Mitigation efficacy of vegetated buffers in reducing non-point source pollution: A critical review and meta-analysis

Xuyang Zhang Ph.D.

California Department of Pesticide Regulation

Paper published in JEQ 39:76-84

Background

- Agricultural non-point source pollution is the leading source of surface water degradation.
- Agricultural best management practices (BMPs) can reduce pollutant runoff.
- Vegetated buffers (VB) are the most studied and widely used BMPs.

Vegetated buffers

Main functions:

- Slow runoff
- Increase infiltration
- Trap pollutants

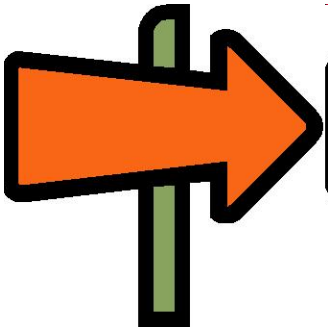
Background

- AG non-point source pollution is the leading source of surface water degradation.
- Agricultural best management practices (BMPs) can reduce pollutant runoff.
- Vegetated buffers (VB) are the most studied and widely used BMPs.
- Field or plot experiments provide valuable quantitative results but are too specific and inconsistent.
- Understanding the removal efficacies and key design factors of VB is essential to successful implementation.

Objectives

(1) aggregate data from many studies on the mitigation efficacies of vegetated buffers

(2) quantify the relationships between pollutant removal efficacy and buffer design factors



Materials and methods

Literature review

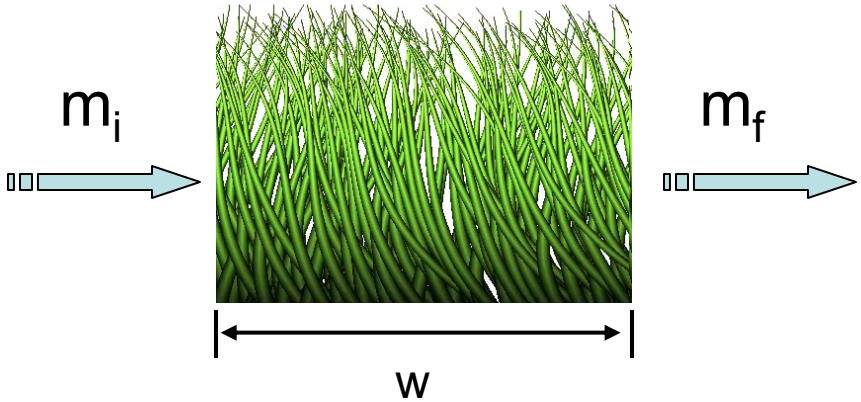
- Online libraries, databases, governmental reports
- A total of 73 studies reviewed
- Record detailed information on author, year, location, buffer width, slope, area to source ratio, pollutant type, soil type, vegetation type etc.

Paper source	Location	Width (m)	Nitrogen				
			Efficacy (%)	Inflow (mg)	Out flow (mg)	Loss (mg)	Form
Dillaha,1988	Virginia	4.6	50.6	686.4	338.8	347.6	N
Dillaha,1988	Virginia	4.6	59.0	928.0	380.4	547.6	N
Dillaha,1988	Virginia	9.1	65.5	686.4	236.6	449.8	N
Lee,2000	Iowa	7.1	61.1	1.3	0.8	0.4	Nitrate
…..							

Theoretical framework: buffer width

Removal efficacy:

$$Y = \left(\frac{m_i - m_f}{m_i} \right) = \left(1 - \frac{m_f}{m_i} \right)$$



The probability that any given amount of pollutant will be removed by the buffer is constant for a given distance traveled through the buffer.

