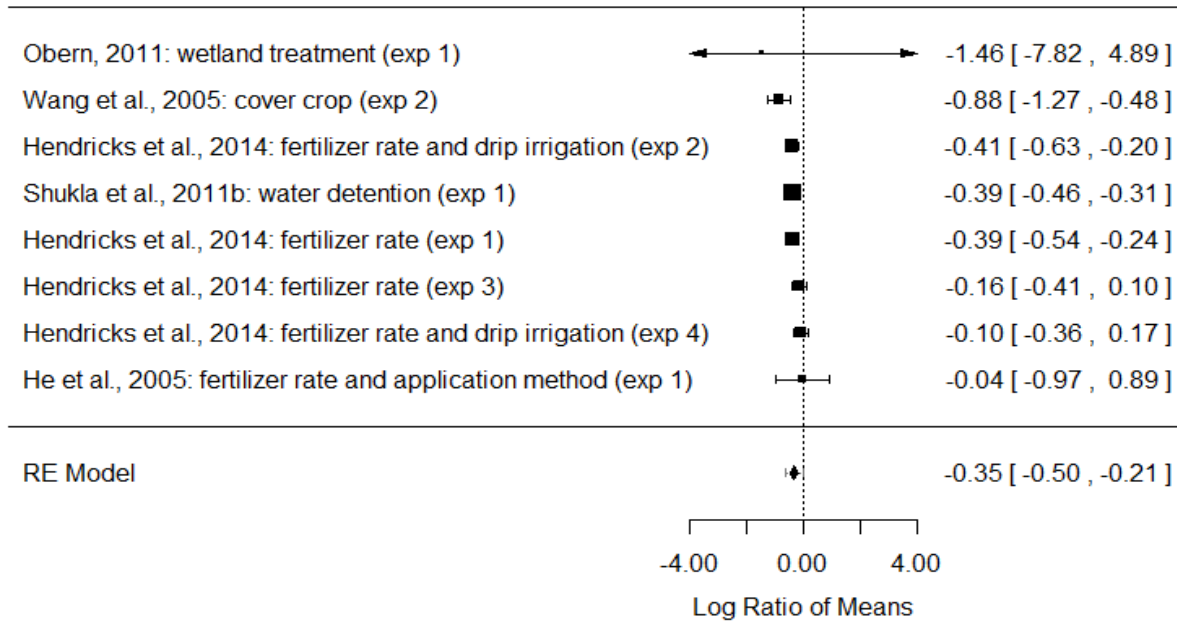


Figure 19. Forest plot of BMP effect size for non-aggregated vegetable crop studies measuring phosphorus as a response.

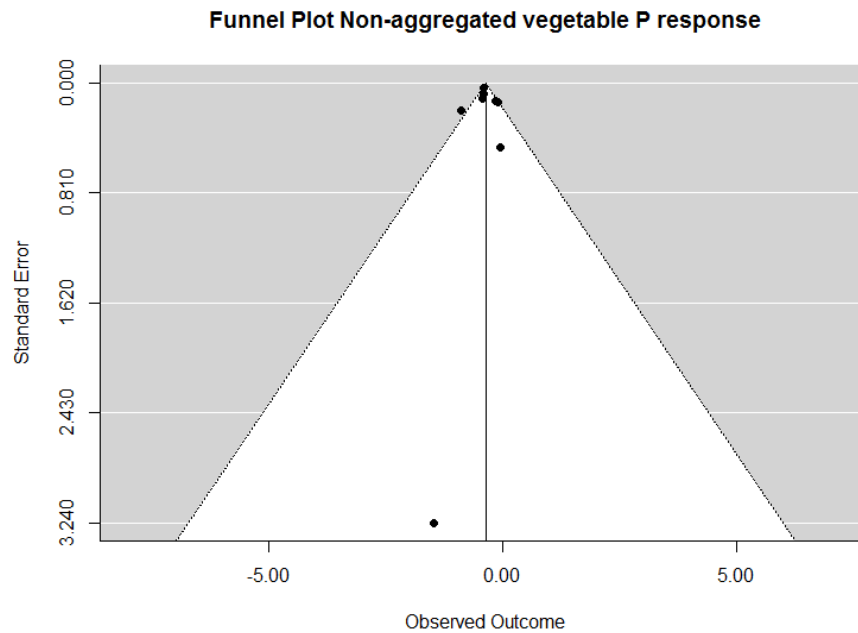


Figure 20. Funnel plot of non-aggregated vegetable crop studies measuring a phosphorus response.

6 DISCUSSION

6.1 EVIDENCE OF EFFECTIVENESS

The meta-analysis results are summarized in **Table 6** and **Table 1**. The meta-analysis of cow/calf BMP effectiveness resulted in no statistically significant effects for either nitrogen or phosphorus. This was likely due to the low number of included studies ($n=4$) and the relatively low absolute value of nutrient concentrations associated with cow/calf operations, compared to other agricultural practices. For example, Capece et al. (2007) found that the TP concentration in the control (non-BMP) treatment averaged a relatively low 0.39 mg/L (± 0.24 SD), remaining relatively constant at 0.40 mg/L (± 0.29 SD) with BMP implementation.

The meta-analysis of agronomic crop BMP effectiveness demonstrated that BMPs provided a significant reduction in nitrogen (equivalent to an **average of 60% reduction** compared to using no BMPs) but no significant reductions in phosphorus. The noteworthy average nitrogen reduction (60%) does not necessarily mean that the nitrogen load entering surface water or groundwater from operations implementing BMPs would always produce no environmental response. For example, Potter et al. (2005), showed that BMPs reduced nitrate that entered groundwater from an average of 5.3 mg/L to 2.8 mg/L. However, groundwater nitrate concentrations of 2.8 mg/L may potentially contribute to eutrophication if leached to springs or other sensitive surface waters. The potential for adverse nutrient effects would be dependent on the dilution and assimilative capacity of the receiving waters, and this determination would benefit from further site-specific evaluation.

The meta-analysis of vegetable crop BMP effectiveness demonstrated that BMPs provided a significant reduction in nitrogen and phosphorus (equivalent to **average reductions of 66% and 35%**, respectively), compared to using no BMPs. Again, these reductions do not necessarily mean that the nutrient loads entering surface water or groundwater from operations implementing BMPs would always produce no environmental response. For example, Hendricks and Shukla (2011) showed that BMPs reduced nitrate that entered groundwater from an average of 28 mg/L to 12 mg/L. However, groundwater nitrate concentrations of 12 mg/L exceed the drinking water quality criterion of 10 mg/L. Because the narrative nutrient criterion (“no imbalances”) is the applicable water quality criterion for surface waters in the region this study took place (Collier County), the potential for adverse nutrient effects would again be dependent on the dilution and assimilative capacity of the receiving waters.

Table 6. Summary of meta-analytical results using the random-effects model.

<i>Commodity</i>	TN Effect Size	TN 95 % CI	Significant?	TP Effect Size	TP 95 % CI	Significant?
<i>Cow/Calf</i>	0.01	-0.12 to 0.14	No	-0.08	-0.4 to 0.23	No
<i>Agronomic Crops</i>	-0.91	-1.72 to -0.1	Yes	0.5	0.0 to 1.01	No
<i>Vegetable Crops</i>	-1.08	-1.6 to -0.5	Yes	-0.43	-0.7 to -0.16	Yes

6.2 REVIEW LIMITATIONS

Meta-analysis is a replicable and scientifically defensible method for synthesizing findings across different studies. It identifies gaps in the research literature, and provides guidance for future research into that area. Most importantly, meta-analysis facilitates the generalization of the knowledge gained through individual studies, which is particularly relevant to policy makers. In addition to these benefits, there are also limitations associated with meta-analysis.

The results and conclusions presented are highly dependent on the studies found and included during the search process. Adherence to strict inclusion/exclusion criteria resulted in a low number of studies, though the included studies tended to be of high quality in terms of experimental design (control vs. impact and BACI studies). Additionally, there is the potential limitation of incomplete retrieval of relevant studies, as an additional exhaustive literature search was not performed. Comparisons between studies are also limited by the original method by which researchers collected and presented their findings. For instance, a mean might be presented where a median is actually more appropriate.

Another difficulty with the results is that not all recommended FDACS BMPs were examined equally and in multiple studies. This limited direct comparison between BMP type for nutrient removal effectiveness, as typically there were overpowering cofactors, such as study design, crop type, and location. Another important limitation is that the absolute nutrient reduction from BMPs was not calculated, as would be done using a standardized mean difference calculation of the overall effect size. Rather, log mean ratios (response ratio) were calculated and used to compare treatments and controls in order to include more studies that reported nutrients in a variety of units. This approach, as described in section 4, is useful for ecological meta-analyses, which tend to have inherent heterogeneity between studies due to the nature of the field (*i.e.* studies are not typically repeated exactly as previously conducted). While this offers several advantages (outlined earlier in section 4), one disadvantage is that the potential environmental effects of the levels of nutrients sampled in the studies can often be overlooked. The calculation of reduction in nutrients is currently limited by the relatively small number of studies available in the literature that meet inclusion criteria, which often report nutrient reductions in multiple ways: concentration (mg/L), load (kg/ha, kg/yr), and location (surface water, groundwater).

6.2.1 Limitations of Meta-Analysis in Ecology

Meta-analysis was first extensively used for synthesizing medical research data. Because of the success in the medical world, meta-analysis has been adapted into the ecological field since 2005. In ecological applications, it is rarely the case that the exact same study has been replicated more than once, as is the case with medical trials. Because of this, there may be some debate on how similar a group of studies must be for a pooled effect size to be meaningful. It is also for this reason that heterogeneity is explored for each calculated effect size (Stewart, 2010). While any synthesis in any field is constrained by the quality and availability of data and the state of the primary literature, the benefits of such a synthesis should not be discounted, particularly for policy makers. An important use of meta-analysis within the field of ecology is to implement evidence-based decision making.

In the case of this report, it was reasoned that by including only studies conducted for the same commodity type within the state of Florida, excessive environmental variance could be minimized. Additionally, the treatment/intervention consisted of adopting any of the FDACS recommended BMPs, which alone (or in combination) should lead to nutrient reductions (which is one of the goals of the BMPs).

7 CONCLUSIONS

The FDACS Best Management Practices are generally “common sense” measures that allow for the optimization of agricultural production while minimizing adverse environmental outcomes. This meta-analysis demonstrated the following:

- There were no statistically significant BMP effects for either nitrogen or phosphorus for the cow/calf operations, likely due to the small number of studies included (four) and relatively low absolute value of nutrients associated with cow/calf operations.
- For agronomic crops, BMPs provided a statistically significant reduction in nitrogen (equivalent to an average of **60% reduction** compared to using no BMPs) but no significant reductions in phosphorus (there were only two agronomic studies that measured a phosphorus response).
- For vegetable crops, BMPs provided statistically significant reductions in both nitrogen and phosphorus (equivalent to average **reductions of 66% and 35%**, respectively), compared to using no BMPs.
- Despite the observed effectiveness of the agronomic and vegetable crop BMPs, further evaluation would be needed to determine if nutrient loads from operations implementing BMPs would be environmentally acceptable on a watershed or springshed scale.
- The results of this meta-analysis could be likely strengthened if data from additional robust studies on Florida agricultural BMPs could be obtained for further analysis.

7.1 IMPLICATIONS FOR MANAGEMENT / POLICY / CONSERVATION

There are several important policy implications from the findings:

- Implementation of BMPs is likely to reduce the level of nutrients reaching the environment from a vegetable or agronomic operation;
- BMPs are effective at reducing high levels of nutrients, depending on the commodity and nutrient type, but BMPs alone may not achieve water quality targets in all situations. Achievement of nutrient thresholds or criteria in downstream waters would likely be dependent on dilution and assimilative capacity of the receiving system;
- Effectiveness of BMPs may decrease as absolute nutrient concentrations decrease; and
- Policy makers and funding agencies need to be clear about the aims of a BMP project, such as desired outcome measures, the desired study design, and minimum reporting requirements for data. This will increase the number of studies included in future systematic reviews.

7.2 IMPLICATIONS FOR RESEARCH

There are also several important implications for future research in this area:

- Studies should ideally be replicated over both time and space (*i.e.*, multiple sites receiving the same treatment measured multiple years);
- Studies should focus on environmental effects of BMP implementation in addition to the impact of BMPs on crop yield and BMP expense;
- Variance of each outcome should always be reported along with a measure of central tendency (*i.e.*, providing a percent reduction without other context is not useful for further meta-analysis). Similarly, the scale over which the variance and central tendency are calculated should be clearly reported (*i.e.*, is variance between plots? treatment types?). Summary and descriptive statistics should be included with a minimum of median, mean, n, standard deviation, and median absolute deviation for treatment and control;
- More research on confounding factors is needed (*i.e.*, does the location where a specific type of BMP is implemented make a large difference in the amount of nutrient reduction achieved?);
- Treatments (BMPs) should be clearly related to the relevant rule language that farmers are required to follow; and
- Nutrient data should be examined for normality through qq plots and the appropriate transformation followed.

8 SOURCES OF SUPPORT AND POTENTIAL CONFLICTS OF INTEREST

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10 APPENDIX A

Searches used for each search engine.

