SETAC PRESS

Environmental Toxicology and Chemistry, Vol. 20, No. 3, pp. 669–678, 2001

Printed in the USA
0730-7268/01 $9.00 + .00

PROBABILISTIC RISK ASSESSMENT OF COTTON PYRETHROIDS: III. A SPATIAL ANALYSIS OF THE MISSISSIPPI, USA, COTTON LANDSCAPE

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(*Received* 15 *November* 1999; *Accepted* 16 *July* 2000)

Abstract—Estimates of potential aquatic exposure concentrations arising from the use of pyrethroid insecticides on cotton produced using conventional procedures outlined by the U.S. Environmental Protection Agency's Office of Pesticide Programs Environmental Fate and Effects Division seem unrealistically high. Accordingly, the assumptions inherent in the pesticide exposure assessment modeling scenarios were examined using remote sensing of a significant Mississippi, USA, cotton-producing county. Image processing techniques and a geographic information system were used to investigate the number and size of the water bodies in the county and their proximity to cotton. Variables critical to aquatic exposure modeling were measured for approximately 600 static water bodies in the study area. Quantitative information on the relative spatial orientation of cotton and water, regional soil texture and slope, and the detailed nature of the composition of physical buffers between agricultural fields and water bodies was also obtained. Results showed that remote sensing and geographic information systems can be used cost effectively to characterize the agricultural landscape and provide verifiable data to refine conservative model assumptions. For example, 68% of all ponds in the region have no cotton within 360 m and 92% of the ponds have no cotton within 60 m. Only 2% of ponds have cotton present in all directions around the ponds and within 120 m. These are significant modifications to conventional pesticide risk assessment exposure modeling assumptions and exemplify the importance of using landscape-level risk assessments to better describe the Mississippi cotton agricultural landscape. Incorporating spatially characterized landscape information into pesticide aquatic exposure scenarios is likely to have greater impact on the model output than many other refinements.

Keywords—Aquatic exposure Geographic information systems Remote sensing Landscape analysis Pyrethroid

INTRODUCTION

The use of conventional pesticide aquatic exposure assessment procedures to investigate the potential aquatic impact of cotton pyrethroids results in anticipated pond concentrations that suggest that no hazard exists for fish. However, the exposure:toxicity ratios for aquatic invertebrates indicate that further assessment may be required. Increasingly sophisticated modeling resulted in lower estimated exposure values, but the predicted exposures, decline curves, and impacts on invertebrates still did not reflect results from the extensive series of mesocosm studies conducted by the Pyrethroid Working Group companies and others in the 1980s [1]. As a result, the Pyrethroid Working Group decided to investigate the validity of some of the assumptions inherent in pesticide exposure assessment modeling procedures using what has been termed a landscape-level analysis. In current pesticide regulatory parlance, a sophisticated analysis of this type should be described as a tier III or tier IV risk assessment [2].

The approach taken by the Pyrethroid Working Group was to examine the probability that some of the key conservative modeling assumptions co-occur within a Mississippi cotton agricultural landscape. Although many of the underlying assumptions merit more detailed consideration, this analysis focused in particular on the following: a 10-ha watershed, 100% cropped with cotton, drains to a 1-ha pond; the runoff slope–length factor is 0.4 (equivalent in Mississippi to slopes ≥3%); all soils are of high erodibility; cropping and treatment occur up to the edge of the pond (i.e., no physical buffers exist between crops and water); drift toward the pond occurs from all applications (i.e., the wind is always blowing to the pond); and no marginal vegetation is present to reduce spray drift deposition from a field to the water body.

To investigate these factors, a relevant cotton-producing county was selected via a progressive approach from the universe of all cotton-producing United States (U.S.) counties. Remotely sensed Landsat Thematic Mapper™ imagery (Earth Resources Observation Systems, Sioux Falls, SD, USA) was spectrally classified to identify water bodies and land cover composition. This information was combined with many other data sets to permit a detailed analysis of the proximity between water bodies and cotton as well as the other factors listed above. Data on each of the approximately 600 ponds in this county was used as input to PRZM-EXAMS modeling to produce a probabilistic distribution of anticipated exposures reflecting the true cotton landscape [3].

MATERIALS AND METHODS

To investigate modeling assumptions, remotely sensed satellite imagery was spectrally classified to identify cotton, water bodies, and other land cover categories. This classification was combined with the U.S. Geological Survey digital line graph hydrology and transportation data sets. Soil and slope information was also incorporated.

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Selection of the study area—Yazoo County, Mississippi, USA

Selection of Yazoo County was a result of a process that examined all U.S. cotton-producing counties based on cotton cropped acreage, total area of water, and insecticide use. The logic tree was as follows, with the number of counties remaining after each step shown in parentheses. (1) Select all U.S. counties producing cotton (449). (2) Select the top 50% of these based on cotton acres in 1987 (225). (3) Select the top 50% of the above counties based on acres of water in the county (113). (4) Select the top 50% of the above counties based on reported insecticide usage (57). (5) Select the top 50% of the above counties based again on cotton acres (29). (6) Eliminate counties isolated from typical cotton areas (26). (7) Eliminate counties where water acres are dominated by marine water types or the Mississippi River (8). (9) Eliminate counties where probable local cooperation was poor (6).