$$\frac{dm}{dx} = -b \cdot m \quad \rightarrow \quad m = A \cdot e^{-bx}$$

at $x = 0 \quad m = m_i \quad \rightarrow \quad A = m_i$

at $x = w \quad m = m_f \quad \rightarrow \quad \frac{m_f}{m_i} = e^{-b \cdot w}$

$$Y = \left(1 - \frac{m_f}{m_i} \right)$$

$$Y = 1 - e^{-b \cdot w}$$

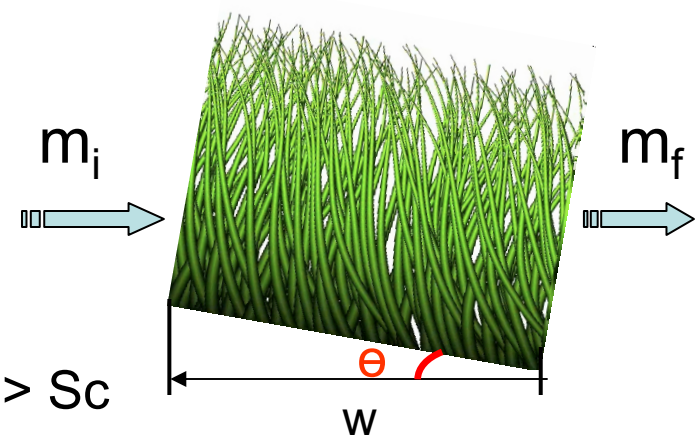
$$0 < K \leq 100$$

$$Y = K \cdot (1 - e^{-b \cdot w})$$

Theoretical framework: buffer slope

Removal efficacy:

$$Y=\begin{cases}\alpha+\beta_1\cdot x & \text{When slope} \leq \text{Sc} \\ \alpha+(\beta_1-\beta_2)\cdot S_c+\beta_2\cdot x & \text{When slope} > \text{Sc}\end{cases}$$



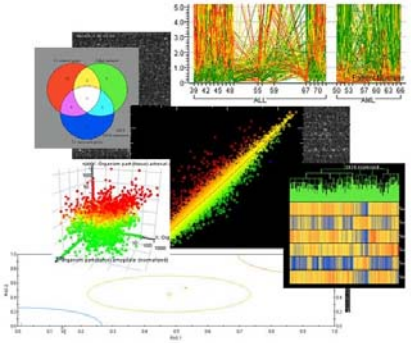
- *x* is the slope of the buffer in percent
- *Y* is the pollutant removal efficacy
- S_c, α, β_1, β_2 are parameters estimated using a non-linear algorithm
- *Sc* is the slope where the relationship between buffer slope and sediment removal efficacy changes drastically from positive to negative

Vegetation and soil type

- vegetation type was classed as either grasses, trees, or a mixture of grasses and trees.
- soil type was categorized by how well the soil drains.
- Soil drainage types were classified as well drained, moderately drained, and poorly drained.
- Dummy variables were used in the analysis to indicate vegetation and soil drainage type