Website	Search	Number of potentially relevant articles (at title level)
https://scholar.google.com Searched on 9/25/15	Florida AND (stream OR water OR groundwater OR leachate) AND (Agronomic OR vegetable OR corn OR peanut OR cotton OR "sugar cane" OR sorghum OR potato* OR strawberr* OR tomato* OR pepper* OR melon* OR cucumber*) AND (BMP OR "best management practice*") AND (nitr* OR phosph*)	8 (all were found to be duplicates)
http://Google.com Searched on 9/25/15	Florida AND (stream OR water OR groundwater OR leachate) AND (Agronomic OR vegetable OR corn OR peanut OR cotton OR "sugar cane" OR sorghum OR potato* OR strawberr* OR tomato* OR pepper* OR melon* OR cucumber*) AND (BMP OR "best management practice*") AND (nitr* OR phosph*)	6 (all were found to be duplicates)

11 APPENDIX B

Quality assessment of studies included.

11.1 Cow/Calf BMP STUDY QUALITY ASSESSMENT

BMP Study Quality Assessment

Citation	County	BMP Intervention	Randomized = 1; Non-randomized = 0	Controlled BACI = 3; Control-Impact = 2; Before-After = 1; No Control = 0	Study >2 years = 2; Study 1 to 2 years = 1; Study < 1 year = 0	Temporal and spatial replication = 2; Replication temporal OR spatial = 1; No replication = 0	Manipulative study = 2; Correlative Study = 1; Sampling study = 0	Total Quality Score
(DeBusk et al., 2013)	Okeechobee	Hybrid chemical and wetland treatment	1	2	1	2	2	8
(Goldstein and Berman, 1995)	Okeechobee	Manure management	1	1	2	1	2	7
(Bohlen and Villapando, 2011)	Okeechobee	Water retention/detention	1	3	1	2	2	9
(Bohlen and	Okeechobee	Water retention/detention	1	3	1	2	2	9

Villapando, 2011)								
(Capece et al., 2007)	Highlands	Stocking rate	1	2	2	2	2	9
(Capece et al., 2007)	Highlands	Stocking rate	1	2	2	2	2	9
(Shukla et al., 2011a)	Okeechobee	Waterway exclusion (culvert crossings and ditch fencing)	1	3	2	1	2	9
(Shukla et al., 2011a)	Okeechobee	Waterway exclusion (culvert crossings and ditch fencing)	1	3	2	1	2	9
(Shukla et al., 2014)	Okeechobee	Water retention/detention	2	3	2	2	2	11
(Shukla et al., 2014)	Okeechobee	Water retention/detention	2	3	2	2	2	11
(Reddy et al., 2007)	Okeechobee	Wetlands Treatment	2	2	1	1	2	8

11.2 AGRONOMIC CROP BMP STUDY QUALITY ASSESSMENT

BMP Study Quality Assessment

Citation	County	BMP Intervention	Randomized = 1; Non-randomized = 0	Controlled BACI = 3; Control-Impact = 2; Before-After = 1; No Control = 0	Study >2 years = 2; Study 1 to 2 years = 1; Study < 1 year = 0	Temporal and spatial replication = 2; replication temporal or spatial = 1; No replication = 0	Manipulative study = 2; Correlative Study = 1; Sampling study = 0	Total Quality Score
(Potter et al., 2005)	Miami-Dade	Cover crop use	1	2	2	2	2	9
(Zotarelli et al., 2008a)	Alachua	Irrigation BMP	1	2	2	2	2	9
(Woodard et al., 2002a)	Suwannee and Gilchrist	Organic, slow release fertilizer use	1	2	2	2	2	9
(Schaffer et al., 2001)	Miami-Dade	Efficient fertilizer application	1	2	1	1	2	7
(Schaffer et al., 2001)	Miami-Dade	Efficient fertilizer application	1	2	1	1	2	7
(IFAS and SRWMD, 2008)	Suwannee and Lafayette	Irrigation and Efficient fertilizer application BMPs	1	2	2	1	2	8
(IFAS and SRWMD, 2008)	Suwannee and Lafayette	Irrigation and Efficient fertilizer application BMPs	1	2	2	1	2	8
(IFAS and SRWMD, 2008)	Suwannee and Lafayette	Irrigation and Efficient fertilizer application BMPs	1	2	2	1	2	8

(IFAS and SRWMD, 2008)	Suwannee and Lafayette	Irrigation and Efficient fertilizer application BMPs	1	2	2	1	2	8
(IFAS and SRWMD, 2008)	Suwannee and Lafayette	Irrigation and Efficient fertilizer application BMPs	1	2	2	1	2	8

11.3 VEGETABLE CROP BMP STUDY QUALITY ASSESSMENT

BMP Study Quality Assessment

Citation	County	BMP Intervention	Randomized = 1; Non-randomized = 0	Controlled BACI = 3; Control-Impact = 2; Before-After = 1; No Control = 0	Study >2 years = 2; Study 1 to 2 years = 1; Study < 1 year = 0	Temporal and spatial replication = 2; replication temporal or spatial = 1; No replication = 0	Manipulative study = 2; Correlative Study = 1; Sampling study = 0	Total Quality Score
(He et al., 2005)	St. Lucie	Efficient fertigation BMP	1	2	2	2	2	9
(He et al., 2005)	St. Lucie	Efficient fertigation BMP	1	2	2	2	2	9
(Hendricks and Shukla, 2011)	Collier	Efficient fertilization BMP	1	2	2	2	2	9
(Hendricks and Shukla, 2011)	Collier	Efficient fertilization and micro-irrigation BMPs	1	2	2	2	2	9

(Zotarelli et al., 2010)	Marion	Tensiometer-controlled irrigation maintained at 10% soil moisture (BMP)	1	2	2	2	2	9
(Zotarelli et al., 2010)	Marion	Tensiometer-controlled irrigation maintained at 12% soil moisture (BMP)	1	2	2	2	2	9
(Zotarelli et al., 2010)	Marion	Efficient fertilization BMP	1	2	2	2	2	9
(Zotarelli et al., 2009a)	Marion	Surface drip irrigation BMP	1	2	2	2	2	9
(Zotarelli et al., 2009a)	Marion	Sub-surface drip irrigation BMP	1	2	2	2	2	9
(Zotarelli et al., 2009a)	Marion	Efficient fertilization and surface drip irrigation BMPs	1	2	2	2	2	9
(Zotarelli et al., 2009a)	Marion	Efficient fertilization and Sub-surface drip irrigation BMP	1	2	2	2	2	9
(Wang et al., 2005)	Miami-Dade	Cover crop use BMP	1	2	0	1	2	6
(Wang et al., 2005)	Miami-Dade	Cover crop use BMP	1	2	0	1	2	6

(Obern, 2011)	Hendry	Optimization of wetland treatment	1	1	1	1	2	6
(Pack et al., 2006)	St. Johns	Controlled release fertilizer use BMP	1	2	0	2	2	7
(Shukla et al., 2011b)	Hendry	Water management BMP	1	2	1	1	2	7
(Hendricks et al., 2014)	Collier	Efficient fertilization BMP	1	2	2	2	2	9
(Hendricks et al., 2014)	Collier	Efficient fertilization and drip irrigation BMPs	1	2	2	2	2	9
(Hendricks et al., 2014)	Collier	Efficient fertilization BMP	1	2	2	2	2	9
(Hendricks et al., 2014)	Collier	Efficient fertilization and drip irrigation BMPs	1	2	2	2	2	9
(Zotarelli et al., 2007)	Marion	Micro-drip irrigation BMP	1	2	0	2	2	7
(Zotarelli et al., 2007)	Marion	Micro-drip irrigation BMP	1	2	0	2	2	7
(Zotarelli et al., 2007)	Marion	Efficient fertilization and micro-drip irrigation BMPs	1	2	0	2	2	7
(Zotarelli et al., 2007)	Marion	Efficient fertilization and micro-drip irrigation BMPs	1	2	0	2	2	7

(Zotarelli et al., 2007)	Marion	Efficient fertilization and micro-drip irrigation BMPs	1	2	0	2	2	7
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12 APPENDIX C

12.1 SUMMARY OF EXTRACTED INFORMATION FOR META-ANALYSIS

A summary of relevant information extracted from each piece of literature is presented by category, including summaries pertinent to each specific BMP recommendation. If there is no literature summary presented under the heading of a specific BMP, that generally means there was no supporting literature found for that recommendation, or that applicable articles were more relevant for another category. While most of the articles did not contain all the components needed for meta-analysis, the findings and conclusions from the studies were still valuable for providing a qualitative to quantitative determination of BMP effectiveness.

A summary of information relevant to cow/calf BMPs is presented in the Appendix, including summaries pertinent to each specific BMP recommendation.

Some studies reported associated means and deviation. Means and deviation were calculated from data present in the following literature:

(Capece et al., 2007; DeBusk et al., 2013; Goldstein and Berman, 1995; He et al., 2005, 2007; IFAS and SRWMD, 2008; Livingston-Way, 2001; Obern, 2011; Pack et al., 2006; Reddy et al., 2007; Schaffer et al., 2001; Shukla et al., 2011b, 2011c, 2014; Wang et al., 2005; Zotarelli et al., 2007, 2009a, 2010)

12.2 Cow/CALF BMPs

Out of all citations reviewed, the following 7 articles met the inclusion criteria for cow/calf operations. Seven studies reported a measure of P and 4 reported a measure of N.

Citation	Commodity/crop, Type of study, BMP	Control mean	Control St. Dev. Or 95% CI or SE	Con n	Treat-ment mean	Treat-ment St. Dev. Or 95% CI or SE	Response variable and units	Treat n
(Bohlen and Villapando, 2011)	Cow/calf in Lake Okeechobee. Study: Control-Impact, partial BACI. BMP: On-ranch water retention/detention to control nutrient loss. Replication: 4 plots control and 4 with water retention, measured water quality 6 times in 2005-2006 at all sites via grab samples. Collected 6 grab samples during flow events in pastures but don't specify if it was 6 per plot, so assume 6 total. Calculation: averages and se taken directly from report. Limitations: Authors mention that pastures with water control structure had significantly lower average annual TN loads before structures installed. They note that magnitude of reduction increased. BACI analysis did not find significant effect from water retention on TP loads.	0.61	0.11 (SE)	6	0.56	0.07 (SE)	TP concentration (mg/L) exiting plots	6
(Bohlen and Villapando, 2011)	Cow/calf in Lake Okeechobee. Study: Control-Impact, partial BACI. BMP: On-ranch water retention/detention to control nutrient loss. Replication: 4 plots control and 4 with water retention, measured water quality 6 times in 2005-2006 at all sites via grab samples. Collected 6 grab samples during flow events in pastures but don't specify if it was 6 per plot, so assume 6 total. Calculation: averages and se taken directly from report. Limitations: Authors mention that pastures with water control structure had significantly lower average annual TN loads before structures installed. They note that magnitude of reduction increased. BACI analysis did not find significant effect from water retention on TP loads.	3.4	0.17 (SE)	6	3.3	0.25 (SE)	TN concentration (mg/L) exiting plots	6
(Capece et al., 2007)	Cow/calf at MacArthur Research Center. Study: Control-Impact. BMP: Stocking rate of cattle. Low level (BMP) was 15 units, high was 35 units (Control) in same area. Replication: 2 replicate plots per treatment, and measured TP in storm water run-off for 6 years.	0.39	0.24	12	0.40	0.29	TP concentration (mg/L) in runoff	12

	Calculation: Data presented as summer and winter mean for each year, and was averaged for all years for an n of 12 (6 years * 2 seasons = 12 data points).							
(Capece et al., 2007)	Cow/calf at MacArthur Research Center. Study: Control-Impact. BMP: Stocking rate of cattle. Low level (BMP) was 15 units, high was 35 units (Control) in same area. Replication: 2 replicate plots per treatment, and measured TKN in storm water run-off for 6 years. Calculation: Data presented as summer and winter mean for each year, and was averaged for all years for an n of 12 (6 years * 2 seasons = 12 data points).	3.32	0.66	12	3.66	1.09	TKN concentration (mg/L) in runoff	12
(Shukla et al., 2011a)	Cow/calf in Okeechobee basin Study: Before-After-Control-Impact BMP: Tested differences in TP in water before vs. after and upstream (control) vs. downstream from the implementation of culvert crossings and ditch fencing BMPs to exclude cattle from the waterway. Replication: 1 cow-calf ranch, measured at main drainage ditch leaving property. Data collected for one pre-BMP summer and 3 post-BMP summers. Calculation: Data presented for post-BMP implementation (3 years of sampling) was averaged for upstream and downstream. N of 1 for before.	281.03	421.53	3	251.87	372.02	TP loading (kg/ha) after BMP implementation	3
(Shukla et al., 2011a)	Cow/calf in Okeechobee basin Study: Before-After-Control-Impact BMP: Tested differences in TP in water before vs. after and upstream (control) vs. downstream from the implementation of culvert crossings and ditch fencing BMPs to exclude cattle from the waterway. Replication: 1 cow-calf ranch, measured at main drainage ditch leaving property. Data collected for one pre-BMP summer and 3 post-BMP summers. Calculation: Data presented for post-BMP implementation (3 years of sampling) was averaged for upstream and downstream. N of 1 for before.	583.57	886.15	3	497.60	745.47	TN loading (kg/ha) after BMP implementation	3
(Shukla et al., 2014)	Cow/calf ranchland in south Florida. Study: Before-After study BMP: Tested differences in TP in water before (control) vs. after implementation of water retention BMP in wetland.	3.02	2.02	5	2.02	2.53	TP loading (kg/ha) after BMP implementation	11

Replication: 2 sites tested, site 1: 3 years pre data, 5 years post. Site 2: 2 years pre data, 6 years post. **Calculation:** Averaged pre for both sites (n=5) and post (n = 11) for both sites.