Of the resulting pool of six counties, Yazoo County was selected because it represents both delta (flatland) and upland cotton cropping that will experience suitably worst-case rainfall occurrence and intensity. Fortuitously, Yazoo County has also been the setting for the modeling scenario for both preliminary and more sophisticated cotton exposure assessments for several years. Consequently, a U.S. Environmental Protection Agency–approved site-specific model input file was available for Yazoo County that proved very valuable in the final step of the pyrethroid exposure estimation and risk assessment [3].

Imagery and geographic information system data sources

The satellite image land use/land cover (LU/LC) classification was the primary data source from which the environmental characterization was conducted. The multispectral data allowed separation of different land cover types. The satellite image was a Landsat Thematic Mapper scene acquired in late July 1991 and consisted of seven spectral bands with a ground resolution of 30 m. This image was selected because of its cloud-free coverage of the region of interest and because the timing was appropriate for the most accurate classification of cotton and discrimination of cotton from other land cover types.

Hydrology data were used to enhance the water classification generated from the satellite imagery (see *Image classification* below). The final water classification used both the spectral characteristics of the satellite imagery and U.S. Geological Survey digital line graph (DLG) hydrology data. These DLG data were provided at 1:100,000 scale for Yazoo County [4].

Several of the analyses were performed using high-resolution aerial imagery. One hundred water bodies were imaged using true-color 9-in. aerial photography from a camera mounted in the belly of a light aircraft flying at a specified altitude relative to ground level. The 9-in. film positives were scanned and formatted for use by the image-processing system. The resulting images had an approximate footprint of 2.4 km per side and a spatial resolution of 1 m.

The baseline soil data used for this study were the STATSGO soil data produced by the U.S. Department of Agriculture Natural Resources Conservation Service (Washington, DC). Larger-scale watersheds for analysis of soil–slope characteristics were defined using the U.S. Geological Survey eight-digit hydrologic cataloging unit (HUC) boundaries [5]. The baseline elevation data digital elevation models were acquired at a scale of 1:250,000 for Yazoo County [6]. These data consist of a regular array of elevations referenced horizontally on the geographic (latitude, longitude) coordinate system. The unit of coverage of these data is a 1 × 1-degree block and elevations are in meters. The spacing of the elevations along each profile is 3 arc-seconds (approximately 90 m). The elevation data were used to confirm HUC watershed boundaries and to generate slope characteristics for the study area.

Image classification

The spectral information contained in the satellite image permitted the identification of different land cover types. Cotton was classified through a two-step process using ERDAS software (Version 7.5, ERDAS, Atlanta, GA, USA). The first step was to identify cotton in the study area using the spectral characteristics of the imagery together with in-field observations. A series of image-processing functions was used to group image pixels with similar spectral characteristics. Once identified, cotton field boundaries were visually delineated around each field and stray pixels within the field were then reassigned to cotton. After initial image processing of high- and low-resolution imagery in ERDAS image-processing software, all subsequent geographic information system data processing, storage, and output were performed using ArcInfo® software (Version 6, Environmental Systems Research Institute, Redlands, CA, USA).

The water classification utilized both the spectral characteristics of the satellite imagery and the DLG hydrology data. The DLG hydrology data consist of lines and polygons that have attributes specifying the type of water body represented. Digital line graph data were combined with the satellite classification and the attributes in the DLGs were used to identify all types of water. Because of the 30-m resolution of the satellite imagery, it was not possible to identify small or narrow water bodies (<30 m) using spectral characteristics of the satellite imagery alone. For these special-case features, the DLG hydrology information was used to provide the location and type of hydrology in the final classification. All classes that comprise other agriculture and vegetative land cover were identified using only the spectral characteristics of the satellite imagery. The final LU/LC classes generated for this study were cotton, other agriculture–bare soil, forest, pasture–brush, catfish ponds, rivers–streams, lakes–ponds, drainage ditches, irrigation canals, wetlands, and roads.

Figure 1 is a low-resolution representation of the LU/LC coverage showing the delta (western) half of the county and also the escarpment that separates the delta from the uplands. Interesting findings were that the largest water bodies were oxbow lakes (lakes arising from historical river meanders that became isolated from the main river channel as a result of natural sedimentation and flow changes) and that cotton seems to be frequently grown on the coarser materials deposited adjacent to old river courses.

Assumptions inherent in the data

The following five assumptions are inherent in the data used for this study and should be considered when interpreting the results. (1) Although all values in the report are quoted for Yazoo County, the Landsat image did not include the entire county—a small portion of the northeastern corner was not included in any of the analyses. (2) The resolution of the satellite classification is 30 m. As a result, land cover types not generated from separate data sets (e.g., rivers, streams,

canals, and roads from the DLGs) and having a minimum dimension less than 30 m were not consistently identified in the classification. (3) Pixels representing cotton mixed with other land cover types were classified so that they would most likely represent cotton land cover. A similar approach was used for water pixel classification. This was a conservative approach to ensure that cotton and water were not missed in the final LU/LC classification. Consequently, the cotton and water assignments overestimated the actual areas present. (4) All roads, streams, and irrigation canals were represented as being 30 m wide (1 pixel) unless they were identified in the satellite imagery as being wider than 30 m. Therefore, roads, streams, and irrigation canals less than 30 m wide had exaggerated areas in these analyses. This also contributed to overestimates of water acreages. (5) All agriculture in the high-resolution aerial imagery was assumed to be cotton, greatly exaggerating the potential interaction between cotton and water.