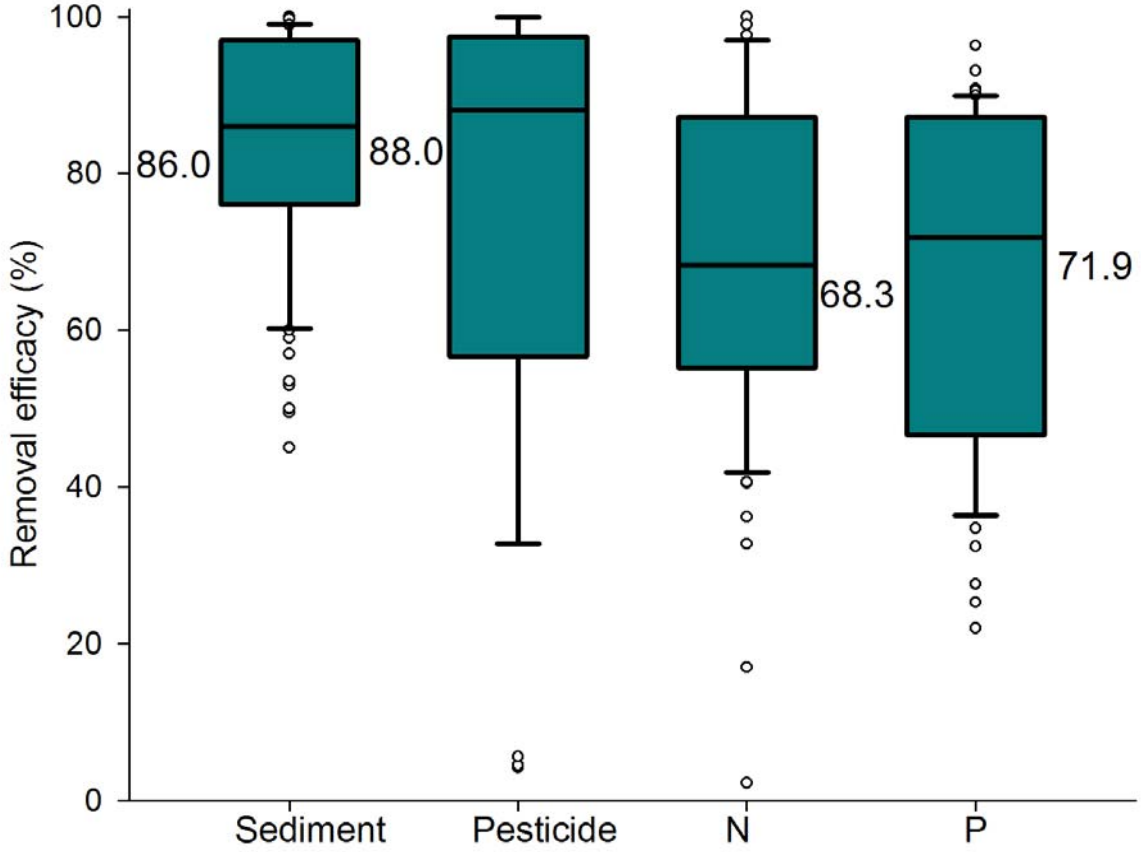
Statistical analysis

- Boxplots to examine the distribution of the efficacy values.
- Non-linear regression analysis on pollutant removal efficacy vs. buffer width
- Segmented linear regression on pollutant removal efficacy vs. slope
- Statistical diagnostics were used to determine whether the residuals met the statistical analysis assumptions (e.g. normality and constant variance).