(Shukla et al., 2014)	Cow/calf ranchland in south Florida.									
	Study: Before-After study BMP: Tested differences in TN in water before (control) vs. after implementation of water retention BMP in wetland. Replication: 2 sites tested, site 1: 3 years pre data, 5 years post. Site 2: 2 years pre data, 6 years post. Calculation: Averaged pre for both sites (n=5) and post (n = 11) for both sites.	7.58	3.97	5	4.51	4.49	TN loading (kg/ha) after BMP implementation	11		

12.3 AGRONOMIC CROP BMPs

A total of 5 studies met inclusion criteria for agronomic crops. Several of these studies reported multiple outcomes, though. In total, 9 measures of N, and 3 measures of P were found for agronomic crops.

Citation	Commodity/crop, Type of study, BMP	Control mean	Control Dev. Or 95% CI or SE	St. Con n	Treat-ment mean	Treat-ment Dev. Or 95% CI or SE	St. Or	Response variable and units	Treat n
(Potter et al., 2005)	Sweet Corn near Homestead FL Study: Random block Control-Impact BMP: Summer cover crop (Sunn hemp) for reducing groundwater nitrate contamination was tested.								
	Replication: 3 control (fallow) plots and 3 test (BMP) plots. Wells under each plot were sampled 63 times over 3 years. Measured pre-bmp and post-bmp Calculation: Report presented summary statistics of cover vs no cover. Limitations: up gradient wells had mean 4.5 nitrate.	5.3	2.2	3	4.8	2.8		Nitrate in groundwater wells (mg/L)	3
(Zotarelli et al., 2008a)	Sweet corn near Gainesville FL Study: Random block Control-Impact. BMP: Compared a 1 day fertilizer residence time in root zone (Control) with a 7 day residence time (irrigation BMP) on nitrate leaching								
	Replication: 4 replicates Calculation: average leaching from fall 2004 and spring 2006 experiments, each with 2 seasons of data, were averaged for an n of 4. Limitations:	267.5	20.5	4	93	11.3		Potential loading of nitrate (kg/ha) to groundwater	4

(Woodard et al., 2002a)	Bermuda grass hay in Middle Suwannee River basin Study: Random block Control-Impact BMP: inorganic nitrogen fertilization (ammonium nitrate) at high N rate (control) and low N rate (BMP) Replication: 2 sites. 4 blocks at site 1 and 3 at site 2. Groundwater was measured in each plot with 2 suction-cup lysimeters 4.7 ft. below surface, sampled every 2 weeks. Averaged over 3 separate years (1999-2001). Calculation: Report presented means of the two locations in each year. For each treatment combination, yearly means were averaged for an n = 3. Limitations: low N. Contrasts not preplanned.	6.1	1.4	3	1.5	1.4	Nitrate (mg/L) in groundwater beneath 3 plots
(Woodard et al., 2002a)	Bermuda grass hay in Middle Suwannee River basin Study: Random block Control-Impact BMP: broiler litter fertilization at high N rate (control) and low N rate (BMP) Replication: 2 sites. 4 blocks at site 1 and 3 at site 2. Groundwater was measured in each plot with 2 suction-cup lysimeters 4.7 ft. below surface, sampled every 2 weeks. Averaged over 3 separate years (1999-2001). Calculation: Report presented means of the two locations in each year. For each treatment combination, yearly means were averaged for an n = 3. Limitations: low N. Contrasts not preplanned.	0.60	0.36	3	0.33	0.26	Nitrate (mg/L) in groundwater beneath 3 plots
(Woodard et al., 2002a)	Bermuda grass hay in Middle Suwannee River basin Study: Random block Control-Impact BMP: broiler litter fertilization at high N rate (BMP) and ammonium nitrate at high N rate (control) Replication: 2 sites. 4 blocks at site 1 and 3 at site 2. Groundwater was measured in each plot with 2 suction-cup lysimeters 4.7 ft. below surface, sampled every 2 weeks. Averaged over 3 separate years (1999-2001). Calculation: Report presented means of the two locations in each year. For each treatment combination, yearly means were averaged for an n = 3. Limitations: low N. Contrasts not preplanned.	6.1	1.4	3	0.6	0.3	Nitrate (mg/L) in groundwater beneath 3 plots
(Woodard et al., 2002a)	Bermuda grass hay in Middle Suwannee River basin Study: Random block Control-Impact BMP: broiler litter fertilization at low N rate (BMP) and ammonium nitrate at low N rate (control) Replication: 2 sites. 4 blocks at site 1 and 3 at site 2. Groundwater was measured in each plot with 2 suction-cup	1.46	1.45	3	0.3	0.26	Nitrate (mg/L) in groundwater beneath 3 plots

lysimeters 4.7 ft. below surface, sampled every 2 weeks.
Averaged over 3 separate years (1999-2001).

Calculation: Report presented means of the two locations in each year. For each treatment combination, yearly means were averaged for an n = 3.

Limitations: low N. Contrasts not preplanned.

(Woodard et al., 2002a)	Bermuda grass hay in Middle Suwannee River basin Study: Random block Control-Impact BMP: broiler litter fertilization at low N rate (BMP) and ammonium nitrate at high N rate (control) Replication: 2 sites. 4 blocks at site 1 and 3 at site 2. Groundwater was measured in each plot with 2 suction-cup lysimeters 4.7 ft. below surface, sampled every 2 weeks. Averaged over 3 separate years (1999-2001). Calculation: Report presented means of the two locations in each year. For each treatment combination, yearly means were averaged for an n = 3. Limitations: low N. Contrasts not preplanned.	6.1	1.4	3	0.3	0.26	Nitrate (mg/L) in groundwater beneath plots	3
(Schaffer et al., 2001)	Corn Study: Random block Control-Impact BMP: Measured nitrate in groundwater under plots, and compared high fertilization control (206 lbs. per acre) with BMP fertilization (181 lbs. per acre). Replication: 1 site measured on 3 dates (April, May and July, 1998). Inflow well water was 1.0 mg/L nitrate. Calculation: Averaged measurements for the three dates presented. Limitations: limited replication/pseudoreplication	2.95	2.72	3	1.36	0.73	Nitrate (mg/L) in groundwater beneath plots	3
(Schaffer et al., 2001)	Corn Study: Random block Control-Impact BMP: Measured TP in groundwater under plots, and compared high fertilization control (206 lbs. per acre) with BMP fertilization (181 lbs. per acre). Replication: 1 site measured on 3 measurements (April, May and July, 1998). Inflow well water was 1.0 mg/L nitrate. Calculation: Averaged measurements for the three dates presented. Limitations: limited replication	0.11	0.16	3	0.21	0.26	TP (mg/L) in groundwater beneath plots	3
(IFAS and SRWMD, 2008)	Corn, peanuts, cotton, potatoes in Suwannee River basin Study: Control-Impact	80.40	35.47	7	78.70	35.60	Nitrate (kg/ha) in soil profile at 2 m depth	7

BMP: Compared conventional “grower” (control) irrigation and fertilizer schedule with BMP recommended irrigation and fertilizer schedule.

Replication: Single site but has 7 years of data

Calculation: yearly averages were used to calculate mean (n = 7 based on yearly averages).

Limitations: Note that soils, not groundwater, is the measured endpoint, making it difficult to determine potential adverse effects off the farm. Control and test site were right next to each other, and test site previously was subject to same conditions as control.

(IFAS and SRWMD, 2008)	Corn, peanuts, cotton, potatoes in Suwannee River basin						Soluble Phosphorus (kg/ha) in soil profile at 2 m depth	Reactive Phosphorus (kg/ha) in soil profile at 2 m depth	4		
	Study: Control-Impact										
	BMP: Compared conventional “grower” (control) irrigation and fertilizer schedule with BMP recommended irrigation and fertilizer schedule.										
	Replication: Single replicate but has 4 years of data										
	Calculation: yearly averages were used to calculate mean (n = 4 based on yearly averages).						0.70	0.33	4	1.41	0.42
	Limitations: Note that soils, not groundwater, is the measured endpoint, making it difficult to determine potential adverse effects off the farm. Control and test site were right next to each other, and test site previously was subject to same conditions as control.										
(IFAS and SRWMD, 2008)	Corn, peanuts, cotton, potatoes in Suwannee River basin						Nitrate groundwater plots	(mg/L) below	7		
	Study: Control-Impact										
	BMP: Compared conventional “grower” (control) irrigation and fertilizer schedule with BMP recommended irrigation and fertilizer schedule.										
	Replication: Single replicate but has 7 years of data										
	Calculation: yearly averages were used to calculate mean (n = 7 based on yearly averages).						28.89	2.45	7	24.80	1.17
	Limitations: Control and test site were right next to each other, and test site previously was subject to same conditions as control. Note that nitrate in BMP treatment is still a high absolute value, well above threshold.										
(IFAS and SRWMD, 2008)	Corn, peanuts, cotton, potatoes in Suwannee River basin						Nitrate shallow groundwater plots	(mg/L) (2 m) below	6		
	Study: Control-Impact										
	BMP: Compared conventional “grower” (control) irrigation and fertilizer schedule with BMP recommended irrigation and fertilizer schedule.										
	Replication: Single replicate but has 7 years of data										
	Calculation: yearly averages were used to calculate mean (n = 7 based on yearly averages).						37.05	14.82	6	38.72	14.21
	Limitations: Control and test site were right next to each other, and test site previously was subject to same conditions as control. Note that nitrate in BMP treatment is still a high absolute value, well above threshold.										

Calculation: yearly averages were used to calculate mean (n = 7 based on yearly averages).

Limitations: Control and test site were right next to each other, and test site previously was subject to same conditions as control. Note that nitrate in BMP treatment is still a high absolute value, well above threshold

(IFAS and SRWMD, 2008)	Corn, peanuts, cotton, potatoes in Suwannee River basin									
	Study: Control-Impact BMP: Compared conventional “grower” (control) irrigation and fertilizer schedule with BMP recommended irrigation and fertilizer schedule. Replication: Single replicate but has 6 years of data Calculation: yearly averages were used to calculate mean (n = 6 based on yearly averages). Limitations: Control and test site were right next to each other, and test site previously was subject to same conditions as control. Note that nitrate in BMP treatment is still a high absolute value, well above threshold	0.03	0.01	6	0.04	0.03	Soluble Phosphorus (mg/L) in shallow groundwater plots	Reactive Phosphorus (mg/L) in 2 m below plots	6	

12.4 VEGETABLE CROP BMPs

A total of 19 studies met inclusion criteria for vegetable crops. Several of these studies reported multiple outcomes, though. In total, 9 measures of N, and 3 measures of P were found for agronomic crops.

Citation	Commodity/crop, Type of study, BMP	Control mean	Control St. Dev. Or 95% CI or SE	Con n	Treat-ment mean	Treat-ment St. Dev. Or 95% CI or SE	Response and units	variable	Treat n
(He et al., 2005)	Vegetables in the Indian River lagoon Study: Random block Control-Impact BMP: Effect of fertigation and fertilizer amount in reducing surface water runoff were tested. Replication: 2 farms. 4 “grower” (control) sites and 4 “BMP” sites, with discharge water from sites measured via auto-samplers. 5 years of data collected, consisting of 1599 water samples. Calculation: study presented annual average BMP and Con by year (5 years) for each site. Limitations: Missing data for some site-year combos, only used paired data.	5.8	4.35	6	5.55	4.92	TP load to surface water (kg/ha)		6
(He et al., 2005)	Vegetables in the Indian River lagoon Study: Random block Control-Impact	1.27	1.00	6	1.00	0.61	Nitrate load to surface water (kg/ha)		6

BMP: Effect of fertigation and fertilizer BMPs in reducing surface water runoff were tested

Replication: 2 farms. 4 “grower” (control) sites and 4 “BMP” sites, with discharge water from sites measured via auto-samplers. 5 years of data collected, consisting of 1599 water samples.

Calculation: study presented annual average BMP and Con by year (5 years) for each site in g/ha load (also in concentration but did not use). Missing data for some sites, only used paired data. Converted to kg/ha.

Limitations: Missing data for some site-year combos, only used paired data.