Proximity analysis

Proximity analyses were designed to provide information regarding the land cover composition near water bodies by measuring the acreage of various land cover types within specified margin distances of water bodies. For this paper, a margin is defined as a notional area created by drawing an imaginary line a fixed distance from the perimeter of a polygon of interest (e.g., a water body or a cotton field). In contrast, the term buffer is used in this paper to refer to the physical area between the edge of a water body and the nearest agricultural land.

Margins were generated around water bodies at four different widths (60, 120, 180, and 360 m) and the distribution of land covers within each margin was measured for each aquatic habitat type (rivers–streams, lakes–ponds, canals, wetlands, and catfish ponds). Figure 2 is an enlarged view of a portion of a proximity analysis showing the LU/LC classification for a margin of 360 m. The LU/LC classification was then used to identify both the total area of the margin and the total area of each of the land covers within the margin. The distances selected to generate margins around water bodies and cotton fields are multiples of the satellite imagery pixel size (30 m) and were chosen to reflect the likelihood of various levels of spray drift arising from aerial spraying of adjacent cotton.

The initial proximity analysis examined all the water bodies of each type within the county as a whole. A second analysis was performed to determine the amount of cotton within the four marginal distances around each individual static water body (597 lakes and ponds). The total margin acreage and the acreage of cotton in the margin for each water body were determined for each margin distance. This second analysis permitted closer, probabilistic assessment of the distribution of cotton near static water bodies in Yazoo County and afforded opportunities to understand how the occurrence of cotton in the margins varied with water body size.

Directional analysis

The spatial distribution of cotton near lakes and ponds was also measured to understand the directional relationship between cotton and static water, because this indicates the potential frequency with which spray drift from a cotton application is likely to occur. This information could be combined with wind speed and direction assessment to provide a detailed probabilistic assessment of the anticipated frequency of spray drift impacting water bodies.

To determine the spatial distribution of cotton in individual static water body margins, sample points along the perimeter of each water body were assigned, spaced approximately 30 m apart. Each of these points was examined to determine if cotton was present within any of eight different compass directions (N, NE, E, SE, S, SW, W, and NW) within each of the four margin distances (60, 120, 180, and 360 m). All directions from each sample point were analyzed, even those that crossed water. The results for each perimeter sample point were combined to produce results for the entire water body. Figure 3 shows two sample points on a water body using different margin distances. This water body has cotton located to the W, NW, N, NE, E, and SE directions within the 360-m margin, and cotton in the NE, E, and SE directions within the 180-m margin.

Runoff transport factors by hydrologic cataloging unit

The analyses in this section are designed to provide information on the associations between cotton cropping and key factors influencing pesticide runoff within the four eight-digit HUCs intersecting Yazoo County. Information on the slopes within each HUC was compared with those associated with cotton cropping, as well as the distribution of soil parameters including hydrologic group (a classification used by the U.S. National Resource Conservation Service reflecting soil permeability), K factor (reflecting soil erodibility), texture, and organic matter within each HUC. The resulting watersheds were visually checked with 90-m digital elevation model data and hydrology from the final land cover classification for quality control and accuracy.

Elevation data were used to generate slope classes for the entire study area. The slope data were then analyzed using only those areas identified as cotton in the LU/LC classification. Cotton fields were grouped by HUC and summarized by slope class.

Soil data were obtained by intersecting STATSGO soil polygons with the HUC boundaries to identify soil associations within each watershed. The STATSGO polygons are at the soil association level, whereas the characteristics of interest are at the soil series level. Accordingly, the soil series data were grouped using an area-weighted averaging technique to produce values for each soil association.

Buffer analysis

Buffer analyses using the aerial imagery provided high-resolution information (1 m as opposed to 30 m) regarding the land cover composition and widths of buffers separating agricultural lands and aquatic habitats. This analysis was only performed to a distance of 60 m to examine only those areas most likely to present cases of high potential exposure. In this way, the average buffer widths were not skewed by extremely large buffers from cotton found large distances away. These analyses provide information about the composition of buffers associated with each type of aquatic system (flowing, static, and irrigation canals), the total widths of the buffers and the widths of the land cover classes present within the buffers, and the extent to which water bodies are directly adjacent to agriculture with no mitigating buffer.

Using the satellite LU/LC classification, all water bodies that were proximate ($\leq$360 m) to cotton were identified and a stratified random sample was selected and imaged using aerial photography. Eliminating water bodies further than 360 m from cotton was done to bias the acquisition process towards

