LAND USE, SOIL EROSION, AND SEDIMENT DELIVERY IN TWO HUDSON RIVER VALLEY WATERSHEDS

A Final Report of the Tibor T. Polgar Fellowship Program

Craig A. Hart
Polgar Fellow

Yale University
School of Forestry and Environmental Studies
New Haven, CT 06511

and

Paul K. Barten, Ph.D.
Associate Professor
University of Massachusetts
Department of Forestry and Wildlife Management
Holdsworth Natural Resources Center
Box 34210
Amherst, MA 01003-4210

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ABSTRACT

Soil erosion and sediment delivery were estimated from 1683 to 1997 for the Stony Creek (Tivoli North Bay) and Saw Kill (Tivoli South Bay) watersheds. It was hypothesized that Stony Creek, originally named White Clay Kill, conveyed larger quantities of sediment to North Bay and contributed to the development of a raised cattail marsh. By contrast, we hypothesized that South Bay received less sediment and remained a shallow embayment with floating and littoral aquatic plants. Eight historical time periods were defined for relatively distinct and consistent agricultural land uses. For each time period, the proportion of the watersheds used for agriculture was estimated from a variety of sources. A GIS-based decision rule used proximity to roads, the Hudson River, and slope gradient (a proxy for soil texture, fertility, and suitability for agriculture) to distribute the settled areas across the landscape. Standard methods were used to estimate soil erosion rates; a digital terrain model was used to estimate sediment delivery. Although agricultural land use was more extensive in the Stony Creek watershed (up to 91%), cumulative sediment delivery to North Bay (129,000 Mg) was about one-half of the predicted loading to South Bay (258,500 Mg). This suggests tidal exchange with the Hudson River and differing trap efficiencies, not watershed characteristics and land use, have been the dominant influence on the current form and function of the Tivoli Bays.

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INTRODUCTION

Tivoli North Bay and Tivoli South Bay, centered at river mile 100 along the Hudson River, provide a novel opportunity to evaluate an unplanned natural experiment in wetland creation. These two bays have very different present forms, despite being geographically contiguous and connected to watersheds of similar size. Tivoli North Bay, once an open embayment, has developed into a raised cattail marsh. Tivoli South Bay remains an open embayment with littoral vegetation such as spatterdock and arrowhead along with a seasonal growth of European water chestnut (Fraser and Barten 1995).

There is no definitive work on how the bays reached their present condition. While there are a number of factors that may have contributed to the differences between the bays, we focused on historical patterns of settlement and agricultural land use in their watersheds. Our principal hypothesis was that the differential mass of accumulated sediment in the Tivoli Bays was caused, in part, by differing temporal and spatial patterns of land use and subsequent rates of soil erosion in the Stony Creek and Saw Kill watersheds. Since the two watersheds have equivalent areas and climate, direct comparison of their development characteristics was possible.

To test our hypothesis we quantified the changes in land use from 1683 to 1997 in the watersheds to reconstruct how these temporal changes interacted with the relatively static physiographic characteristics (e.g., terrain features, soils, etc.) of the watersheds. The quantification of the changing land use variable allowed us to estimate soil erosion in the watersheds and sediment deposition to the bays. Our study focuses on agricultural land uses, which accounted for up to 91% of land use during the study period, and does not consider industrial, manufacturing or other small-scale land uses.

SITE DESCRIPTION

The study site (Figure 1) encompasses Tivoli North Bay and the Stony Creek watershed (5,569 hectares) and Tivoli South Bay and the Saw Kill watershed (6,882 hectares). The Tivoli Bays are located in Dutchess and Columbia Counties, New York, and are part of the Hudson River National Estuarine Research Reserve. Cruger Island, a

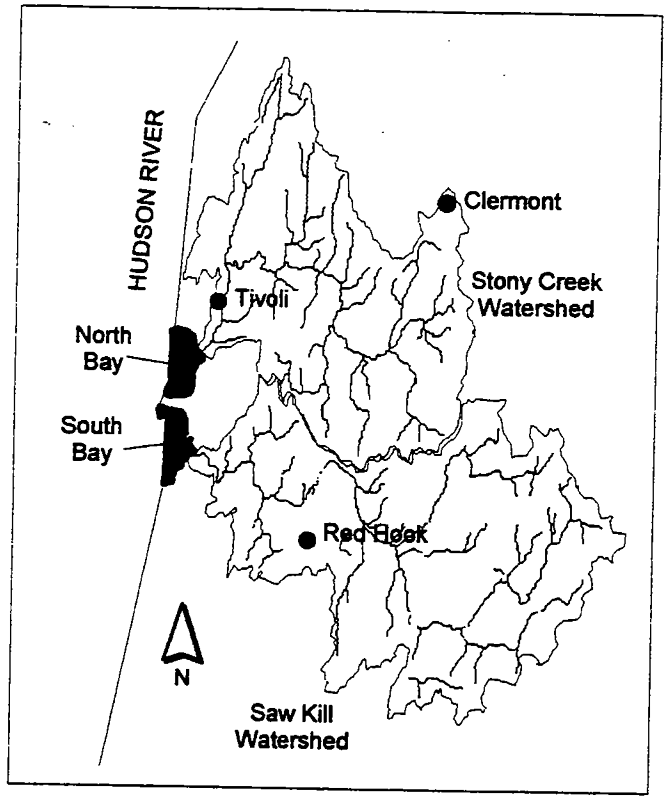


FIGURE 1: Location map for Tivoli Bays and the Stony Creek and Saw Kill watersheds, Hudson River Valley, New York.

peninsula, limits tidal exchange between the bays. Both bays are bordered to the west by a railroad causeway constructed in 1851. Tidal exchange with the Hudson River occurs through five bridge openings (Carey and Waines 1986).