(Hendricks and Shukla, 2011)	Vegetables (watermelon, tomatoes). Flatwoods in South Florida Study: Random block Control-Impact, BMP: Compared high fertilization/seepage irrigation with BMP recommended fertilizer/seepage irrigation Replication: 6 hydrologically isolated plots total. 2 plots per treatment. Calculation: Reported mean and se in shallow groundwater in paper. Limitations: Hurricane Wilma impacted the study site in Oct 2005, delivering high rainfall. Both treatments used seepage irrigation.	28	3 (SE)	2	12	2 (SE)	Nitrate concentration in shallow groundwater (mg/L)	2
(Hendricks and Shukla, 2011)	Vegetables (watermelon, tomatoes), Study: Random block Control-Impact BMP: Compared high fertilization/seepage irrigation with BMP recommended fertilizer/micro-drip irrigation Replication: 6 hydrologically isolated plots total. 2 plots per treatment. Calculation: Reported mean and se in shallow groundwater in paper. Limitations: Hurricane Wilma impacted the study site in Oct 2005, delivering high rainfall. Both treatments used seepage irrigation.	28	3 (SE)	2	15	2 (SE)	Nitrate concentration in shallow groundwater (mg/L)	2
(Zotarelli et al., 2010)	Vegetables (bell pepper) near Citra, FL Study: random block Control-Impact BMP: Test difference between timed irrigation (control) and tensiometer-controlled irrigation maintained at 10% soil moisture (BMP). Replication: Groundwater under plots measured for 3 years. Calculation: Weekly sampling of lysimeter leachate was presented as total NO3 leached per year for each main effect. Three years were averaged for a mean and used for variability. Limitations: not set up as a contrast before experiment was performed.	42.67	4.27	3	16.90	5.55	Cumulative Nitrate loading leached to groundwater (kg/ha)	3
(Zotarelli et al., 2010)	Vegetables (bell pepper) near Citra, FL Study: random block Control-Impact BMP: Test difference between timed irrigation (control) and tensiometer-controlled irrigation maintained at 12% soil moisture. Replication: Groundwater under plots measured for 3 years.	42.67	4.27	3	29.27	5.60	Cumulative Nitrate loading leached to groundwater (kg/ha)	3

	Calculation: Weekly sampling of lysimeter leachate was presented as total NO₃ leached per year for each main effect. Three years were averaged for a mean and used for variability. Limitations: not set up as a contrast before experiment was performed.								
(Zotarelli et al., 2010)	Vegetables (bell pepper) near Citra, FL Study: random block Control-Impact BMP: Test difference between high fertilization (control, 330) and moderate fertilization (220). Replication: Groundwater under plots measured for 3 years. Calculation: Weekly sampling of lysimeter leachate was presented as total NO₃ leached per year for each main effect. Three years were averaged for a mean and used for variability. Limitations: not set up as a contrast before experiment was performed.	37.53	1.78	3	23.53	3.93	Cumulative loading to groundwater (kg/ha)	Nitrate leached to groundwater (kg/ha)	3
(Zotarelli et al., 2009a)	Vegetables (tomato), near Citra FL Study: random block Control-Impact, BMP: Tested difference between timed irrigation/high fertilization (control) with surface drip irrigation and same high fertilizer regime. Replication: Groundwater under plots measured for 3 years. Yearly average for each treatment presented. Calculation: Data presented as yearly average for each treatment. Three years were averaged for mean and deviation. Limitations: not set up as a contrast before experiment was performed. Used two drip lines, but growers usually uses one drip line	40.30	27.36	3	5.10	1.71	Cumulative load to groundwater (kg/ha)	Nitrate leached to groundwater (kg/ha)	3
(Zotarelli et al., 2009a)	Vegetables (tomato), near Citra FL Study: random block Control-Impact BMP: Tested difference between timed irrigation/high fertilization (control) with sub-surface drip irrigation and same high fertilizer regime. Replication: Groundwater under plots measured for 3 years. Data presented as yearly average for each treatment. Calculation: Three years were averaged for mean and deviation. Limitations: not set up as a contrast before experiment was performed. Used two drip lines, but growers usually uses one drip line	40.30	27.36	3	4.43	1.95	Cumulative load to groundwater (kg/ha)	Nitrate leached to groundwater (kg/ha)	3
(Zotarelli et al., 2009a)	Vegetables (tomato) near Citra FL Study: random block Control-Impact, BMP: Tested difference between timed irrigation/moderate fertilization (control) with surface drip irrigation and same moderate fertilizer regime. Replication: Groundwater under plots measured for 3 years. Data presented as yearly average for each treatment. Calculation: Three years were averaged for mean and deviation. Limitations: not set up as a contrast before experiment was performed. Used two drip lines, but growers usually uses one drip line	20.80	15.24	3	2.63	0.35	Cumulative load to groundwater (kg/ha)	Nitrate leached to groundwater (kg/ha)	3

(Zotarelli et al., 2009a)	Vegetables (tomato), near Citra FL Study: random block Control-Impact, BMP: Tested difference between timed irrigation/ moderate fertilization (control) with sub-surface drip irrigation and same moderate fertilizer regime. Replication: Groundwater under plots measured for 3 years. Data presented as yearly average for each treatment. Calculation: Three years were averaged for mean and deviation. Limitations: not set up as a contrast before experiment was performed. Used two drip lines, but growers usually uses one drip line	20.80	15.24	3	3.77	1.37	Cumulative Nitrate load leached to groundwater (kg/ha)	3
(Wang et al., 2005)	Vegetables, Study: random block Control-Impact BMP: Tested difference between nitrate leaching between fallow (control) and pots with cover crops (Sunn hemp, cowpea, velvet bean, and sorghum) Replication: 4 replicates of each plant type. Collected leachate once per week. Calculation: Presented the average concentration of N and P in leachates across all sampling dates from pots with fallow and cover crops. 4 different cover crop averages, n=4. One fallow average presented. Limitations: conducted in pots, not in a field.	16.1	0	1	1.5	0.51	Nitrate load leached (kg/ha)	4
(Wang et al., 2005)	Vegetables, Study: random block Control-Impact BMP: Tested difference between nitrate leaching between fallow (control) and pots with cover crops (Sunn hemp, cowpea, velvet bean, and sorghum) Replication: 4 replicates of each plant type. Collected leachate once per week. Calculation: Presented the average concentration of N and P in leachates across all sampling dates from pots with fallow and cover crops. 4 different cover crop averages, n=4. One fallow average presented. Limitations: conducted in pots, not in a field.	0.12	0	1	0.05	0.02	Soluble P load leached (kg/ha)	4
(Obern, 2011)	Vegetables, Study: Before-After BMP: Tested effect of optimization of wetland treatment via creation of cells and increased hydraulic retention time. Replication: 377 (mostly daily) water quality measurements. N of 360 for inflow, N = 376 for outflow. Calculation: Daily data was averaged and standard deviation was taken. Limitations: There is a much higher n (temporally) in this study than the n that can be calculated for other studies. Because the n is so high for this study (replication over time), it might have a very large effect on the	21.97	67.87	1	5.08	4.97	Daily loading of TP (kg) into vs. out of wetland treatment	1

overall meta-analysis if time is treated as the unit for replication. Using spatial replication, there is an n of 1.

(Pack et al., 2006)	Potatoes Study: random block Control-Impact, BMP: Tested differences in nitrate leaching between conventional inorganic fertilizer use (control, ammonium nitrate, applications at 146 and 225 kg/ha) and eighteen Controlled Release Fertilizer formulations (urea-based, also applied at 146 and 225 kg/ha). Replication: Shallow groundwater measured 5 times per treatment, between 39 to 95 days after planting). Calculation: Averaged ammonium nitrate (both rates) across 5 days for n = 10. Did the same for CRFs (9 types, 2 rates) for n=90. Limitations: not separating out rate variable. Unbalanced size between control and treatment. High n might influence meta-analysis more than is appropriate.	46.36	19.12	10	18.72	7.63	Nitrate (mg/L) in shallow (30 cm) groundwater below plots 90
(Shukla et al., 2011b)	Vegetables farm near Clewiston, FL. Study: control-treatment (inflow-outflow) BMP: water impoundment aimed at reducing P runoff Replication: pump one = 429, pump 2 = 176, pump 3 = 448, discharge = 857. Calculation: Presented averages and standard deviation for TP load (kg) for pumps 1-3 and discharge. The TP in pumps 1, 2, and 3 were combined for total input, and the discharge was used for output. Limitations: Farm divided into drainage basins, pumps groundwater for irrigation. Might not be easy to implement in other places. Large sample size compared to other studies because many data points, but only 1 year long.	542.3	610.8	1053	368	148	TP in inflow and outflow water of wetland/water holding area (µg/L) 857
(Hendricks et al., 2014)	Watermelon and tomatoes, Study: random block Control-Impact, BMP: Tested differences in phosphorus leaching in groundwater between conventional farmer fertilizer application rate (control) and recommended fertilizer application rate (BMP). Replication: Shallow groundwater above the spodic horizon measured weekly over 3 years. 2 replicate plots Calculation: Article presented mean and standard error, did not specify n. Limitations: n was assumed to be 2 based on 2 replicate plots. No information on weekly data, only see means presented.	3090	175 (SE)	2	2098	107 (SE)	TP (µg/L) in shallow groundwater above the spodic horizon 2
(Hendricks et al., 2014)	Watermelon and tomatoes, Study: random block Control-Impact, BMP: Tested differences in phosphorus leaching in groundwater between conventional farmer fertilizer application rate (control) and	3090	175 (SE)	2	2048	192(SE)	TP (µg/L) in shallow groundwater above the spodic horizon 2

	recommended fertilizer application rate, coupled with drip irrigation (BMPs). Replication: Shallow groundwater above the spodic horizon measured weekly over 3 years, 2 replicate plots Calculation: Article presented mean and standard error, did not specify n. Limitations: n was assumed to be 2 based on 2 replicate plots. No information on weekly data, only see means presented.						
(Hendricks et al., 2014)	Watermelon and tomatoes, Study: random block Control-Impact, BMP: Tested differences in phosphorus leaching in groundwater between conventional farmer fertilizer application rate (control) and recommended fertilizer application rate (BMP). Replication: Deeper groundwater below the spodic horizon measured weekly over 3 years, 2 replicate plots Calculation: Article presented mean and standard error, did not specify n. Limitations: n was assumed to be 2 based on 2 replicate plots. No information on weekly data, only see means presented.	1302	141 (SE)	2	1115	79 (SE)	TP (µg/L) in groundwater below the spodic horizon 2
(Hendricks et al., 2014)	Watermelon and tomatoes, Study: random block Control-Impact, BMP: Tested differences in phosphorus leaching in groundwater between conventional farmer fertilizer application rate (control) and recommended fertilizer application rate, coupled with drip irrigation (BMPs). Replication: Deeper groundwater below the spodic horizon measured weekly over 3 years, 2 replicate plots Calculation: Article presented mean and standard error, did not specify n. Limitations: n was assumed to be 2 based on 2 replicate plots. No information on weekly data, only see means presented.	1302	141 (SE)	2	1181	97(SE)	TP (µg/L) in groundwater below the spodic horizon 2
(Zotarelli et al., 2007)	Peppers, tomato, zucchini Study: random block Control-Impact BMP: Water control devices (BMP) vs timed irrigation at 1.0 IFAS fertilizer Replication: 3 crop varieties, each with a lysimeter and soil core measurement (n = 6 per treatment) Calculation: The reported mean from lysimeters and shallow (core) wells were averaged and used for variance calculation. Limitations: combined lysimeter and soil core measurements, did not included ceramic suction cups because authors stated they were problematic for consistency. Comparisons not preplanned.	30.4	7.5	6	14.2	11.5	Nitrate (kg/ha) in groundwater below plots 6

(Zotarelli et al., 2007)	Peppers, tomato, zucchini Study: random block Control-Impact BMP: Water control devices (BMP) vs timed irrigation at 1.5 IFAS fertilization rate. Replication: 3 crop varieties, each with a lysimeter and soil core measurement (n = 6 per treatment) Calculation: The reported mean from lysimeters and shallow (core) wells were averaged and used for variance calculation. Limitations: Combined lysimeter and soil core measurements, did not included ceramic suction cups because authors stated they were problematic for consistency. Comparisons not preplanned.	47.4	12.2	6	21	12.9	Nitrate (kg/ha) in groundwater below 6 plots
(Zotarelli et al., 2007)	Peppers, tomato, zucchini Study: random block Control-Impact BMP: IFAS recommended fertilizer (1.0) vs 1.5 times IFAS with use of water control devices Replication: 3 crop varieties, each with a lysimeter and soil core measurement (n = 6 per treatment) Calculation: The reported mean from lysimeters and shallow (core) wells were averaged and used for variance calculation. Limitations: combined lysimeter and soil core measurements, did not included ceramic suction cups because authors stated they were problematic for consistency. Comparisons not preplanned.	21	12.9	6	14.2	11.5	Nitrate (kg/ha) in groundwater below 6 plots
(Zotarelli et al., 2007)	Peppers, tomato, zucchini Study: random block Control-Impact BMP: IFAS recommended fertilizer (1.0) vs 1.5 times IFAS with timed irrigation Replication: 3 crop varieties, each with a lysimeter and soil core measurement (n = 6 per treatment) Calculation: The reported mean from lysimeters and shallow (core) wells were averaged and used for variance calculation. Limitations: combined lysimeter and soil core measurements, did not included ceramic suction cups because authors stated they were problematic for consistency. Comparisons not preplanned.	47.4	12.2	6	30.4	7.5	Nitrate (kg/ha) in groundwater below 6 plots
(Zotarelli et al., 2007)	Peppers, tomato, zucchini Study: random block Control-Impact BMP: IFAS recommended fertilizer (1.0) with water control devices vs 1.5 times IFAS with timed irrigation Replication: 3 crop varieties, each with a lysimeter and soil core measurement (n = 6 per treatment) Calculation: The reported mean from lysimeters and shallow (core) wells were averaged and used for variance calculation.	47.4	12.2	6	14.2	11.5	Nitrate (kg/ha) in groundwater below 6 plots

Limitations: combined lysimeter and soil core measurements, did not include ceramic suction cups because authors stated they were problematic for consistency. Comparisons not preplanned.

13 APPENDIX D

This section contains a summary of each article examined by Frydenborg Ecologic pertinent to cow/calf, vegetable crops, and agronomic crop BMPs. The full document is also available (Frydenborg and Frydenborg, 2014).