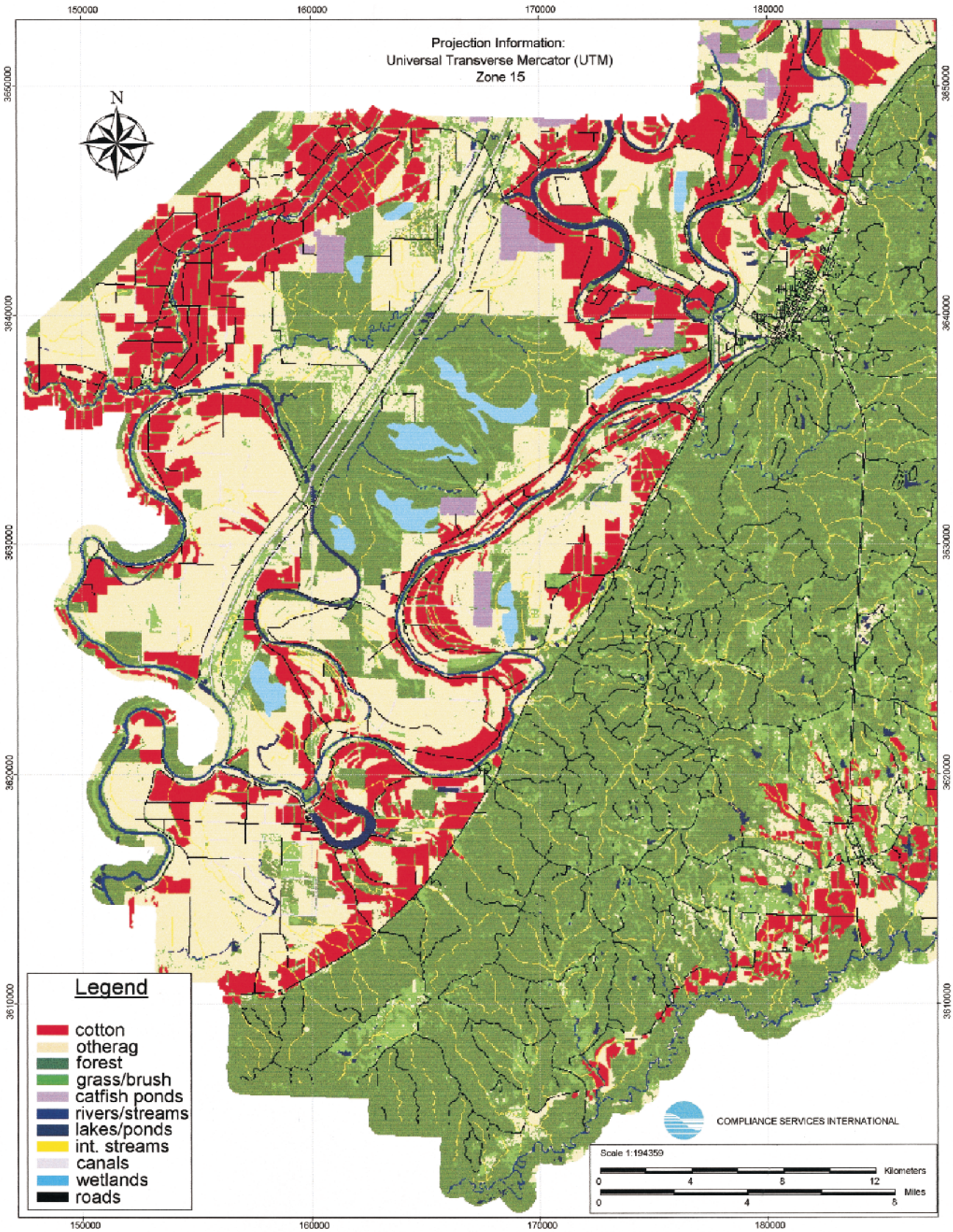
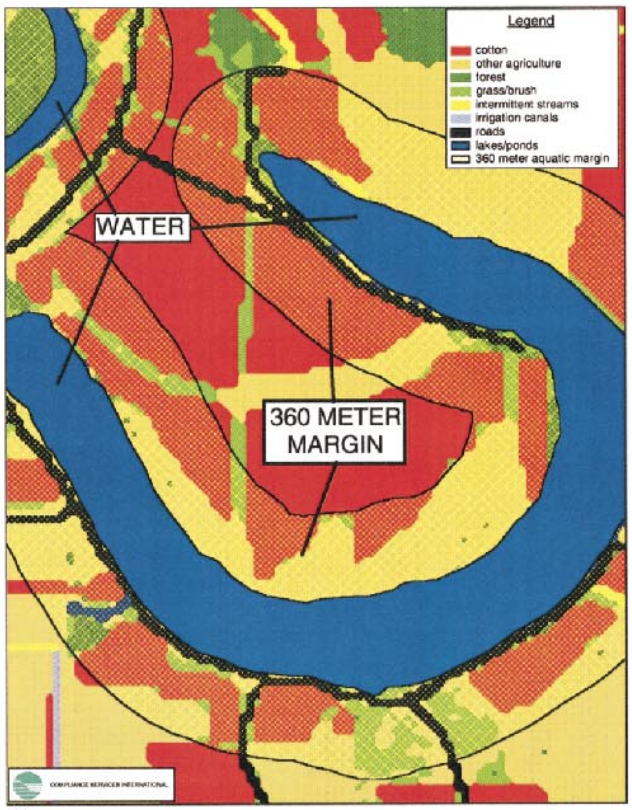


Fig. 1. Land use/land cover for the western one half of the study area.



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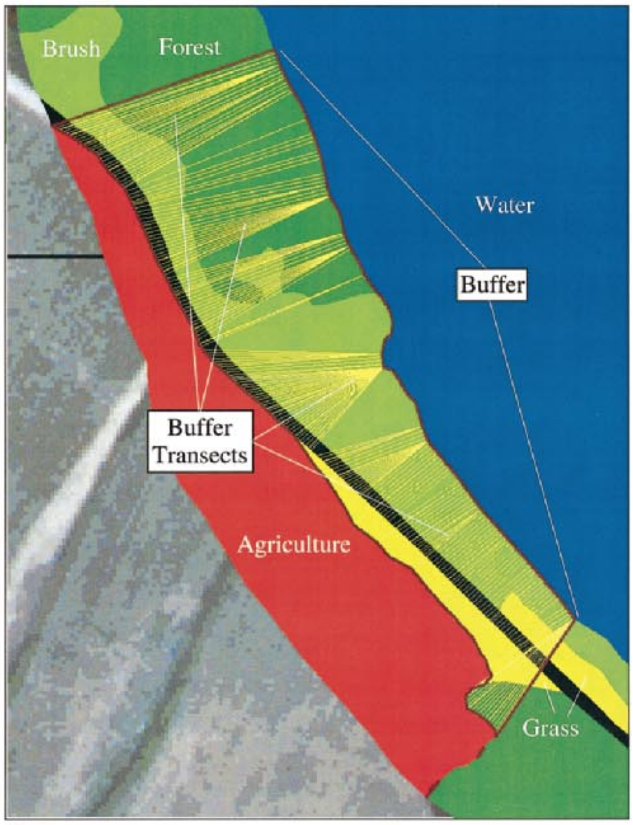