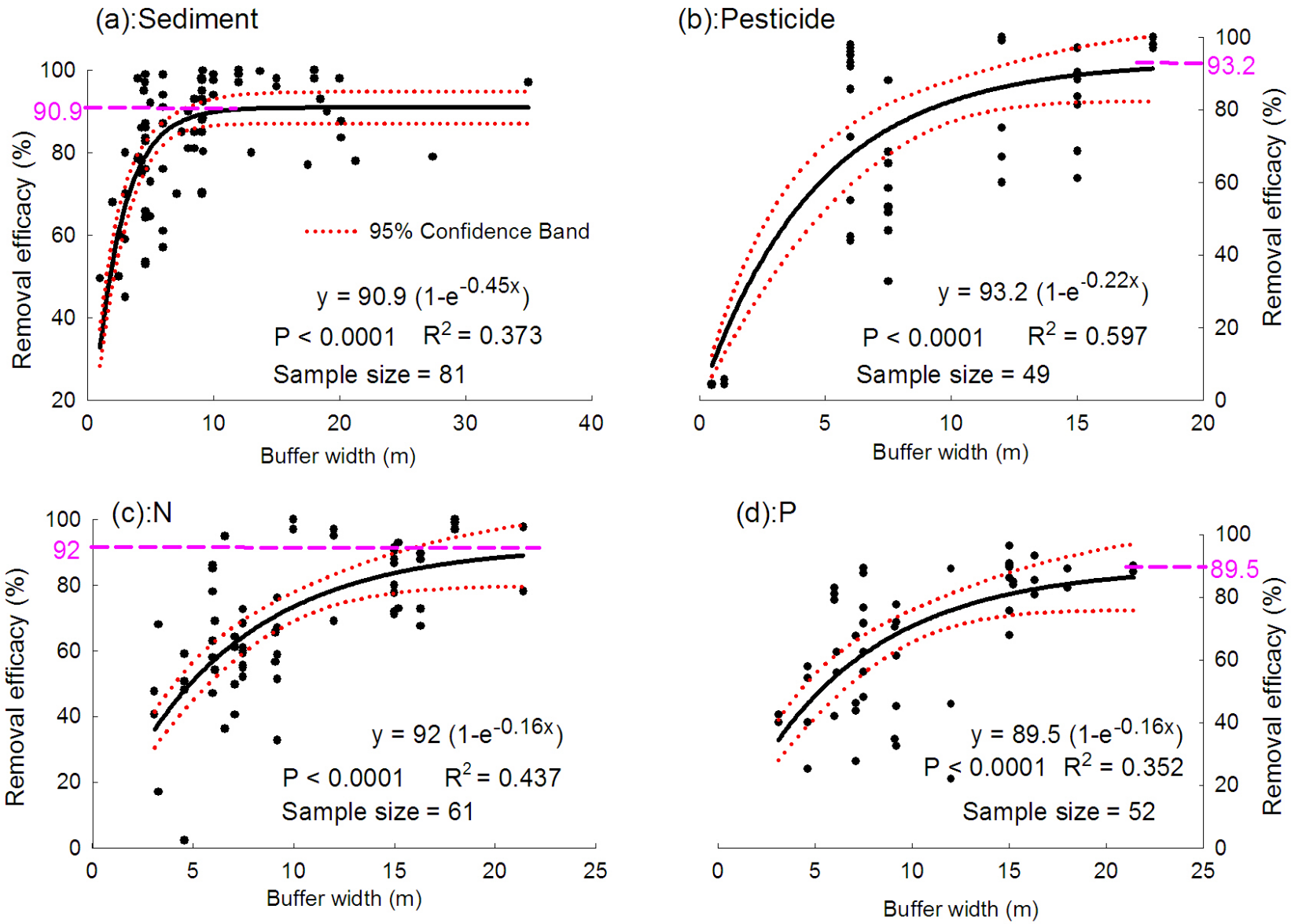
Results

Distribution of pollutant removal efficacy



Boxplot of pollutant removal efficacy values.