The majority of the watershed system (73%) lies within the Town of Red Hook, Dutchess County. The Saw Kill watershed lies entirely within Dutchess County, with 74.2% in the Town of Red Hook and 25.8% in the Town of Milan. The Stony Creek watershed lies in both Dutchess and Columbia Counties with 70.8% in the Town of Red Hook and 29.2% in the Town of Clermont.

The Stony Creek and Saw Kill flow through glacial till and glacial Lake Albany clays and on to Normanskill Formation shales and sandstones (Carey and Waines 1986). Soils in the Tivoli Bays watersheds are quite varied, representing some 40 different soil types ranging across all textural classes. Yet, approximately 75% of the soils are silt loams derived from glacial till. These may be shallow (0.8 meters to bedrock) or moderately deep (2.3 meters to bedrock), with a relatively well-drained surface layer underlain by a poorly-drained layer (Reichheld and Barten 1992). Climate in the mid-

Hudson River Valley is influenced by continental polar and maritime air masses. Mean January and July air temperatures are -4 °C, and 23 °C, respectively. Annual precipitation ranges from 900 to 1,100 mm and is relatively uniform in distribution throughout the year.

METHODS

Historical data were collected to describe and quantify temporal changes in land use in the Stony Creek and Saw Kill watersheds. A review of regional and local history revealed distinct time periods during which land use patterns and agricultural practices were relatively constant. Based on this information, we subdivided our analysis into eight time periods. For each period we determined total area settled and proportions of different land uses (e.g., row crop, pasture, woodlot, etc.). Primary data were gathered from three sources: (1) historical references and interviews, (2) map interpretation, and (3) analysis of census data. Because available data and information varied for many time periods, so did our methods for estimating the total area of settled land. However, our methods were consistent between the watersheds for each time period.

We used the estimates of settled land to create GIS layers that depict the settlement patterns for each time period. The spatial distribution of settled areas was predicted with a decision rule using historical patterns of access to the Hudson River and roads, as well as terrain features. We calculated annual soil erosion for each watershed with the Modified Universal Soil Loss Equation (MUSLE) (Brooks et al. 1997) and sediment delivery to the bays using the Spatially Explicit Delivery Model (SEDMOD) developed by Fraser and others (1996).

RESULTS AND DISCUSSION

Land Use History and Time Periods

As noted earlier, eight time periods emerge as descriptors of land use history in this part of the Hudson River Valley (adapted from Danhoff 1969; Ellis 1946; Hasbrouck 1909; Hedrick 1933; Kim 1978; McDermott 1986; Secor 1939; Zimmerman 1988). They vary in duration from 30 to 70 years and encompass the dramatic changes in the landscape since European settlement began in 1683 (Table 1). Within each period the nature of agricultural land use and crop types remained relatively constant. Therefore, predictions of soil erosion and sediment delivery as functions of crop type and settlement pattern are derived from best estimates of watershed characteristics for each period. The salient details are discussed below.

TABLE 1: Historical time periods and land use in the Tivoli Bays watersheds, Hudson River Valley, New York.

before 1683	pre-European Settlement
1683 - 1720	Land Patent Period
1720 - 1750	Pioneer Settlement Period
1750 - 1820	Grain Period
1820 - 1860	Transition Period
1860 - 1910	Dairy and Manufacturing Period
1910 - 1950	Population Growth Period
1950 to present	Modern Era

Before 1683: pre-European Settlement

Prior to 1683, Mahican Indians lived on the eastern side of the Hudson River in the vicinity of what is now Dutchess County in small, permanent villages (Jeanneney and Jeanneney 1983; Secor 1939). Land between settlements was not inhabited and only small areas were cleared for crops (Secor 1939). The Dutch began to settle in the Hudson River Valley in the early 1600s, but did not colonize Dutchess County until later in the century (Jeanneney and Jeanneney 1983).

Several sources confirm that Native American settlement in the northeastern U.S. was extensive, and that forest clearing for agriculture and understory burning for hunting were significant (Thompson and Smith 1970; Day 1953). However, most archeological evidence indicates that the location of villages and agricultural practices were typically limited to floodplains (Whitney 1994). Significant settlements along floodplains in the region would have been limited to the Roeliff Jansen Kill to the north and Esopus Creek on the west side of the Hudson River (C. Lindner, Resident Assistant Professor of

Archeology, Bard College, pers. comm.). The floodplain areas of the Saw Kill and Stony Creek are thought to be too small and dispersed to have been cleared for Native American agriculture. Our assumption of complete forest cover is consistent with similar land use studies (Davis 1976; Howarth et al. 1991) for pre-European settlement.