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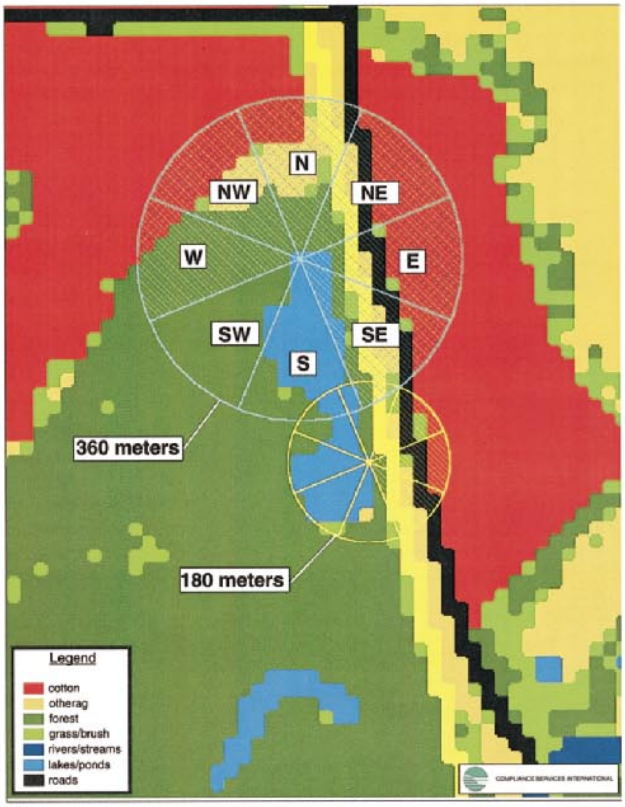

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Fig. 2. Delineation of the 360-m water margins for proximity analyses. The presence of land cover classes within the margins is indicated in shaded patterns.

Fig. 3. Determination of the spatial distribution of cotton in static water margins. The presence of cotton in a particular direction is symbolized by shading in the octant.

Fig. 4. Example of buffer area and buffer transects between agriculture and water.

Table 1. Static water body acreage and occurrence

Size class (acres)	Surface acreage of water bodies	% Total acreage of water bodies	No. water bodies	% Total number of lakes and ponds
<1	80	2	172	29
1 to <5	606	12	255	43
5 to <10	490	9	68	11
10 to <20	858	17	60	10
20+	3,143	61	42	7
Subtotal	5,177	100	597	100

the worst-case scenario for cotton–water proximity. For selection, linear water bodies (rivers–streams and canals) were divided into subunits based on the mean shoreline length of static water bodies found in the study area. Thus, the linear water bodies were incorporated into the stratified random sampling along with the static water bodies. The intent of the aerial imagery sampling methodology was to obtain a sample size large enough to provide 95% confidence that buffer width measurements were within 5 m (approximately five aerial image pixels) of the actual widths. Based on these criteria, 50 static and 50 flowing water bodies were selected and imaged. However, many of the images contained multiple water bodies and the final sample size was 169 water bodies, providing a 95% confidence interval of 3.4 m for buffer width measurements from aerial photographs.

All the area within 60 m of water was classified into a different LU/LC system using visual analysis of the high-resolution aerial imagery. Figure 4 illustrates the concept of the buffer analyses. The classes used were static water, flowing water, irrigation canal, agriculture, dense trees, sparse trees, brush, grass–pasture, bare ground, built-up land (buildings), and roads.

Buffer widths were measured using transect lines generated at 1-m intervals along the perimeters of agricultural fields within 60 m of water and drawn to the nearest point on the water body being examined. The length of each line segment passing through each LU/LC class within the buffers was measured to generate average buffer width and land cover width statistics. When calculating the overall buffer width mean, zero length transects were included if the field was directly adjacent to water. More than 65,000 transects between agriculture and water were generated and examined for this analysis.

The selected water bodies were also examined to identify those that border directly upon agriculture fields. The perimeter length comprising the direct agriculture–water border was recorded.

RESULTS

Land use/land cover classification

Based on the satellite imagery, cotton accounted for 13% of the study area acreage. Other agriculture and bare soil accounted for 23%, forest accounted for 40%, and pasture–brush accounted for 15%. All other LU/LC classes were 4% or less of the total area. After adjustments for the missing portion of the county and the exaggerated area of intermittent streams and farm roads arising from the merging of the DLG and remotely sensed coverage, the total acreage of cotton classified is 93% of that reported in the 1991 Mississippi Agricultural Statistics [7]. The intermittent drainage ditches were not included in the reported water analyses because they support no permanent aquatic populations and tend to be dry except immediately after a rainfall event.