13.1 COW/CALF GENERAL BMP FINDINGS AND OUTCOMES

An algal bioreactor was designed to remove nutrients from manure and produce high protein algal feed for cows. Three replicate bioreactors and 3 sources of manure were used. TN removed from 3 manure sources was 0.27 g/m²/day, 0.26 g/m²/day, and 0.39 g/m²/day. Standard Deviation for the 3 respective manure sources was plus or minus 0.76, 0.108 and 0.92, respectively. TP removed using the algal bioreactors was 0.11 g/m²/day, 0.08 g/m²/day and 0.08 g/m²/day, respectively. Standard Deviation for TP removal was plus or minus 0.031, 0.033, and 0.019, respectively. Was not used for meta-analysis because the BMP is not one listed by FDACS (Wilkie and Mulbry, 2002).

Van Horn et al. (1994) provided a general discussion on managing dairy manure to prevent receiving water issues through composting and reuse on fields at a proper loading rate, as well as a discussion on the benefits of energy recovery from the organic matter.

Macon et al. (2002) tested different cropping systems for utilization of dairy waste effluent and found that the different systems had an impact on forage yield and nutritive value, but N rates above 450 kg/ha had little effect on these responses (Macon et al., 2002).

Sigua et al. (2006) concluded that the 39 kg/ha/yr of P fertilization in 4 Hernando County pastures was not associated with either soil TP increases or eutrophication in adjacent lakes.

Shukla et al. (2014) concluded that water retention BMPs on ranchlands could not always be assumed to result in reduced nutrient loads. Study results were mixed, with a 30% reduction in flow and 20% reduction in TP loads at one site with a large wetland, while at another site with a smaller wetland (closer to the typical of pastures in the Lake Okechobee basin), the flows and TP loads **increased** by almost 20% and 45%, respectively. The water retention BMP involves interaction of surface and subsurface water and nutrient processes, which when combined with climatic variability, uncertainty in measurements, and unequal number of pre- and post-BMP periods, made it difficult to detect statistically significant changes and/or attribute the changes in flow and nutrient loads to the BMP alone (Shukla et al., 2014).

Botcher (1995) studied approaches for BMPs for reducing N and P discharged from dairies and concluded: the N and P content of lactating cow manure was found to be higher than literature design values; lactating cows will defecate about 12 and urinate about 8 times a day with the urination frequency increasing during warmer weather; lactating cows were found to defecate and urinate at about the same frequency throughout the dairy, thus giving credence to the assumption that the of N and P are lost in the sand trap and a storage pond with a short detention time (about 4 days); most of the N lost in a short detention time (less than 7 days) waste storage system is after land application of spray effluent, with total N losses being greater than 40 percent; phosphorus is more conservative and moves through the waste management system to the sprayfield with minimal losses (less than 5 percent); atmospheric (volatilization) losses of N from raw feces appear to be small over the first 30 days after deposition, but

high variability in the data limited conclusions; atmospheric (volatilization) losses of N from urine were extremely high for both soil (91 percent for 30-day N loss) and hard surface (97 percent 30-day N loss) deposition areas. Nearly half of these losses occurred within 24 hours; the majority of atmospheric losses will occur within 30 days of land application because the nitrification process will have converted the majority of the remaining ammonia by this time; and use of N: P ratios for the soil-matrix volatilization pans (SVPs) is unreliable and should be re-evaluated for future studies (Bother 1995).

An animal confinement facility BMP was implemented to eliminate manure deposits from milk herd pastures by confining animals, and it was found that use of the facility reduced phosphorus in off-farm surface discharge and increased efficiency of milk production (Goldstein and Berman, 1995).

The annual net groundwater loading from a cattle operation to a drainage ditch (ultimately discharging to Lake Okeechobee) ranged from 0.1 kg to 0.2 kg TP and 2.1 kg to 4.5 kg TN, and the authors concluded that groundwater was a major contributor of TP to Lake Okeechobee (Goswami et al., 2012).

Although improperly managed waste from dairy farms can create nitrate enrichment in groundwater, recommended cost-effective BMPs to help mitigate these effects include construction of lined or unlined lagoon/waste ponds, cooling feed barns (with fans), use of a waste irrigation system, and use of solids separators (Holloway et al., 1996).

Most phosphorus fed to dairy cows is excreted in the feces and milk, and authors recommended lowest optimal P diet to reduce runoff and downstream eutrophication in Lake Okeechobee (Morse et al., 1992). Feeding a lower amount of P in feed did not affect milk quality or yield but resulted in 35% less P in manure (Sharpley et al., 2006).

Nordstedt et al. (1998) demonstrated that cow manure could be transformed into an exportable composted product through the addition of bulk organic carbon (e.g., sawdust, peanut hulls, yard waste, pine bark) to achieve a moisture content of 70%. The microbially regulated operating temperatures for producing a good quality compost was 130 to 150 degrees F. Composting reduces odors and fly breeding potential, stabilizes the material, and produces an economically exportable product (Nordstedt et al., 1998).

Leader et al. (2005) operated eighteen wastewater treatment systems for one year to investigate phosphorus (P) removal. The treatment systems consisted of paired co-treatment reactors containing iron or calcium drinking water treatment residuals with vertical-flow constructed wetland mesocosms planted with bulrush (*Schoenoplectus tabernaemontani*). For secondary municipal wastewater, TP concentrations were reduced up to 95%. For anaerobically digested dairy wastewater, TP was reduced by 53%.

A computer model was developed to evaluate various pasture nutrient management scenarios, with cattle stocking densities adjusted to conform to forage nutrient uptake requirements. The fertilizer and manure applied to pastures were adjusted to minimize N and P export. The nitrogen-based option resulted in a 3% profit increase, while the P option resulted in 6 to 18% decline in profits (Osei et al., 2003).

Alum or ferric chloride significantly reduced TP in cow manure flush water to very low levels, but the economics of the treatment are not favorable (Sherman et al., 2000).

The MacArthur Agro-ecology Research Center (2004) tested the effect of cattle stocking rates (0, 3.7, 6.5, 8.6 acres/cow) on nutrient loads in surface runoff and found that stocking rates did not influence the amount of P or N, but that P was much higher in summer (when pastures were fertilized at 56 kg N/ha,

unlike winter). P loads were 5-7 times greater during summer than winter, and N loads tended to be greater for improved summer pastures as well. Based on these results, the authors concluded that cattle stocking rates are not an effective BMP, and BMPs should instead focus on preventing P accumulation and/or loss of accumulated P (Bohlen et al., 2004).

Bohlen et al. (2009) evaluated the feasibility of on-ranch water retention/detention to control P loss and found that water retention primarily reduced TKN, not TP, but that P did accumulate in the soils of pastures with control structures (Bohlen et al., 2009).

Pandey et al. (2006) assessed the accuracy of two computer models for Lake Okeechobee basin nutrient fluxes from cattle operations. Runoff was over-predicted by WAMView at all the sites, whereas ACRU2000 over-predicted runoff at some sites. With ACRU2000, the nutrient predictions followed the runoff predictions, with some exceptions, where the WAMView model under predicted TP at all the sites and over-predicted TN at some sites (Pandey et al., 2006).

Reddy et al. (2012) concluded that management of vegetation and hydrology were the key to long-term accretion of P, N, and C in isolated wetlands, that stability of soil P is linked to the stability of soil organic matter, and that management strategies that will increase the proportion non-reactive pools of P need to be explored. The authors were uncertain if plant uptake of P from soil and potential for litter mineralization and leaching was offset by increased P accretion in organic matter deposition when compared to grazing effects on biomass and P lability (Reddy et al., 2012).

Shukla et al. (2011b) assessed two BMPs (ditch fencing/culvert crossing, wetland water retention) for a cow-calf operation in The Lake Okeechobee basin. TN loads downstream were sometimes lower post-BMP but sometimes higher, depending on the distance downstream. TP reductions post-BMP were statistically significant. Results from the wetland water retention as a BMP were inconsistent (Shukla et al., 2011c).

13.1.1 Nutrient Management

13.1.1.1 Using UF/IFAS recommended fertilization rates

Nitrate in wells beneath Bermuda grass fields receiving IFAS recommended fertilizer rate (nitrogen additions of 100 lbs/acre/growth interval) generally averaged between 3 and 6 mg/L, although nitrate values up to 40 mg/L were observed (using lysimeters) within 5 feet of the surface. These high values appeared to be diluted with other lower nitrate groundwater, resulting in the 3-6 mg/L range observed in the wells (Sollenberger et al., 2006).

The University of Florida Institute for Food and Agricultural Sciences (IFAS) recommended 80 lbs N/acre/growth period for Bermuda grass, and concluded that at a 75 lbs N/acre/growth period application rate, nitrate in groundwater below the fields was less than 10 mg/L (Woodard et al., 2002a). During the time of the study, DACS recommended 100 lbs N/acre/growth period for Bermuda grass.

13.1.1.2 Utilizing soil and tissue tests for pH and nutrient analysis

Spodosols with low Fe and Al concentrations have limited P retention capability, demonstrating the importance of soil testing to determine the amount of P applied that would result in P release to the environment (Chakraborty et al., 2011).

Silveira et al. (2010) concluded that the role of phosphorus in agricultural/environmental interactions is complex and must be addressed, recommending proper nutrient and pasture management.

Lake Okeechobee basin soils had had negative soil P storage capacity at the surface and had a high equilibrium P concentration, and the authors concluded that neither wetland nor upland soils could safely sequester additional P, and that the surface soils were a potential source of P (Bhadha et al., 2010).

Phosphorus held in the Bh (spodic) horizon is a significant source of phosphorus for plants, meaning no additional P is needed for optimum Bahia grass growth on spodosols (Obour et al., 2011).

13.1.1.3 Appropriately storing fertilizer, as well as chemicals

13.1.1.4 Establishing and maintaining vegetative buffer strips to filter runoff before entering waterbodies

A study examining soils collected at the surface (0-10 cm) in wetlands and surrounding uplands associated with a cow-calf pasture concluded that the hydroperiod should be increased to retain more P, that soils should remain wet to decrease P release, and that there was a significant relationship between P release from uplands and the corresponding nutrient content (Dunne et al., 2010).

Surface soils were found to be the largest reservoir for P in the Lake Okeechobee basin, and the authors concluded that P storage would increase if the accumulation of soil organic matter in wetland soils was increased (Dunne et al., 2007).

Newton et al. (2003) found that riparian vegetated buffers removed 78% of nitrate and 66% of TP and that recycling manure to produce forage allows reduction in nutrient runoff and is economically beneficial. N and P recoveries were greatest in a corn silage/Bermuda grass hay/rye haylage system. Bermuda grass was more effective at nutrient uptake during the autumn-winter than was corn (Newton et al., 2003).

Rechcigl et al. (2002) found that Star grass on Immokalee fine sand does not need any P fertilization, that P fertilization is positively correlated with P runoff, and that addition of lime or gypsum did not significantly reduce P losses from pastureland. However, proper pasture cropping effectively minimized P loss. Increasing water retention in wetlands and ensuring cover plantings were also recommended ways to reduce P export (Rechcigl et al., 2002).

13.1.1.5 Utilizing cross fencing or fencing of sensitive areas to allow for animal rotation and protection of waterbodies

Shukla et al. (2011c) conducted a Before-After-Control-Impact study on the effectiveness of a BMP suite (ditch fencing and providing cattle crossings over streams) for nutrient reduction. The average of three post-BMP period loads showed a 10% reduction of TP loads at the downstream (251.8 kg) compared to the upstream (281.0 kg) location. Reductions in P loads for two scenarios were estimated at 0.35 and 0.44 kg/day, respectively. The phosphorus removal cost was approximately \$12.61/kg of P, which is considerably less than the cost of other P reduction strategies in the basin (Shukla et al., 2011d).

Line et al. (2000) found that excluding cattle from streams significantly reduced nitrates, TKN, TP, sediment loads from an intensively grazed pasture.

Shukla et al. (2011b) evaluated a ditch fencing/culvert crossing BMP for cow-calf operations in the Lake Okeechobee basin, and found that TN loads were not consistently reduced but that TP was significantly reduced by the BMP. The wetland water retention BMP produced inconsistent results (Shukla et al., 2011a).

13.1.1.6 Placing water troughs away from heavily used waterbodies

Providing an off stream water source (trough) resulted in cattle choosing the trough 92% of the time, compared with drinking from the stream. The reduction in the number of cattle entering the stream resulted in reductions of TSS, TN, and TP in the stream by 90%, 54%, and 81%, respectively. This was proposed as an alternative to fencing, but the steep slopes in Virginia are not comparable to Florida conditions (harder for cattle to reach stream at bottom of the mountain) (Sheffield et al., 1997).

13.1.1.7 Properly utilizing waste to be spread on pastures

Addition of organic material (JEA Greenedge) increased the concentrations of metals leached into groundwater in Spodosols and Alfisols, and consequently, it was recommended no more than 10 g/kg of JEA Greenedge be added to sandy soils (Yang et al., 2008a).

Addition of organic material (JEA Greenedge) increased TP availability in the root zone and reduced TP leaching in Spodosols and Alfisols (Yang et al., 2008b).

Low TP concentrations beneath experimental plots (Central Highlands Chandler soils) receiving cow patty and urine suggests no adverse TP leaching (N was not evaluated) at the loading rates used, which was up to 1,249 kg/ha (Woodard et al., 2013).