Efficacy vs. Buffer width

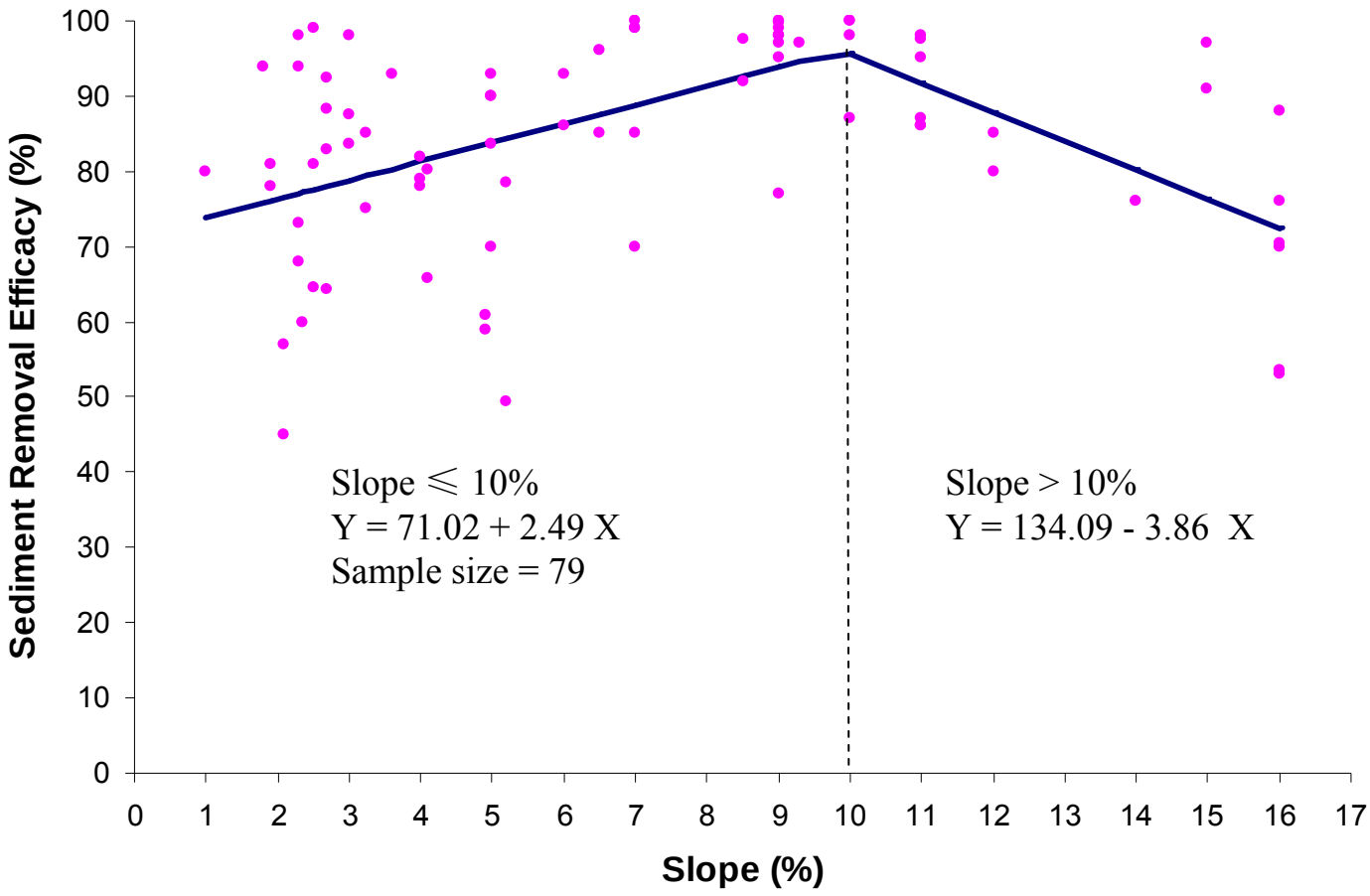


Parameter estimates

Pollutant	$Y = K * (1-e^{-bx})$				Estimate of K			Estimate of b		
	N	R^2	P	SE[a]	K	SE[b]	P	b	SE[c]	P
Sediment	81	0.373	<0.001	11.44	90.9	1.96	<0.001	0.446	0.047	<0.001
Pesticide	52	0.597	<0.001	18.30	93.2	5.86	<0.001	0.215	0.045	<0.001
Total N	61	0.437	<0.001	15.94	92.0	6.40	<0.001	0.160	0.028	<0.001
Total P	52	0.352	<0.001	17.18	89.5	7.47	<0.001	0.157	0.033	<0.001

a Residual standard deviation of regression model.
b Standard error of the estimate of K.
c Standard error of the estimate of b.

Efficacy vs. slope



	Sediment	Nitrogen	Phosphorus	Pesticide
Buffer width	Exponential	Exponential	Exponential	Exponential
Vegetation	Grasses / trees > mixed grass and trees†	Trees > grasses / mixed grasses and trees	Trees > grasses / mixed grasses and trees	Not significant
Soil drainage type	Not significant	Not significant	Not significant	Not available
Slope	Positive when slope ≤ 10% Negative when slope > 10%	Not available	Not available	Not available
Full model	(a) Slope ≤ 10% ; mixed grasses and trees $Y = 6.9 + 2.0 \cdot X_{slope} + 61.0 \cdot (1 - e^{-0.35 \cdot x_{width}})$ (b) Slope ≤ 10% ; grasses / trees only: $Y = 21.7 + 2.0 \cdot X_{slope} + 61.0 \cdot (1 - e^{-0.35 \cdot x_{width}})$ (c) Slope > 10% ; mixed grasses and trees $Y = 64.9 - 3.8 \cdot X_{slope} + 61.0 \cdot (1 - e^{-0.35 \cdot x_{width}})$ (d) Slope > 10% ; grasses / trees only $Y = 79.7 - 3.8 \cdot X_{slope} + 61.3 \cdot (1 - e^{-0.35 \cdot x_{width}})$	(a) Mixed grasses and trees / grasses only $Y = 10.2 + 91.4 \cdot (1 - e^{-0.11 \cdot x_{width}})$ (b) (b) Trees only $Y = 23.9 + 91.4 \cdot (1 - e^{-0.11 \cdot x_{width}})$	(a) Mixed grasses and trees / grasses only $Y = 30.5 + 147 \cdot (1 - e^{-0.03 \cdot x_{width}})$ (b) (b) Trees only $Y = 59.8 + 147 \cdot (1 - e^{-0.03 \cdot x_{width}})$	$Y = 93.2 \cdot (1 - e^{-0.22 \cdot x_{width}})$
Statistics	R^2 = 0.654 N = 81 P < 0.001	R^2 = 0.492 N = 61 P < 0.001	R^2 = 0.475 N = 52 P < 0.001	R^2 = 0.597 N = 49 P < 0.001