The ability to distinguish cotton from other agriculture in the Landsat imagery was a critical component of this study. Four areas within the county, representing both lowland and upland cotton mixed with a variety of land cover types, were selected to calculate the accuracy of agricultural classification. Crop maps pertaining to the 1991 growing season were obtained from the Yazoo County Farm Service Agency office (Yazoo City, MS, USA). The four sample areas totaled more than 11,600 acres (4,695 ha), within which the cropping in approximately 90% of the fields was identified by the Farm Service Agency. Each Farm Service Agency–designated field was compared with the final LU/LC classification. Of the 233 labeled fields, 187 were classified correctly as either cotton or other agriculture, 23 more were classified as cotton when they were actually other agriculture, and 23 were classified as other agriculture that were truly cotton. Any pixels identified as cotton but not within a manually delineated field boundary were reclassified to the majority nonagriculture land cover class within a 5×5 window of pixels. Because of this processing methodology, instances of nonagricultural land cover classes being classified as cotton did not occur and this is reflected in the error matrix.

The U.S. Geological Survey LU/LC classification system recommends a minimum interpretation accuracy of 85% [8]. The overall classification accuracy was 80.3%, but much of the perceived inaccuracy was actually the result of the con-

Table 2. Acres of cotton in various margins around water bodies in Yazoo County, Mississippi, USA

	60-m Margin		120-m Margin		180-m Margin		360-m Margin	
Class	Acres[a]	%[b]	Acres[a]	%[b]	Acres[a]	%[b]	Acres[a]	%[b]
Rivers–streams	910	6	2,976	10	5,452	12	13,852	17
Lakes < 1 acre	6	1	47	2	116	2	608	4
Lakes 1–5 acres	21	1	119	2	298	3	1,377	5
Lakes 5–10 acres	13	1	38	1	92	2	505	5
Lakes 10–20 acres	24	2	106	4	229	5	835	7
Lakes 20+ acres	300	10	1,025	17	1,767	19	4,191	22
Catfish ponds	135	7	361	10	636	12	1,750	16
Canals	867	12	2,011	14	3,144	15	6,633	17
Wetlands	21	2	80	3	136	3	415	5
Total area of cotton	2,288	7	6,673	10	11,558	12	27,224	15
Total area of margin	34,245		68,199		98,827		186,907	

[a] Total acres of cotton within the aquatic margin.
[b] Percent of aquatic margin composed of cotton.

servative assumptions made during the conduct of the study. To meet the regulatory goals of this study, it was considered important to be conservative in the classification of cotton. This meant that if the actual classification of an agricultural land cover class was in doubt, the field was assumed to be cotton. With this conservative viewpoint, we can consider cases of commission (where other agriculture was classified as cotton) to be acceptable. This results in a 90.1% accuracy (210 conservatively classified fields of a total sample size of 233) in classifying the actual cotton pixels as cotton.

Cotton field sizes ranged from less than 10 acres (4 ha) to more than 500 acres (200 ha) with the majority of fields between 10 acres (4 ha) and 50 acres (20 ha). All the data reflected a clear division in landscape feature between the delta areas and the more hilly and dissected terrain toward the east of the county.

Water body size and frequency

Further analysis focused on static water bodies (ponds and lakes) because they are considered to represent the worst case for exposure and are the focus of existing pesticide aquatic risk assessment procedures. Exposure in flowing water bodies is mitigated by flow dilution, and wetlands tend to have extensive deposition zones to protect them from runoff entry with heavy foliage to help reduce spray drift.

The distribution of lakes and ponds by size class is illustrated in Table 1. More than 60% of the pond–lake acres were accounted for by just 42 water bodies larger than 20 acres (8 ha). These water bodies were generally long, narrow oxbow lakes formed by river course changes and occur in the delta area. Most of the smaller water bodies are found in the upland regions of the eastern portion of the county.

Proximity analysis

Table 2 summarizes the results of proximity analyses conducted on the entire class of each type of flowing and static water body for 60-, 120-, 180-, and 360-m margins. Using the worst case scenario analyzed (the 360-m margin around the water bodies), 15% of the marginal area was composed of cotton. Although a 360-m margin is not exactly equivalent to a watershed, these results differ substantially from the conventional exposure assessment modeling assumption of 100% cropping within the watershed. The 60-m marginal composition for all water bodies is only 7% cotton. Less than 10% of the cotton that occurs in the 360-m margin is within 60 m of a water body.

Lakes and ponds were analyzed individually to determine the frequency of occurrence and extent of cotton cropping within a specified margin distance for five water body size classes (Table 3). The average percent of cotton for each size class was derived using only the water bodies with cotton contained in the margin. Water bodies with no cotton in the margin were not used to compute the class average. For example, 70 of the 255 (27.5%) 1- to 5-acre static water bodies have cotton in the 360-m margin, and that margin is composed, on average, of 15% cotton. The remaining 72.5% of the 1- to 5-acre static water bodies (185 ponds) have no cotton in their margins.