Bermuda grass was most effective at removing nitrate (up to 585 kg/ha) beneath cow waste spray fields located in an excessively drained Kershaw sand (Woodard et al., 2002b).

Bermuda grass was most effective at removing TP (67 kg/ha during 5 years) beneath a cow waste spray field located in an excessively drained Kershaw sand (Woodard et al., 2007).

Broiler litter applications produced only 48% to 67% of the Bahia grass growth that ammonium nitrate fertilizer did, but had negligible nitrate leaching, while there was significant nitrate leaching associated with ammonium nitrate. Ammonia may volatilize from broiler litter during hot summer months (Woodard and Sollenberger, 2011).

Alum residuals associated with drinking water treatment were applied to Bahia grass pastures to assess potential reductions in soil TP contamination. Results indicate reduction in TP mobility in the Spodosols tested, with minimal reductions in Bahia biomass, suggesting alum residual application is an acceptable practice for pastures (Silveira et al., 2013a).

A model for dairy nutrient management determined that it was economically beneficial to utilize more acreage to grow forage crops than the minimum needed to remove nutrients from dairy manure (Henry et al., 1995).

Bermuda grass and limpograss were both effective at removing P from P contaminated soils, with an N application rate of 67 kg/ha/harvest. P removal ranged from 27.6 kg/ha/yr to 29.5 kg/ha/yr (Newman et al., 2009).

Bahia grass (*Paspalum*) pastures receiving dairy wastewater accumulated 11-17 mg/kg P in soil at the depth of 30 cm and 37-169 mg/kg P in the upper 15 cm of soil. The P removed by various *Paspalum* cultivars was between 24-52 lbs/acre annually (Mackowiak and Blount, 2006).

Pant et al. (2002) recommended improved P remediation in impacted sites by producing high quality and quantity of forage while optimizing the nutrient uptakes.

13.1.1.8 Managing livestock distribution to reduce any concentrated accumulation of waste that could lead to contaminating ground water or surface waters

Grazing strategies that increase the uniformity of excreta deposition on Bahia grass pastures would increase nutrient removal and produce higher grass forage biomass (White-Leech et al., 2013).

The effect of cattle nutrient supplement placement on cattle spatial distribution was studied in the Sierra Nevada foothills, and concluded that cows could be attracted to different zones by using a food source (George et al., 2008).

A study on beef cattle ranches in the Lake Okeechobee basin found that cattle stocking rate did not affect nutrient concentrations or loads in surface runoff, and that differences in P runoff were related to differences in soil P, thought to be from prior fertilization. The authors concluded that reducing the stocking rates was not effective for reducing nutrient loads and that reducing overall volume of surface discharge would be more effective (Capece et al., 2007).

Dubeux et al. (2009) examined the effects of cattle management on animal behavior and soil nutrient concentrations. Nutrient concentrations (after 3 years) were greatest near shade and water, which was associated with the time cattle spent in the area. The authors conclude that having portable shade and water troughs would help to more uniformly distribute excreta and reduce areas of concentrated loading (Dubeux et al., 2009).

13.1.1.9 Utilizing controlled-release fertilizers

13.1.2 Alternative Water Supply Sources

13.1.2.1 Capturing rainwater in stormwater ponds for later use

A four year study to evaluate pasture water management for nutrients in the Everglades found that pasture water retention can be an effective approach for reducing runoff volume and TN loads from cattle pastures, but that TP loads can be increased from this practice (Bohlen and Villapando, 2011).

13.1.2.2 Utilizing reuse (treated wastewater) water for irrigation

French et al. (1997) applied dairy wastewater to different crops for a season and measured the amount of nutrients (P and N) in the crops compared to the amount added, and concluded that most of the forage production potential and nitrogen removal capacity of the three cropping systems was achieved with the control (effluent) N loading rate of 360 lb N/a/yr. Substantial increases in either component did not occur with the low N rate (effluent plus 230 lb fertilizer N/a) being applied, and therefore, the optimum annual loading N rate in terms of yield and N removal is likely a level between the control and low N rate. The results also suggested that if N pollution is the major concern in a particular area, a perennial peanut/rye crop rotation would be a good treatment choice, but if P is the major concern, the corn and forage

sorghum/rye and corn perennial peanut/rye cropping systems would be better choices (French et al., 1997).

13.1.2.3 Constructing troughs or tanks for a clean water supply to prevent health hazards

13.1.3 Prescribed Grazing

13.1.3.1 Grazing on established forage heights to maintain plant vigor, prevent soil erosion, and maintain soil moisture levels

Moderate stocking densities were associated with higher water infiltration rates and reduced soil erosion, compared to high stocking densities. The percent organic cover was a robust predictor for erosion potential (Thurrow et al., 1988).

Intensive cattle grazing, resulting in stubble height of 8 cm, was associated with a loss of readily decomposable soil organic carbon, implying that this level of grazing is not sustainable (Silveira et al., 2013b).

13.1.3.2 Incorporating flash grazing in established wetland exclusion areas to manage existing vegetation

13.1.4 Water Resources Management

13.1.4.1 Determining the general water requirements for primary forage grasses and improved pastures

13.1.4.2 Replacing dilapidated water control structures with structures that match original specifications and use good sediment and control measures

13.1.5 Wellhead Protection

13.1.5.1 Excluding livestock within a 75-foot radius of potable wells

Constructing new wells up-gradient as far as possible from likely pollutant sources such as petroleum storage tanks, septic tanks, chemical mixing areas, and livestock confinement facilities

13.2 GENERAL VEGETABLE/AGRONOMIC CROP BMP FINDINGS AND OUTCOMES

The combined use of water table management and nutrient management BMPs for potatoes and cabbage in the Tri-county Agricultural Area (Flagler, Putnam, St. Johns) was predicted by a model to achieve long term reductions in TN and TP of 21% and 13%, respectively (Livingston-Way, 2001).

Adjusting N fertilizer application to maximize potato yields (280 kg N/ha) in the Tri-County potato farming area was associated with high levels of nitrate contamination in groundwater (averaging from ~10 mg/L to ~25 mg/L during 3 samplings). Even IFAS recommended rates (168 kg N/yr) were associated with nitrate above 1-2 mg/L. Sorghum planted after potato rotation was helpful in reducing nitrate. Authors recommend use of controlled release fertilizers and cover crops with high N scavenging ability to help mitigate nitrate contamination (Munoz-Arboleda et al., 2008).

Controlled release fertilizer (CRF) with 146 kg/ha N rate resulted in potato yields comparable to those using highest 224 kg/ha N rate, but the low dose CRF was expected to reduce nitrate leaching, although

nitrate levels were still very high in lysimeters (8.2 mg/L) after 95 days using the low rate (Pack et al., 2006).

Reclaimed water has an excellent safety record and has been successfully used for 40 years. Reclaimed water can be used for edible crops, except for a Florida regulation against direct contact with salad crops, although California has no such restrictions, and there have been no documented illnesses associated with reclaimed water use there (Parsons et al., 2010).

Minimal soil P leaching was observed using seepage irrigation and recommended P fertilization rates for tomatoes (Sato et al., 2009a).

Minimizing water level fluctuations and applying low N application rate are critical for reducing nitrate leaching (Sato et al., 2009b).

Scholberg et al.(2009) concluded that fertilizer uptake capacity in young bell peppers is limited and that daily, small doses of fertilizer and irrigation control would help prevent nitrate leaching.

Based on a model, any increases in corn yield approached zero above fertilizer applications of 168 kg N ha⁻¹, however, the lowest amount of N leaching occurred when no N was applied during the small-leaf stage. Simulated corn yields changed only slightly at application rates less than 70 kg N ha⁻¹ per fertigation event, however, smaller application rates per fertigation decreased N leaching substantially, especially for rates less than 70 kg N ha⁻¹ (He et al., 2012).

A green bean crop, planted in rotation with potatoes, led to positive potato production results and no excessive movement of nitrate into the perched water table, suggesting the inclusion of this cropping system as a BMP. Growers can confidently use a lower nitrogen rate on potatoes and maintain crop quality and yield (Hutchinson, 2006).

A study that evaluated the application of poultry manure mixed with fertilizer concluded that a combination of slow release manure with highly soluble N source was found to provide optimum N requirement for vegetable crops, while also minimizing risk of leaching (Hochmuth and Mylavarapu, 2007).

Franklin et al. (2007) compared the effects of constant vs. variable rainfall patterns on N and P losses from cotton fields managed under conventional and strip-till practices and found that conventional till resulted in more TKN and TP loss, while strip tillage resulted in more reactive P and nitrate loss (Franklin et al., 2007).

The use of recycled runoff tail-water from seepage irrigated potato and cabbage farms resulted in 30% to 46% reduction in water consumption (Haman et al., 1989).

Fertilizer applied at rates higher than those recommended by IFAS produced a 60-80% higher watermelon yield during one year of the study, while the other year showed no difference in yields based on fertilizer application (Hendricks et al., 2007).

Hendricks and Shukla (2011) conducted a 3 year study to evaluate the effects of fertilizer and water rates using seepage and sub-surface irrigation and found that N leached beneath high fertilizer application treatment was greater than recommended (both types of irrigation) and that nitrate was higher in higher

fertilized areas compared to both recommended treatments. The authors conclude that decreased fertilizer and water table levels will improve groundwater quality by reducing N leaching (Hendricks and Shukla, 2011).

Pre- and post- BMP monitoring of groundwater and soil nitrate concentrations was conducted to verify the effectiveness of selected BMPs. For row crops, there was an annual groundwater nitrate reduction between 5.4 and 21.1% after implementation of the BMPs (IFAS and SRWMD, 2008).

The combined use of water table management and nutrient management BMPs in the Tri-county Agricultural Area (Flagler, Putnam, St. Johns) were predicted by a model to achieve long term reductions in TN and TP of 21% and 13% respectively (Livingston-Way, 2001).

Irrigating with reclaimed water in the Orange/Lake County area was found to have benefits to citrus tree canopy and fruit production, with minimal detrimental effects (more weed growth, but that was controlled via herbicide). Although the reclaimed water had 7 mg/L nitrate, additional N fertilization was required for desired yields. Boron increased in leaves, meaning foliar application of boron should be proportionately reduced (Morgan and McAvoy, 2012).

Morgan et al. (2007) studied 2 rates of controlled release fertilizers (CRF) and 4 combos of soluble N. The rates used were 120, 180, 240 lbs/acre N. The treatments included soluble fertilizer, 3 month release rate CRF, 5 month release rate CRF, and a combination of the two release rate CRFs. Treatments had no effect on yield and biomass consistent across 2 seasons studied. Increasing N rate tended to increase leaf N (Morgan et al., 2007).

Labeled isotopes of fertilizer were used in an uptake trial for sweet corn, and demonstrated efficiency in slow release fertilizer, and demonstrated that use of ammonium based and/or slow release fertilizers is preferable. Also confirmed that using sensor based irrigation leads to much more efficient water use and reduced leaching (Scholberg et al., 2007).

Three water and nutrient management regimes for tomato and watermelon were evaluated with respect to production, water quality, and farm income. The grower treatment had the highest levels of ortho P and TP (~3 mg/L) in groundwater samples. IFAS drip treatment has lowest ortho P, and IFAS seepage treatment has lowest TP (both less than 1.5 mg/L). Grower treatment had highest levels of nitrate (14mg/L), while seepage was 1 mg/L and drip was 5.8 mg/L. Grower also maintained a higher water table and soil moisture level. Yield was similar across treatments. No variability reported (Shukla et al., 2007)

Simonne et al. (2007) found that sometimes rates greater than the recommended BMPs are justified. It is also inexpensive for farmers to fertilize above recommended rates because only need an increase of 3 to 40 25 lb boxes/acre to offset cost of 100 lbs/acre fertilizer. The recommend a range of recommendations based on season and irrigation method.

Zotarelli et al. (2009a) evaluated the interaction between N-fertilizer rates and irrigation scheduling on yield, water use, and root distribution. N rates were 176, 220, and 230 kg/ha N. Irrigation consisted of surface drip, subsurface drip, and conventional (once per day). The surface drip required 15-51% less irrigation than conventional, and subsurface required 7-21% less. Yields were higher by 11-81% for these methods as well. Since less water is needed for higher yield, this should significantly reduce N leaching (Zotarelli et al., 2009b).

13.2.1 Precision Agriculture

13.2.1.1 *Using precision agriculture technology, such as GPS*

By accounting for the El Nino Southern Oscillation weather pattern, a CROPGRO peanut model was developed that predicted a 1% to 8% increase in peanut yields and a 1% to 11% decrease in nitrate leaching (Mavromatis et al., 2002).

Banded fertilizer application for phosphorus reduced the amount of P required compared to broadcast methods, with a relative efficiency of 3:1 (band: broadcast) in low P histosols. Banding is a viable strategy to reduce P use for sweet corn production (Sanchez et al., 1991).

13.2.2 Irrigation System Maintenance and Evaluation

Daroub et al. (2011) reviewed EAA BMPs and their effect on P removal, and found a trend of decreasing P concentrations, drainage flows, and P loads. Water management practices were found to be the primary factors effecting P loads out of the EAA, and the authors recommend additional research be focused on water management for farms with deeper soils in order to achieve further P reductions. Finally, they note that the high nutrient levels in irrigation water from Lake Okeechobee is likely to impact the performance of BMPs (Daroub et al., 2011).