Model Prediction

		Predicted removal efficacy (%)			
	Buffer width =	5m	10m	20m	30m
Sediment	(a) Slope = 5% ; mixed grass and trees	**67**	**76**	**78**	**78**
	(b) Slope = 5% ; grass / trees only	**82**	**91**	**93**	**93**
	(c) Slope = 10% ; mixed grass and trees	**77**	**86**	**88**	**88**
	(d) Slope = 10% ; grass / trees only	**92**	**100†**	**100**	**100**
	(e) Slope = 15% ; mixed grass and trees	**58**	**67**	**68**	**68**
	(f) Slope = 15% ; grass / trees only	**73**	**81**	**83**	**83**
Nitrogen	(a) Mixed grass and trees / grass only	**49**	**71**	**91**	**98**
	(b) Trees only	**63**	**85**	**100**	**100**
Phosphorus	(a) Mixed grass and trees / grass only	**51**	**69**	**97**	**100**
	(b) Trees only	**80**	**98**	**100**	**100**
Pesticide		**62**	**83**	**92**	**93**

† If predicted values exceed 100, the value of 100 was assigned instead.

Discussion

Interpretation of K and b

$$Y = K \cdot (1 - e^{-b \cdot w}) \qquad 0 < K \leq 100$$

K < 100 implies that vegetated buffers would remove less than 100% of pollutants from runoff. Why ?

- Variance of data statistical estimates of K are statistical mean
- Unexplained mechanisms by the simplified model
  e.g. additional nutrients may be released from vegetation in a buffer
- Chemical partitioning between the water and sediment column potentially column maintains pollutant residues in water as long as the amount of runoff water is not zero.

Sediment Removal

- VBs are effective
- 8-12% slope is ideal
- 20m buffer remove > 88% sediment
- > 20 m does not increase removal efficacy significantly
- Width, slope and vegetation together explained 65% of total variance
- Unexplained variations could due to: flow, particle size

N and P Removal

- 20 m buffer removes about 90% and 97% of N and P from runoff
- Buffer width and vegetation explain about 50% of variation in N removal efficacy and 48% of variation in P removal efficacy
- Buffers composed of trees generally remove more N, P from runoff than those with grasses
- No significant effect associated with soil type
- Other important factors: slope, subsurface hydrology, subsurface biogeochemistry.

Pesticide Removal

- VBs are effective with a capacity of 93.2%
- 30m buffer remove ~93% pesticides
- > 20 m does not increase removal efficacy significantly
- Studies mainly on herbicides k_{oc} = (100, 1000)
- Hydrophobic pesticides (e.g. Pyrethroids) could be removed at higher efficacy
- Width alone explain ~50% of the variations
- Other important factors: slope, Koc

Model uncertainties

- Oversimplified theoretical model
- Implementation settings and management scenarios of surveyed studies vary
- Lack of information on slope for N, P and pesticide removal
- Optimum buffer width for field implementation may vary from the model prediction

Conclusions

- Vegetated buffers are effective in removing agricultural non-point source pollution
- The relationship between removal efficacy and buffer width could be quantified in the model

$$Y = K \cdot (1 - e^{-b \cdot w}) \qquad 0 < K \leq 100$$

- Buffer width, slope and vegetation type are important design factors for mitigation efficacy
- Slope between 8-12% is optimal for sediment removal
- Further studies are needed to include other possible factors such as sediment particle size and pesticide properties.

ACKNOWLEDGMENTS

The authors thank California State Water Resources Control Board and the Coalition for Urban/Rural Environmental Stewardship (CURES) for financial support of the research.

Thank you!

Effects of slope

- Buffer slope varied from 2% to as high as 16%
- Sediment removal efficacy increases as slopes increase from 0 to 10%. Buffers steeper than 10% become less effective with increasing slope
- that with 95% confidence, a slope between 8.14 and 11.72% is optimum for removing sediments by vegetated buffers.