1683-1720: Land Patent Period

European colonial settlement of the lands around the Stony Creek and Saw Kill watersheds began in the late 1680s. In 1683, the Province of New York was divided into counties and land patents were granted to "men of influence" to promote settlement (Hasbrouck 1909). Most of the land in the Stony Creek and Saw Kill watersheds (73%) was granted in 1688 to Colonel Peter Schuyler, henceforth known as Schuyler's Patent (Hasbrouck 1909). The remaining 27% of the watersheds not in the original Schulyer Patent corresponds to the portions of the watersheds that occupy the present day Towns of Milan and Clermont (Hasbrouck 1909). The Milan portion of the Saw Kill was part of the Little Nine Partners Patent and the Clermont portion of the Stony Creek watershed was part of Livingston Manor.

Little settlement occurred in the Stony Creek and Saw Kill watersheds until 1720. Schuyler's Patent was held as an investment and then was sold to other interests in 1704 and 1719. Settlement on the Little Nine Partners Patent was sparse through 1737 (McDermott 1986) and began on the Livingston Patent property in Clermont in 1715 with the arrival of a group of German Palatines (Hedrich 1933). Population and infrastructure data confirm this lack of settlement. In 1703, only 10 to 12 families lived in all of Dutchess County (W. McDermott, Local Historian, pers. comm.). By 1714, this number had grown to 49 families with only nine families living in what was known as the North Ward; a composite of Schuyler's Patent, Little Nine Partners Patent, and Rhinebeck Patent (Figure 2) (McDermott 1986). Except for the Post Road, no other roadways or mills were established in this area until 1720 (Hasbrouck 1909). This period of very limited settlement was represented in the GIS and subsequent calculations in a completely forested condition.

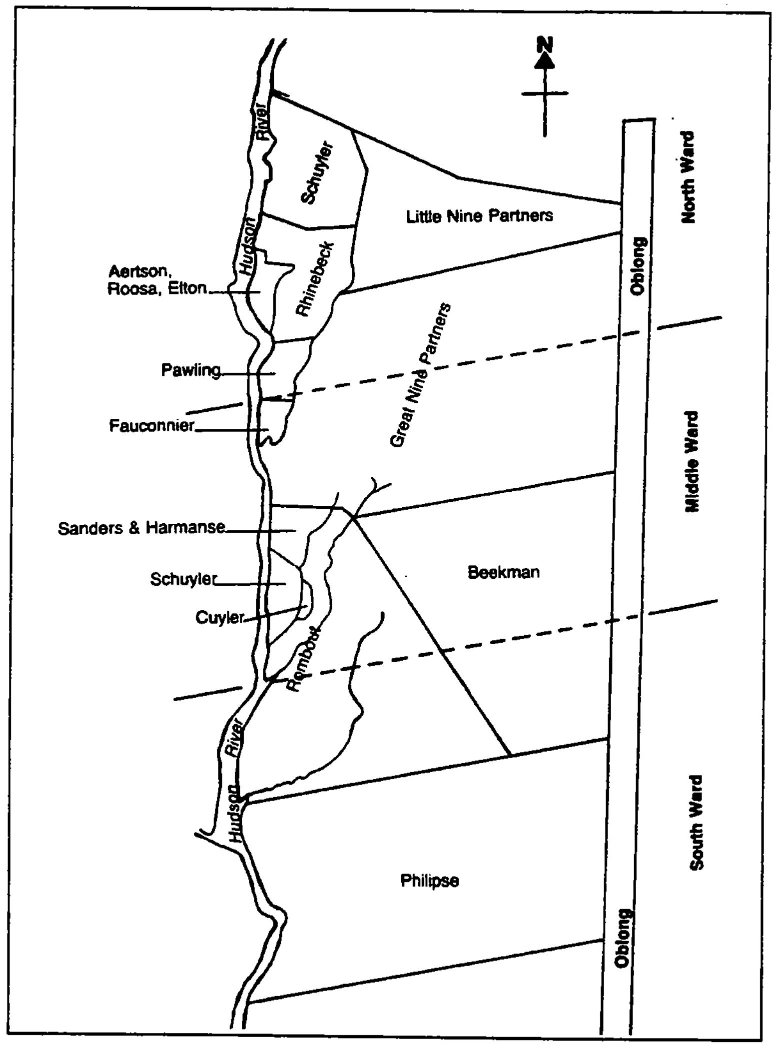


FIGURE 2: Map of land patents in Dutchess County, New York. Reprinted from McDermott (1986).

1720-1750: Pioneer Settlement Period

Clearing of forest land by pioneer settlers began in earnest around 1720 under the leasehold system. Owners of land patents actively recruited settlers who leased lands for farming (Hedrick 1933). Farms were nearly self-sufficient, and cash crops were rare (Secor 1939). Settlement rates during this period were slow. Population in the North Ward of Schuyler's Patent increased from 9 heads of household in 1714, to 121 in 1727, and 197 in 1737 (Hasbrouck 1909).

Land settlement increased moderately during the period without ever exceeding the degree of settlement of 1750 (McDermott 1986; Hasbrouck 1909). Unfortunately,

these data could not be converted into a meaningful estimate of area of settled land and, therefore, linear interpolation of more reliable estimates for adjacent time periods was used.