Glaz and Morris (2006) evaluated the effects of water-table depth on sugarcane and found that yields increased as water-table depth increased for some genotypes.

Izuno et al. (1995) studied the effect of BMPs on reducing TP concentrations and loadings in the EAA, and had these findings: there were no differences in P in drainage water between sugarcane and fallow fields; slowly drained plots had higher TP concentration than quickly drained plots, but TP loads were higher for fast drained plots; rice crops reduced TP concentrations/loadings; banded P applications reduced TP compared to broadcast methods; and overall, the EAA system is a net assimilator of P (Izuno et al., 1995).

Izuno et al. (1999) examined 10 farms in the EAA that have implemented BMPs to determine if they were reducing the legislatively required TP load sufficiently, and confirmed the effectiveness of the BMPs (Izuno et al., 1999)

McCray et al. (2012) developed an updated P fertilizer application test based on the Mehlich 3 soil extraction, and recommend no P application if P is present greater than 30 g/m³.

McCray et al. (2010) conducted field studies on organic soils to determine sugarcane yield in response to P fertilizer, and recommended that a maximum of 36 kg P/ha/yr be applied for optimum sugarcane production (McCray et al., 2010).

Obreza et al. (1998) concluded that the optimum water table for sugar cane production was ~0.6 m, that low dose, more frequent applications of N fertilizer produced maximum yields, and that magnesium was not a factor limiting cane growth (Obreza et al., 1998).

Controlled release Fertilizer (CRF) treatment (75%) and the CRF with soluble P and K (75%) treatment had significantly higher sugarcane yields compared to the 100% soluble fertilizer treatment (Morgan, 2009).

13.2.2.1 Understanding the level of irrigation system efficiency

Use of Sensor-based irrigation (0.15 m subsurface) reduced nitrate leaching by 93% compared to standard timed irrigation (Zotarelli et al., 2008b).

At an intermediate nitrogen application rate on tomatoes, surface and subsurface drip irrigation systems reduced nitrate leaching to 5 and 35 kg/ha, while at the highest N-rate, corresponding values were 7 and 56 kg N/ha. N application rates above 220 kg/ha did not result in benefits, but substantially increased nitrate leaching for the control treatment. Appropriate use of subsurface drip irrigation and/or sensor-based irrigation systems can sustain high yields while reducing irrigation application, as well as reducing nitrate leaching in low water holding capacity soils (Zotarelli et al., 2009a).

Sensor controlled irrigation reduced water use in tomatoes by 15-51% (95 % confidence interval) compared to timed irrigation (Zotarelli et al., 2009c).

Using sensors to maintain bell pepper soil moisture levels at 10% and 12% reduced nitrate leaching between 25% and 73%, compared to timed irrigation, with no difference in crop yields (Zotarelli et al., 2010).

Stanley and Clark (1995) concluded that the use of a Fully Enclosed Seepage system with the water table maintained at 24 inches below the surface, coupled with fertilizing nitrogen at 190-240 lbs /acre, yielded good tomato growth and would minimize water use and minimize nitrate leaching.

Water use was 36% lower using an automatic drip irrigation system compared with traditional irrigation, and concurrently, crop yields exceeded the industry standard (Smajstrla et al., 2000).

Tensiometer controlled micro-drip irrigation resulted in improved tomato yields, with lower water consumption (Smajstria and Locascio, 1996).

Shukla et al. (2006) found that drip irrigation on watermelons was associated with lower N seepage and lower evapotranspiration, and consequently, recommended drip irrigation as a BMP.

In the Miami-Dade area, optimization of irrigation schedules via sensors (including use of tensiometer readings that were regressed against capacitance probe output) was an important BMP to reduce water use. Well water in the area is already contaminated with ~7 mg/L nitrate, therefore nitrate increases associated with various N application rates was not significant (Schaffer et al., 2001).

Hochmuth et al. (2000) found that plant plugs of strawberries can be established with less water than is traditionally used.

Using sensors to maintain soil moisture levels in tomatoes at 10% and 12% reduced nitrate leaching between 25% and 73%, compared to timed irrigation, with no difference in crop yields (Zotarelli et al., 2010).

13.2.2.2 Properly maintaining irrigation system for distribution uniformity

The optimal sweet corn yield with minimum water usage was achieved with soil moisture set to 10-12% for 23 cm deep (Dukes and Scholberg, 2005).

Applying ammonia fertilizer on potatoes during dry conditions (20% field capacity) resulted in 2-3 fold greater rates of volatilization than during increased moisture conditions (80% field capacity), meaning that volatilization and N loss is accelerated at low soil water regimes (Liu et al., 2007).

Improved water table management using sensors and maintaining a lower water table for seepage irrigation resulted in reduced water use by 36% compared to the conventional method, but the BMP improved average crop yield and reduced plant disease outbreaks (Pandey et al., 2007).

13.2.3 Tissue Testing

13.2.3.1 Utilizing tissue testing to determine crop nutrient needs as part of a comprehensive fertilizer management plan

Application timing of N and K (40% pre-plant, 60% drip-irrigated) yielded the best sap N and K, leaf N and K, and fruit. However, when excessive rains occurred, resulting in leaching, yields were similar (Locascio et al., 1997).

Simonne et al. (2008) developed N fertilizer recommendations for grape tomatoes, although environmental BMPs were not discussed.

Use of slow release fertilizers for tomatoes resulted in significantly less leaching than conventional ammonia nitrate applications (Fan and Li, 2009).

Hutchinson et al. (2003) found that excellent potato yields were obtained using polymer-coated sulfur urea slow release fertilizer at an application rate of 168 kg N/ha, comparable to yields produced using 224 kg N/ha of conventional fertilizer.

13.2.4 Soil Testing

13.2.4.1 Utilizing soil testing to determine crop nutrient needs as part of a comprehensive fertilizer management plan

Applying fertilizer in excess of BMP recommendations increased nitrate leaching by 64%, 59%, and 32%, respectively, for pepper, tomato, and zucchini (Zotarelli et al., 2007). Increasing fertilizer retention time in the root zone of corn crop reduces nitrate leaching (Zotarelli et al., 2008a).

Slow release fertilizers produced higher potato biomass and it was assumed by the authors, less adverse runoff, than typical fertilization practices (Worthington et al., 2007).

Hochmuth and Jones (2004) demonstrated that applying fertilizer as plants emerge results in similar yields as applying the fertilizer earlier, when increased leaching would be expected to occur.

Maximum tomato yields occurred at 172 and 298 kg N/ha in 2 successive years, which are different from the IFAS recommended rate of 224 kg N/ha. No environmental BMPs were discussed, but reducing fertilizer would be expected to reduce leaching (Ozores-Hampton et al., 2012).

A higher N application rate for tomatoes was associated with increased N leaching (41-43% at the high N application compared with 35-38% at the lower rate) (Sato et al., 2010).

13.2.5 Conservation Tillage

13.2.5.1 *Practicing conservation tillage, maintaining a minimum of 50 percent residue cover throughout the year*

Application of a cover crop (vetch and rye) significantly reduced need for fertilizer on corn, and also reduced weeds (Zotarelli et al., 2009c).

Use of summer cover crops (legumes) prevented TN loss off site by 88-94% and TP loss by 50-83% compared to bare/fallow soil (Wang et al., 2005).

Vieira et al. (2008) found that addition of organic matter to acidic soils helped mitigate aluminum toxicity to plants.

Strip till techniques resulted in significantly less loss of organic matter, silt/clay, and nitrogen when compared with conventional full till methods (Strickland et al., 2012).

Addition of composted yard waste increased the saturation volumetric water capacity, field capacity, and plant available water in pastures by 10%, 32% and 30% respectively, compared with non-composted fields, and was especially effective in the top 30 cm, providing significant water retention and irrigation reduction benefits (Shukla and Pandey, 2008).

Hutchinson and Mylavarapu (2002) found that use of cover crops could increase potato yields compared to allowing Tri-County potato production area land to remain fallow, that cover crops could decrease inorganic fertilizer applications required, and recommended increasing crop diversity as a BMP.

Use of organic amendments for vegetable production was comparable to inorganic fertilizer application in terms of N leaching in the groundwater, but produced similar or higher yields (Jaber et al., 2005).

Nitrogen loss in soils was higher when N was applied at a higher rate, and hairy vetch (a cover crop) did not reduce N loss compared to weeds growing in fallow fields (Sainju et al., 1999).

Sunn hemp is recommended as a cover crop to produce biomass and to incorporate N-fixation into soils, as part of crop rotation (Schomberg et al., 2007).

A study of conservation tillage as a water management tool for cotton crops determined that strip tillage could reduce water requirements (Bosch et al., 2005). The authors found that that the surface water runoff loss from conventionally tilled plots exceeded the strip till method by 81%, and that subsurface losses from strip plots were greater than conventional tillage by 73%.

13.2.6 Field Borders

13.2.6.1 Maintaining vegetated field borders around the perimeter of the field, especially where runoff enters or leaves the field

13.2.7 Contour Farming

13.2.7.1 Establishing row direction as closely as possible to the natural contour in order to minimize erosion

13.2.8 Wetlands and Springs Protection

13.2.8.1 Maintaining a 25-foot undisturbed upland buffer exterior to the landward extent of wetlands

Sweeney and Newbold (2014) found that streamside forest buffer widths greater than 40 m removed 89% (27-99%) of nitrate leaching to adjacent streams, and concluded that buffers of > 30 m would generally protect physical, chemical, and biological health of streams (Sweeney and Newbold, 2014).

13.2.9 Water Supply Protection

13.2.9.1 Utilizing a backflow prevention device to prevent contamination to the water source

13.2.10 Tailwater Recovery

13.2.10.1 Properly maintaining a tailwater recovery system and integrating the water source into an irrigation plan

Capture and re-use of deep aquifer irrigation water used for freeze prevention (strawberries) resulted in 50-70% reduction in deep aquifer withdrawals (Stanley et al., 1991).

13.2.11 Grassed Waterways

13.2.11.1 Using visual inspections, topographic maps, and/or basic survey equipment to identify areas where grassed waterways are needed to convey water from fields

13.2.12 Integrated Pest Management

13.2.12.1 Storing pesticides in an enclosed, roofed structure with an impervious floor, away from surface waters and above the 100-year floodplain

13.2.13 Nutrient Management

13.2.13.1 Using tissue testing to determine the effectiveness of a fertilizer program, as well as needs for supplemental fertilization

13.2.13.2 Calibrating fertilizer equipment for uniform distribution

13.2.13.3 Using split applications for soluble fertilizer

13.2.13.4 If using reclaimed water, adjusting fertilization rates to account for the nutrient content in the reclaimed water, based on the water quality data from the water supplier

13.2.13.5 Adjusting fertilizer rate if using composted manures, treated domestic wastewater residuals, or other biosolids

13.2.14 Irrigation Scheduling

13.2.14.1 Determining the available soil moisture content and maintaining soil moisture within the recommended range for the crop and soil type, in order to reduce possibility of over irrigation or leaching

Evapotranspiration-based automatic irrigation controllers did not consistently reduce the amount of water applied to residential landscapes, and often resulted in increased water consumption (Dukes et al., 2011).

13.2.14.2 Adjusting irrigation timing and amount to account for rainfall events and growth stage of the turf grass

13.2.14.3 Using backflow-prevention devices at the wellhead to prevent contamination of water sources

13.2.15 Wetlands and Springs Protection

13.2.15.1 Maintaining a 25-foot undisturbed upland buffer exterior to the landward extent of all perennial watercourses and associated adjacent wetlands

Sweeney and Newbold (2014) found that streamside forest buffer widths greater than 40 m removed 89% (27-99%) of nitrate leaching to adjacent streams, and concluded that buffers of > 30 m would generally protect physical, chemical, and biological health of streams (Sweeney and Newbold, 2014).

13.2.16 Irrigation System Maintenance and Evaluation

13.2.16.1 Periodically checking system uniformity

13.2.16.2 Establishing a written schedule for inspection and maintenance of all irrigation system components

13.2.17 Wellhead Protection

13.2.17.1 Reviewing local comprehensive plan to determine if land uses within wellhead protection areas conform to local codes

13.2.18 Mowing Management

13.2.18.1 Establishing a mowing frequency to maintain optimal turf growth

13.2.18.2 Recycling, composting, or disposing of clippings in an environmentally acceptable fashion

13.2.19 Integrated Pest Management

13.2.19.1 Storing pesticides in an enclosed, roofed structure with an impervious floor and lockable door at least 100 feet away from surface waters

14 APPENDIX E

Example explanations of quantitative studies not meeting inclusion criteria:

(Bhadha et al., 2011)	No control to compare wetland P treatment to. Estimated P budget. No measure of error. Modeling focused paper.
(Bhadha et al., 2010)	No control to compare wetland treatment to. Examining P loading storage capacity of soils, not BMP implementation.
(Dunne et al., 2010)	Examined short term P dynamics between soils and overlying water from wetlands and surrounding uplands in cow/calf pastures. Developed linear models between P release and hydroperiod/inundation. Not comparing BMP to non BMP.
(Dunne et al., 2007)	Examined potential for isolated wetlands to provide P storage sink from agriculture runoff. No control (non BMP).
(Min et al., 2010)	Focused on hydrology of ditched systems that are candidates for restoration to reduce P into Lake Okeechobee. No measure of nutrients, were only concerned with water and extrapolated that to helping nutrient reductions.
(Woodard et al., 2003)	Study 1: compare normal spraying to no spraying (not a BMP, some spraying will be done). Calculating degree of P saturation. Study 2: Don't report P measurements of lysimeters from below root zone for comparison between high, medium, and low loading rate treatments to cover crops. Report yield, P removal, P concentration of crops.
(Hochmuth et al., 2014)	Not comparing BMP vs non BMP. Comparing different crops.
(Woodard et al., 2000)	Measured the capacity of different forage crops to remove N and P at 3 rates. Measured the N and P in harvested plant matter. Also looked at nitrate leaching below root zone, but did not report data. Figures that present data range from between 10 to 50 mg/L nitrate in soils.
(Livingston-Way, 2001)	Modeled data, not actual data. Would have been very useful otherwise.