Directional analysis

Table 4 summarizes the results of cotton directional analysis. These results indicate how often, and to what degree, water bodies are surrounded by cotton. For example, for water

Table 3. Cotton in margins of individual static water bodies in Yazoo County, Mississippi, USA

Water body size (acres)	Total number[a]	60-m margin			120-m margin			180-m margin			360-m margin		
		No. with cotton[b]	% With cotton[c]	Avg. % cotton[d]	No. with cotton[b]	% With cotton[c]	Avg. % cotton[d]	No. with cotton[b]	% With cotton[c]	Avg. % cotton[d]	No. with cotton[b]	% With cotton[c]	Avg. % cotton[d]
<1	172	7	4.1	15	13	7.6	20	19	11.0	18	43	25.0	14
1–5	255	14	5.5	16	30	11.8	16	45	17.6	15	70	27.5	15
5–10	68	1	1.5	97	7	10.3	15	12	17.6	12	26	38.2	11
10–20	60	8	13.3	12	11	18.3	17	16	26.7	15	26	43.3	15
>20	42	15	35.7	19	19	45.2	23	21	50.0	24	25	59.5	25
Totals	597	45	7.5	32	80	13.4	18	113	18.9	17	190	31.8	16

[a] Total number of water bodies in the study area.
[b] Number of water bodies whose margin contains cotton.
[c] Percentage of all water bodies in that size class whose margin contains cotton.
[d] Average percentage of margin that is cotton (including only water bodies whose margin contains cotton).

Table 4. Spatial distribution of cotton around static water bodies in Yazoo County, Mississippi, USA

	60-m margin			120-m margin			180-m margin			360-m margin		
Directions[a]	Number[b]	Percent[c]	Percent[d]	Number[b]	Percent[c]	Percent[d]	Number[b]	Percent[c]	Percent[d]	Number[b]	Percent[c]	Percent[d]
0 (no cotton)[e]	569	95.3	—	539	90.3	—	512	85.8	—	454	76.0	—
1	9	1.5	32.1	5	0.8	8.6	5	0.8	5.9	11	1.8	7.7
2	3	0.5	10.7	10	1.7	17.2	20	3.4	23.5	26	4.4	18.2
3	3	0.5	10.7	12	2.0	20.7	11	1.8	12.9	23	3.9	16.1
4	5	0.8	17.9	8	1.3	13.8	12	2.0	14.1	22	3.7	15.4
5	1	0.2	3.6	5	0.8	8.6	14	2.3	16.5	11	1.8	7.7
6	2	0.3	7.1	3	0.5	5.2	2	0.3	2.4	14	2.3	9.8
7	1	0.2	3.6	3	0.5	5.2	4	0.7	4.7	11	1.8	7.7
8	4	0.7	14.3	12	2.0	20.7	17	2.8	20.0	25	4.2	17.5
Totals	597	100	100	597	100	100	597	100	100	597	100	100

[a] Number of directions containing cotton.
[b] Number of water bodies with cotton in the specified number of directions.
[c] Water bodies with cotton in the specified number of directions, as a percentage of all water bodies.
[d] Water bodies with cotton in the specified number of directions, as a percentage of water bodies with cotton in the margin.
[e] Water bodies with zero directions containing cotton indicates that cotton is not present in the water body margin.

bodies with cotton within 360 m, only 17.5% had cotton present in all eight directions but this represents only 4.2% of the total number of water bodies in the study area (25 of 597). Even this case is not as extreme as it sounds because not every perimeter pixel in these 25 ponds has cotton within 360 m in every direction; it is possible to have cotton within 360 m of only eight separate points, each in a single different direction, to qualify the water body as having potential drift from all eight directions.

Note that the number of water bodies with cotton in a given number of directions is not cumulative. For example, a water body with cotton in three directions would not be counted as having cotton in two and one directions as well. Note that the number of water bodies that have cotton contained in their margin is smaller than the same measurement performed for the proximity analysis. This is due to slightly different methods (vector vs raster) of determining the presence of cotton in the water body margin.

Runoff analysis by hydrologic cataloging unit

A comparison of slopes for the study area as a whole and for cotton fields reveals that 83.9% of the total study area is 3% or less in slope, and 97.3% of cotton is grown on 3% or lower slope. Only 2.7% of all cotton is grown on greater than 3% slope, in contrast to the standard exposure modeling assumption that the slope–length factor is 0.4 (slope $>$ 3%) for cotton.

Analysis of the hydrologic group, texture, and soil erosivity K factors indicates that nearly one half of the soils are of hydrologic group C, with the remainder divided nearly equally between B and D types. The predominant soils are silt loams and silty clay loams with similar distribution across the HUCs.

High-resolution imagery buffer analysis

Buffer composition (Table 5) describes the type of land cover found between agriculture and water. Dense trees comprise at least 50% of the area between agriculture and water for all three water body types (54%, 69%, and 51% for static, flowing, and canals, respectively).

Table 6 presents overall buffer width statistics, summarized by water body type and the land covers that comprise those buffers. Overall buffer widths represent the total distance of nonagricultural land use between agriculture and water. Individual land cover widths represent those segments of the overall buffer that correspond to that specific land cover type. For example, an overall buffer transect may be 35 m, but can be composed of 20 m of dense trees, 5 m of sparse trees, and 10 m of grass. Because this analysis was based on 1-m aerial imagery, the minimum measured width for individual land cover types is 1 m.

The direct adjacency analysis indicates that of the 85 static water bodies used for this analysis, only 4 (4.7%) were directly adjacent to agriculture, accounting for only 5.1% of the total perimeter. For flowing water bodies, 24.7% of the perimeter is directly adjacent to agriculture, and for irrigation canals, 12.4% is adjacent to agriculture.