1750-1820: Grain Period

The year 1750 marks a turning point in land settlement patterns and population growth in Dutchess County (Secor 1939). The Little Nine Partners and Great Nine Partners Patents (Figure 2) in the middle and northeastern portions of the county were subdivided for sale. The end of the leasehold system in these areas sparked a rapid growth in settlement and associated population increases. The total population of Dutchess County was 1,727 in 1731, 14,148 in 1756, and 42,566 in 1790 (Hasbrouck 1909). Because the leasehold system continued in the Rhinebeck, Schuyler and Livingston Patents until 1840, the rate of population growth was less dramatic in the Stony Creek and Saw Kill watersheds (McDermott pers. comm.). Nevertheless, settlers continued to clear forest lands to grow grain. During the period of the Revolutionary War, Dutchess County was known for its wheat production and was referred to as "the breadbasket of the Northern Revolutionary Army" (Kim 1978). After the war, population increases in New York City sustained huge demands for wheat and Dutchess County farmers enjoyed prosperous times.

For this time period, we calculated the percentage of settled land by interpreting a 1797 survey map showing the roads, farms and mills in the Red Hook-Rhinebeck region (Figure 3). By transferring the watershed boundaries to this map, we were able to estimate the total number of farms in each watershed. The Thompson survey does not contain the Milan portion of the Saw Kill watershed nor the Clermont portion of the Stony Creek watershed. We estimated the number of farms in these areas with the farm density calculated from the Red Hook-Rhinebeck portion.

To estimate the total amount of settled land in the watersheds, we multiplied the number of farms by the typical farm size for this period. A review of historical literature reveals a wide variance in farm size in the Dutchess County region. Average farm sizes for different areas of the Hudson River Valley in the 1700s include: 218 acres for Schulyer's Tenants, 256 acres in the Beekman Patent (Kim 1978), 171 acres as the

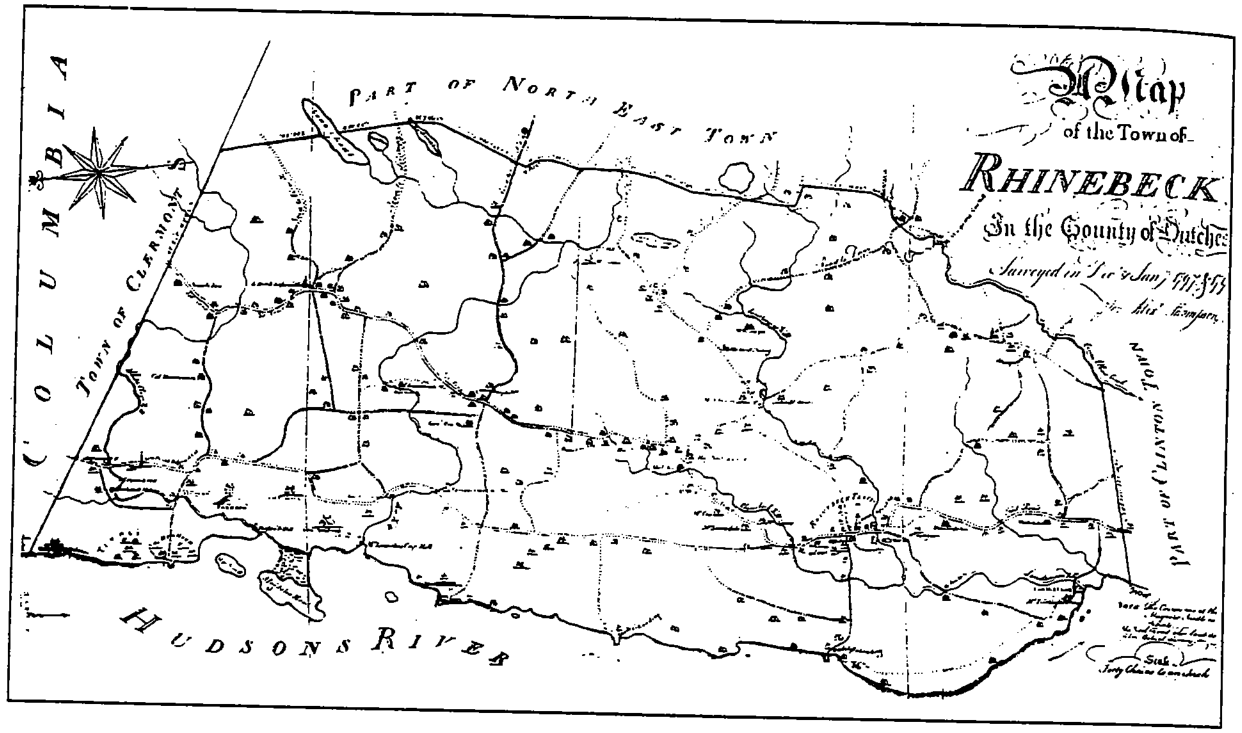


FIGURE 3: Survey map of Rhinebeck in 1797 (Thompson).

average leasehold for New York State, 128 acres for the Clermont estate, and 150 acres in the Red Hook region.

Preliminary results of William McDermott's (1986, 1997) ongoing research of farm conditions in the Red Hook-Rhinebeck region in the 1700s indicate that the median farm size during this period was 85 acres (McDermott pers. comm.). We elected to use 85 acres for our research with the view that a locally-derived estimate is preferable to general references pertaining to a larger region. It appears that the 85 acre median farm size is significantly smaller than other historical references because other research has calculated the mean farm size and included large landholdings that were probably not cleared and cultivated.