Example of a study that would have been useful except it presented modelled data, not actual data. R² of real and predicted data was only 0.24 and 0.26 for N and P.

(Livingston-Way, 2001)	Potatoes and cabbage, Study: Random block Control-Impact as input to model. BMP: Predicted differences between no BMPs (control) and with water level and fertilizer BMP combined (treatment). Nutrient BMPs were soil testing, IFAS fertilizer rates, split applications, tissue testing for nutrient need (applying less fertilizer basically). Also used water table BMPs and sediment BMPs.	12.8	5.61	4	7.6	2.74	TN concentration exiting the farms to surface water (mg/L)	4
	Replication: 4 farms. 3 had nutrient BMPs, 3 water BMPs, 2 sediment BMPs. Collected grab and automated samples, converted into a daily avg. Calculated flow weighted concentrations, no interpolation was done. Calculation: Report presented a table with BMP effects on annual N and P concentrations, separated by farm, with treatments of actual, no bmp, water bmp, nutrient bmp, and both bmp. Limitation: Did not have a hold-out set for model verification.							
(Livingston-Way, 2001)	Potatoes and cabbage, Study: Random block Control-Impact as input to model. BMP: predicted differences between no BMPs (control) and water level BMP alone (treatment). Nutrient BMPs were soil testing, IFAS fertilizer	12.8	5.61	4	13.0	5.78	TN concentration exiting the farms to surface water (mg/L)	4

(Livingston-Way, 2001)	rates, split applications, tissue testing for nutrient need (applying less fertilizer basically). Also used water table BMPs and sediment BMPs. Replication: 4 farms. 3 had nutrient BMPs, 3 water BMPs, 2 sediment BMPs. Collected grab and automated samples, converted into a daily avg. Calculated flow weighted concentrations, no interpolation was done. Calculation: Report presented a table with BMP effects on annual N and P concentrations, separated by farm, with treatments of actual, no bmp, water bmp, nutrient bmp, and both bmp. Limitation: Did not have a hold-out set for model verification. Potatoes and cabbage, Study: Random block Control-Impact as input to model. BMP: predicted differences between no BMPs (control) and fertilizer BMP alone (treatment). Nutrient BMPs were soil testing, IFAS fertilizer rates, split applications, tissue testing for nutrient need (applying less fertilizer basically). Also used water table BMPs and sediment BMPs.	12.8	5.61	4	7.7	3.0	TN concentration exiting the farms to surface water (mg/L)	4
	Replication: 4 farms. 3 had nutrient BMPs, 3 water BMPs, 2 sediment BMPs. Collected grab and automated samples, converted into a daily avg. Calculated flow weighted concentrations, no interpolation was done. Calculation: Report presented a table with BMP effects on annual N and P concentrations, separated by farm, with treatments of actual, no bmp, water bmp, nutrient bmp, and both bmp. Limitation: Did not have a hold-out set for model verification. Potatoes and cabbage, Study: Random block Control-Impact as input to model. BMP: Predicted differences between no BMPs (control) and with water level and fertilizer BMP combined (treatment). Nutrient BMPs were soil testing, IFAS fertilizer rates, split applications, tissue testing for nutrient need (applying less fertilizer basically). Also used water table BMPs and sediment BMPs.	0.80	0.16	4	0.71	0.15	TP concentration exiting the farms to surface water (mg/L)	4
	Replication: 4 farms. 3 had nutrient BMPs, 3 water BMPs, 2 sediment BMPs. Collected grab and automated samples, converted into a daily avg. Calculated flow weighted concentrations, no interpolation was done. Calculation: Report presented a table with BMP effects on annual N and P concentrations, separated by farm, with treatments of actual, no bmp, water bmp, nutrient bmp, and both bmp. Limitation: Did not have a hold-out set for model verification. Potatoes and cabbage, Study: Random block Control-Impact as input to model. BMP: predicted differences between no BMPs (control) and water level BMP alone (treatment). Nutrient BMPs were soil testing, IFAS fertilizer rates, split applications, tissue testing for nutrient need (applying less fertilizer basically). Also used water table BMPs and sediment BMPs.	0.80	0.16	4	0.85	0.17	TP concentration exiting the farms to surface water (mg/L)	4

(Livingston-Way, 2001)

Replication: 4 farms. 3 had nutrient BMPs, 3 water BMPs, 2 sediment BMPs. Collected grab and automated samples, converted into a daily avg. Calculated flow weighted concentrations, no interpolation was done.

Calculation: Report presented a table with BMP effects on annual N and P concentrations, separated by farm, with treatments of actual, no bmp, water bmp, nutrient bmp, and both bmp.

Limitation: Did not have a hold-out set for model verification.

Potatoes and cabbage,

Study: Random block Control-Impact as input to model.

BMP: predicted differences between no BMPs (control) and fertilizer BMP alone (treatment). Nutrient BMPs were soil testing, IFAS fertilizer rates, split applications, tissue testing for nutrient need (applying less fertilizer basically). Also used water table BMPs and sediment BMPs.

Replication: 4 farms. 3 had nutrient BMPs, 3 water BMPs, 2 sediment BMPs. Collected grab and automated samples, converted into a daily avg. Calculated flow weighted concentrations, no interpolation was done.

Calculation: Report presented a table with BMP effects on annual N and P concentrations, separated by farm, with treatments of actual, no bmp, water bmp, nutrient bmp, and both bmp.

Limitation: Did not have a hold-out set for model verification.

0.80

0.16

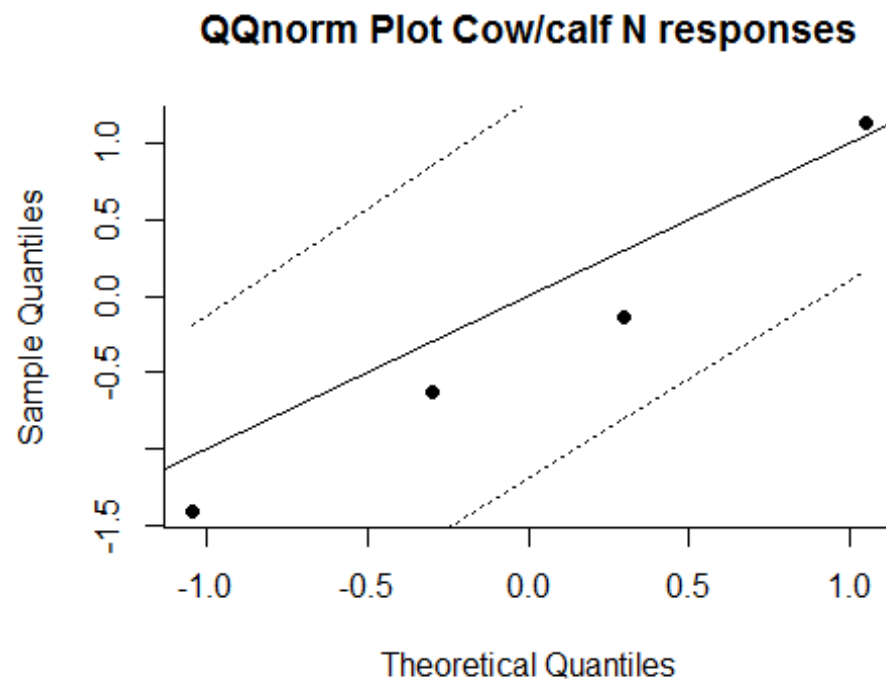
4

0.66

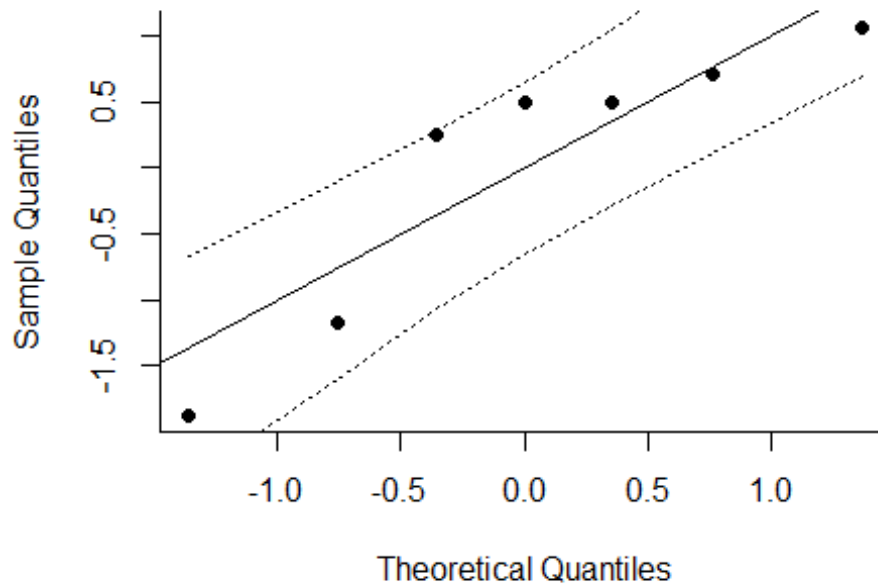
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TP concentration exiting the farms to surface water (mg/L) 4

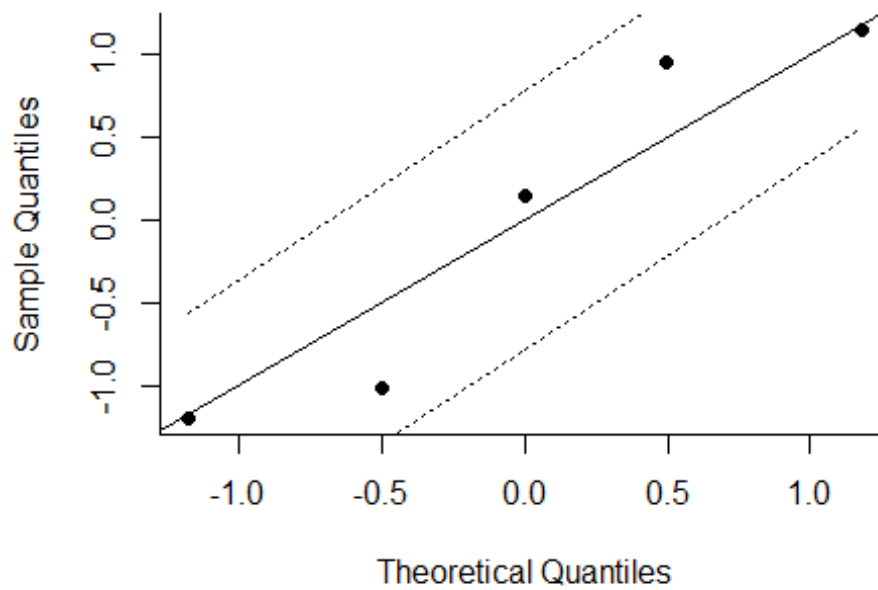
15 APPENDIX F



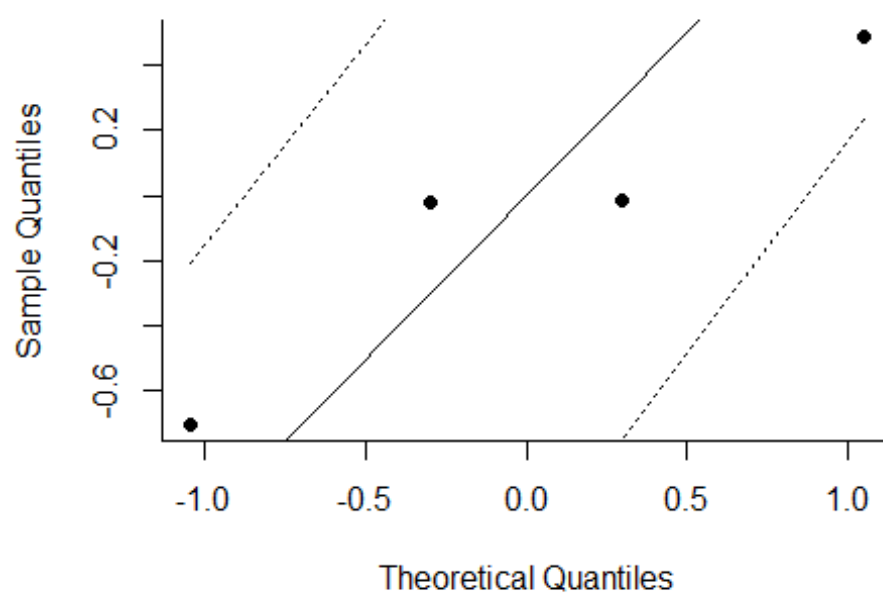
Funnel Plot vegetable P response



QQnorm Plot Agronomic N response



QQnorm Plot Cow/calf P response



QQnorm Plot Vegetable P response