Table 5. Overall buffer acreage and the percent composition of the buffer for each land cover

Water body type	Overall	Dense trees	Sparse trees	Brush	Grass	Bare ground	Built-up land	Roads
Static water								
Acres	182.4	98.2	11.9	33.1	29.5	2.8	0.2	6.7
%	100	54	7	18	16	2	0	4
Flowing water								
Acres	406.3	281.9	41.3	32.7	30.9	8.5	0.1	10.9
%	100	69	10	8	8	2	0	3
Irrigation canals								
Acres	184.5	93.7	12.9	37.4	26.9	2	0	11.5
%	100	51	7	20	15	1	0	6

Table 6. Overall buffer width and the width of buffer land cover components for each land cover (in meters)

Water body type	Overall	Dense trees	Sparse trees	Brush	Grass	Bare ground	Built-up land	Roads
Static water								
Minimum	0[a]	1	1	1	1	1	1	1
Maximum	60	60	50	60	60	60	17	46
Mean	25	24	15	14	11	12	9	8
SD[b]	16	12	8	10	10	11	4	4
Flowing water								
Minimum	0[a]	1	1	1	1	1	1	1
Maximum	60	60	60	60	60	39	12	41
Mean	29	27	12	14	11	8	6	7
SD[b]	16	13	8	11	10	6	3	4
Irrigation canals								
Minimum	0[a]	1	1	1	1	1	—	1
Maximum	60	60	60	60	60	53	—	60
Mean	19	21	13	11	10	10	—	8
SD[b]	15	13	9	8	11	10	—	7

[a] A buffer width of 0 indicates that agriculture is directly adjacent to water.
[b] SD = standard deviation.

DISCUSSION

A detailed analysis of cotton agriculture in Yazoo County using remote sensing has provided an improved general understanding of this agricultural landscape as well as details describing key regulatory model scenario parameters for each of the 597 static water bodies in the county.

The LU/LC analysis indicated that cotton comprised approximately 13% of the study area and ground truthing showed that this was an accurate assessment. Water represents 4.4% or less of the study area. These data also provided the information necessary to focus further analysis on the static water bodies.

Proximity analysis showed that 65% of all cotton acres had no water of any type within 360 m. Analysis of the margins surrounding static water bodies revealed that 68% of all ponds had no cotton within 360 m, whereas 92% of ponds had no cotton within 60 m. Cotton was more prevalent within 360 m of the larger ponds (on average, 9–23% of the marginal area for pond size classes >10 acres) than 1- to 10-acre ponds (3–5%). For the subset of ponds with cotton within 360 m (190 ponds), 58% had no cotton within 120 m. These values show that the potential for spray drift and runoff routes is much lower than assumed in the standard aquatic exposure modeling scenarios. Most importantly, approximately 66% of static water bodies are unlikely to receive any exposure arising from cotton agriculture and, therefore, offer refugia with potential to be sources of recolonization.

Moreover, analyses of the spatial distribution of cotton around static water bodies showed that only 4% of ponds had the potential for wind from every direction to deposit spray drift on the water surface. Only 2% of ponds had cotton in all directions and within 120 m of the water. Only 43% of ponds with cotton within 360 m would receive drift from more than one half of the wind directions (assuming that the wind speed was sufficient to cause drift).

The last set of model scenario parameters investigated in this study examined slope and factors influencing soil erosivity in areas defined by the eight-digit hydrologic unit. Only 2.7% of the fields cropped to cotton had slopes ≥ 3%; 92.5% had slopes ≤ 2%. Similarly, although the soil erodibility K value selected using conventional exposure assessment modeling procedures would be 0.49, this value applies to only 24% of Yazoo County, whereas a value of 0.43 or 0.37 is appropriate for the remaining 76%.

Finally, high-resolution imagery provided detailed information on the buffers that separate water from agricultural fields. The results showed that ponds were infrequently (<5%) directly adjacent to agriculture, and of those ponds that did have direct adjacency, only 5% of their shoreline met this criterion. Additionally, 54% of static water body buffers were composed of dense trees with a mean buffer width of 24 m (± 12 m). Ninety percent of the pond perimeters had buffers at least 13 m wide.

This analysis generated detailed numeric values for replacing some of the standard factors in regulatory aquatic exposure assessments. However, analyzing some of the underlying assumptions that make even this analysis conservative is instructive. One example is in the proximity analysis. Although the assessment of the composition indicates how much of the notional marginal area is cotton, it does not reflect the fact that much of the area of the water body may be considerably further away than the notional value, especially with the long, linear water bodies in this county. Similarly, the directionality algorithm assesses the vulnerability of each pixel around the perimeter and although that spot might be subject to spray drift from cotton from a given wind direction, it does not necessarily mean that significant portions of the pond area will receive drift from that direction. Also, remember that the directionality assessment indicates the potential for drift; actual drift can only occur if the wind speed at the time of spraying is sufficient to cause drift. A significant approximation associated with this technique with currently unknown impact on the results is the use of a uniform notional margin around the water margins rather than an actual watershed based on topography.

The study shows that remotely sensed imagery coupled with a geographic information system can be used cost effectively to characterize an agricultural landscape and provide verifiable data to refine conventional model assumptions. These tools can be usefully employed for regional analyses. In addition, information on the individual ponds within a region permits a detailed assessment of the distribution of landscape com-

positions for use in probabilistic risk assessment. This study shows that regulatory model scenarios would benefit from incorporation of agricultural landscape information.

Acknowledgement—Support was provided by the member companies of the Pyrethroid Working Group: AgrEvo USA, Bayer, DuPont Agricultural Enterprise, FMC, Valent USA, and Zeneca.

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