Several references establish that approximately 30% of the average farm during this period was maintained in forest to provide fuelwood for heating and cooking (Aldrich 1979; Goddard 1988; Kim 1978). Less than one percent of the average farm consisted of house and barn structures, home gardens, and small orchards (Kim 1978). The remaining area of the average farm (70%) was dedicated to wheat production (Kim

1978). Smaller quantities of corn, rye, and other grains also were grown for family use and livestock feed (McDermott pers. comm.). Thus, an average 85 acre farm of the period in the Stony Creek or Saw Kill watersheds probably retained about 25 acres of forest with the remaining 60 acres used for crop and livestock production (Figure 4).

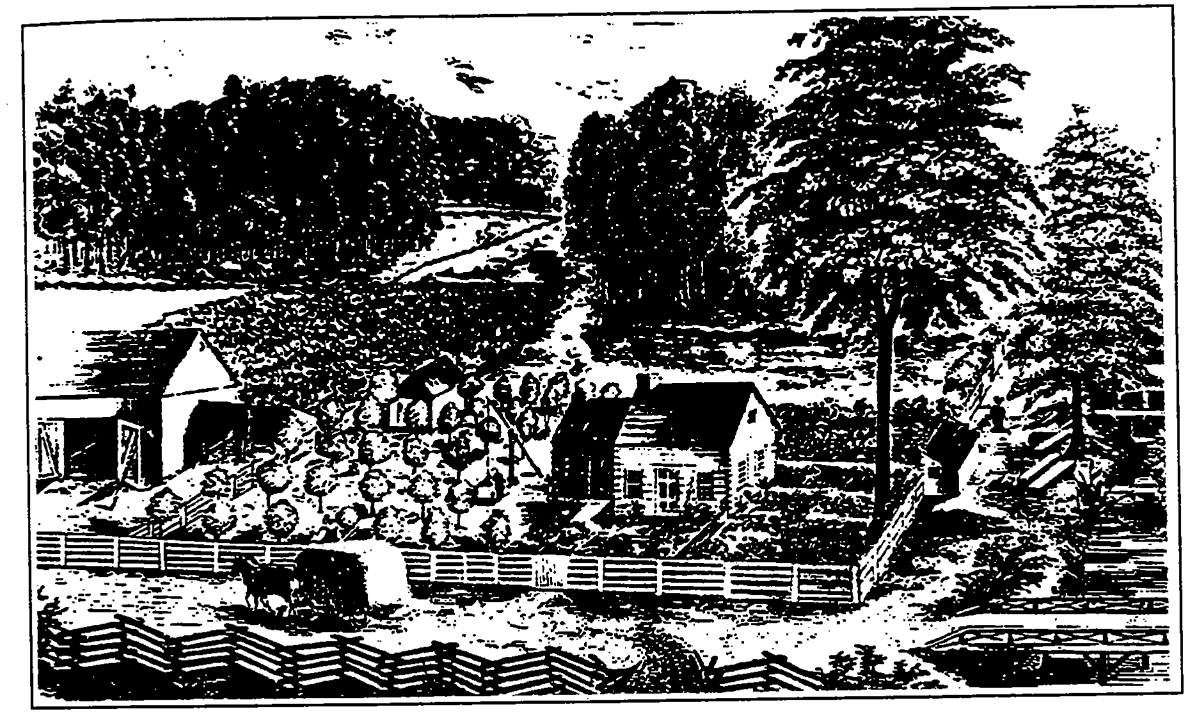


FIGURE 4: A New York farm in the late 1700s. Reprinted from Thompson (1977).

1820-1860: Transition Period

A transition in the agricultural practices of Hudson Valley farmers began in the years following the prosperous Grain Period. Several factors in the region combined to begin a gradual shift from wheat production and subsistence farming to dairy production and industrial expansion in the Hudson Valley (Danhoff 1969; Whitney 1994; Zimmerman 1988). The year 1820 marks the beginning of this transitional period.

The hilly, thin soils of eastern New York were quickly becoming depleted after decades of intensive wheat production (Jeanneney and Jeanneney 1983). Depletion of the soils was exacerbated by the infestation of black stem rust and the Hessian fly, both of which served to further deteriorate the quality of Hudson Valley wheat (Ellis 1946). With the opening of the Erie Canal in 1825, already struggling wheat farmers of eastern

New York were faced with ever increasing competition from western farmers. Wheat produced from the virgin, fertile soils of western New York and the Ohio Valley quickly upstaged the eastern wheat farmers and initiated the shift from wheat to dairy production.

Derivation of the amount of land settled during the time period 1820-1860 relied primarily on historical references. Macauley (1829) recorded the number of improved acres within each county in the State of New York in 1829. Improved land was interpreted to include all lands where forest cover had been removed. The fraction of the Stony Creek watershed in Columbia County was multiplied by the value of settled land for the county and summed with the similar product from the Dutchess County fraction of the watershed. The improved acreage in the Saw Kill watershed was calculated directly from Dutchess County data.

1860-1910: Dairy and Manufacturing Period

The completion of the railroad in 1851 allowed farmers to ship fresh milk to New York City. This solidified the importance of dairy production in the region and accelerated the transition from wheat production to dairying. Diverse farms that formerly maintained sheep and swine now added more cattle and cleared still more land for pasture (Jeanneney and Jeanneney 1983).

Increased demand for dairy pasturage led directly to increased rates of forest clearing. The development and commercialization of steamboats and locomotives also increased the demand for fuelwood, railroad cross-ties, and oak for shipbuilding. By the late 1800s, the clearing of land had peaked (Ellis 1946) and the landscape was a patchwork of small fields separated by stone walls and split-rail fences. The woodlot on the average farm had decreased in size from 30% of total farm area in the late 1700s, to approximately 12% of total farm area in 1875. The mean farm size in the Stony Creek and Saw Kill watersheds was approximately 115 acres (Hough 1877).

Detailed state census data exist for the years 1855, 1865, and 1875 and was organized by town, as well as by county. The state census data from these years is much more reliable than in previous years because it was conducted by appointees of the Secretary of State, as opposed to groups of people appointed by local town authorities.

This helped to minimize errors by standardizing the approach of census takers (Hough 1867).

The inclusion of town data in the census was particularly helpful for our study since it allowed the compilation of separate statistics for portions of the watersheds in the Towns of Milan, Red Hook and Clermont. By differentially weighting the state census statistics according to the amount of the watershed within each town, we were able to compare land use conditions in the Saw Kill watershed with those in the Stony Creek watershed and develop accurate estimates of both the percent of each watershed that was settled and the profile of land use on the average farm.

Our main reference point for the 1860-1910 time period was 1875 because it contained the most detailed agricultural statistics (Hough 1867). The 1875 census lists the total area of land contained in farms in each of the towns in the state. Total farm area was divided by the total number of acres of land in each town to derive the total percentage of settled land in each town for the year 1875. To arrive at the estimate of settled land in each watershed for the time period, the relative proportions of the watershed within each town were used to estimate weighted averages and the total settled area.

Following the calculation of settled land for each watershed in 1875, we turned to the categories of the census data that detailed the relative proportions of land use on the farms in each town to generate a profile of the average farm per watershed. In particular, we concentrated on the proportion of *improved* land (number of acres plowed, pasture, mowed for hay, or other) versus *unimproved* land, which includes areas reserved for woodlot and areas labeled as "other" (presumably including wetlands, rocky areas, and other "unusable" land). Table 2 summarizes the data that we compiled for Milan, Red Hook and Clermont. To estimate conditions on the average farm in the Stony Creek and Saw Kill watersheds from these statistics, we again used a weighted mean. For each watershed, the percentage of a particular land use (e.g., 18% for plowed land in Red Hook) was multiplied by the relative size of both towns in that watershed (e.g., 71% for Red Hook and 29% for Milan in the Saw Kill watershed). These products were summed to produce the overall percentage of that land use for each watershed.

TABLE 2: Agricultural Statistics for 1875 in the Towns of Red Hook, Milan, and Clermont, New York (New York State Census of 1875).

	Red Hook		Milan		Clermont	
	(acres)	(%)	(acres)	(%)	(acres)	(%)
Total Area in Farms (% of total watershed area)	20,607	87.7	22,805	82.1	11,255	97.7
Improved Land (% of total farm area)						
Area Plowed	3,733	18.1	5,006	21.9	2,900	25.8
Area in Pasture	3,131	15.2	4,415	19.4	1,413	12.6
Area Mown	8,611	41.8	5,306	23.3	5,054	44.9
Other	1,988	9.6	2,859	12.5	71	0.6
Unimproved Land (% of total farm area)						
Area in Woodlot	2,592	12.6	3,864	16.9	1,036	9.2
Other	552	2.7	1,355	6.0	781	6.9

1910-1950: Population Growth Period

After the turn of the century, the gradual decline of agriculture led to the abandonment of marginal land and subsequent regrowth of forests. Manufacturing and associated residential development increased and the population of Dutchess and Columbia Counties grew rapidly. For the time period 1910-1950, we quantified both the percentage and spatial distribution of settled lands in the watersheds. A land cover layer showing the actual areas of settled and forested lands was created from a 1938 USGS topographic quadrangle map. By convention, green areas on the map were interpreted to indicate tracts of remaining forest, while white areas were categorized as *settled* lands. This spatial information was digitized and then analyzed with the ArcView GIS package (ESRI 1996) at a 30 meter grid cell resolution.

1950 to present: Modern Era

The rural population of Dutchess and Columbia Counties continued to increase during the second half of the twentieth century as agricultural production declined.

Forest regrowth continued as more field and pastures were abandoned. Improved highway access brought more summer and suburban residents to the area.

Data for the Modern Era were developed with a combination of digital satellite imagery and 1:24,000 enlargements of 1995 National High Altitude Photography program (NHAP) color infrared aerial photographs. A land cover layer was developed with on-screen digitizing of the different land use categories using ArcView to display a 1995 Satellite Pour I'Observation de la Terre (SPOT) satellite image. The NHAP aerial photographs and field inspections were used to verify land cover classifications. Land cover was divided into five categories: forest, row-crop agriculture, pasture/mown areas, orchards, and development. The last four classes comprise the settled category. Roads, streams, and lakes were added to the land cover layer from the Tivoli Bays GIS database developed by Fraser and Barten (1995).

Summary of Land Settlement Over Time

Figure 5 depicts the shifting balance between forest and settled land in the Tivoli Bays watersheds. It illustrates two important trends. First, relevant to both watersheds, is the general pattern of land settlement from pre-European settlement to the present. Forests were cleared for agricultural purposes throughout the 18th and 19th centuries with the maximum amount of clearing in the late 1800s during the Dairy and Manufacturing Period (86% for the Saw Kill; 91% for the Stony Creek). The twentieth century marks the decline of agriculture and the natural regeneration of forests on abandoned farm lands. This pattern was typical of New York and New England (Foster 1992; Whitney 1994). Second, Figure 5 shows a larger proportion of the Stony Creek watershed was settled, at any given time, than the Saw Kill watershed.

GIS Modeling

Spatial Distribution of Settlement Patterns

Once the proportion of settled and forested land was estimated for each watershed and time period, GIS layers were created to spatially represent these changes. The distribution of settled lands in the watersheds was accomplished by creating an algorithm to mimic historical settlement patterns. Settlement appears to principally have followed

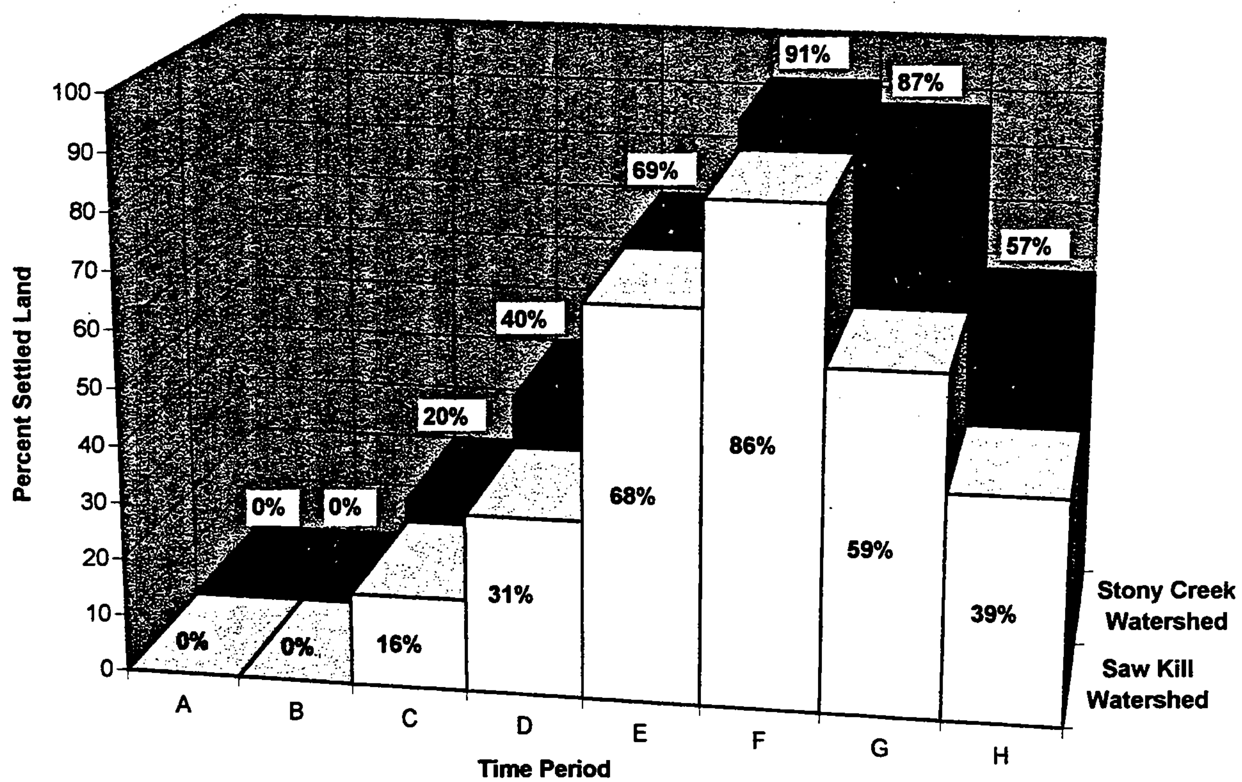


FIGURE 5: Percent of settled land during historical time periods for the Stony Creek and Saw Kill watersheds, Hudson River Valley, New York. Time periods: (A) Before 1683: pre-European Settlement; (B) 1683 - 1720: Land Patent Period; (C) 1720 - 1750: Pioneer Settlement Period; (D) 1750 - 1820: Grain Period; (E) 1820 - 1860: Transition Period; (F) 1860 - 1910: Dairy and Manufacturing Period; (G) 1910 - 1950: Population Growth Period; (H) 1950 to present: Modern Era.

existing road networks and to have moved progressively inland from the Hudson River. In addition, settlement was more likely to occur first on gentle slopes with deeper, fertile soils, with later development moving onto steeper slopes with shallow, stony soils. This settlement pattern was common throughout the northeast due to the direct correlation between slope gradient and desirable soil attributes for farming such as thickness, fertility, depth and water retention. Foster (1992) concluded that proximity to roads was the primary determinant of settlement patterns in his study of the Prospect Hill tract in the Harvard Forest in central Massachusetts. Although other factors such as market

conditions, land tenure, and demographic shifts also influenced settlement patterns, our decision rule used three parameters that can be consistently implemented with the GIS.

Distance from existing roads was calculated and valued so that regions closest to roads were assigned the highest values (most likely to be cleared and settled). Distance from the Hudson River was calculated next and assigned a range of similar values. The lowest values were assigned to the region immediately adjacent to the Hudson River because maps (Thompson 1797; Beers 1891) and other references indicated that this property was held by wealthy landowners and was not settled by individual farmers (R. Wiles, The Charles Ranlett Flint Professor of Economics, Bard College, pers. comm.). To the east of this relatively undeveloped region, a range of values were assigned decreasing progressively to the eastern boundary of the study area. Similarly, slope gradients ranging from level areas to steep hillsides were represented with a linear suitability scale from high to low, respectively.

Once these attributes were completed, an algorithm was developed to sum their overall influence on settlement patterns. The range of values derived for the distance from the Hudson River was assigned a base value of 1, while the value range for slope steepness was weighted by a factor of 2, and the value range for distance from existing roads, perhaps the most influential characteristic, was weighted by a factor of 5. The composite GIS layer representing likelihood of settlement was iteratively resampled, proceeding from the highest to the lowest value, until the appropriate total area of settled lands was reached (Figures 6 and 7).

Soil Erosion

The GIS layers for each period were used to solve the Modified Universal Soil Loss Equation (MSLE). MSLE extends the application of the Universal Soil Loss Equation to range and forest land. Empirically defined from field data, the MSLE equation is: $A = R\,K\,(LS)\,(VM)$; where A = predicted soil loss (tons/acre)/year; R = rainfall erosivity factor; K = soil erodibility factor; LS = slope length and steepness factor; and VM = vegetation management factor (Brooks et al. 1997).

The Tivoli Bays GIS database (Fraser and Barten 1995) includes four of the five parameters needed to calculate soil erosion with the MSLE equation: soil erodibility,

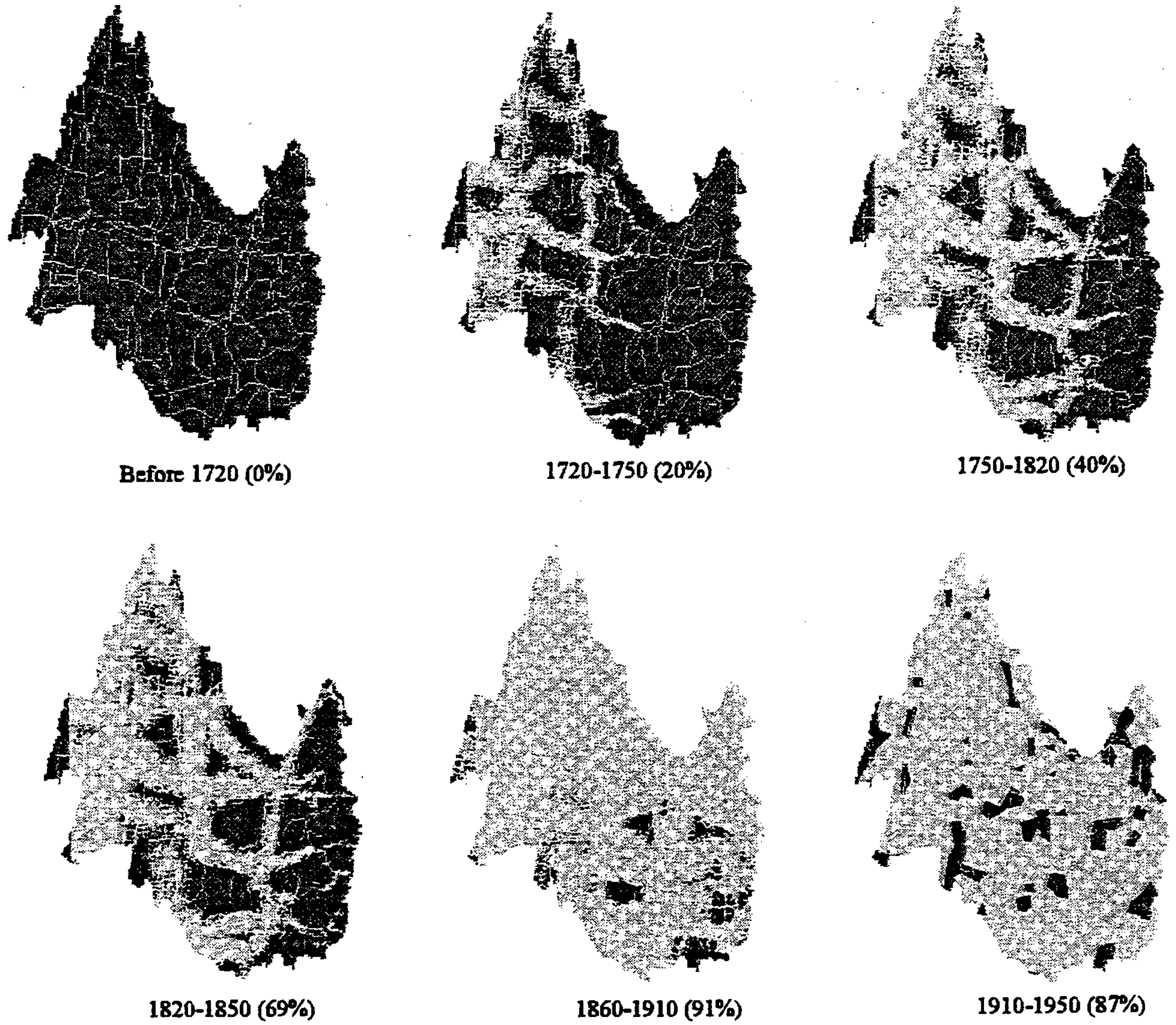
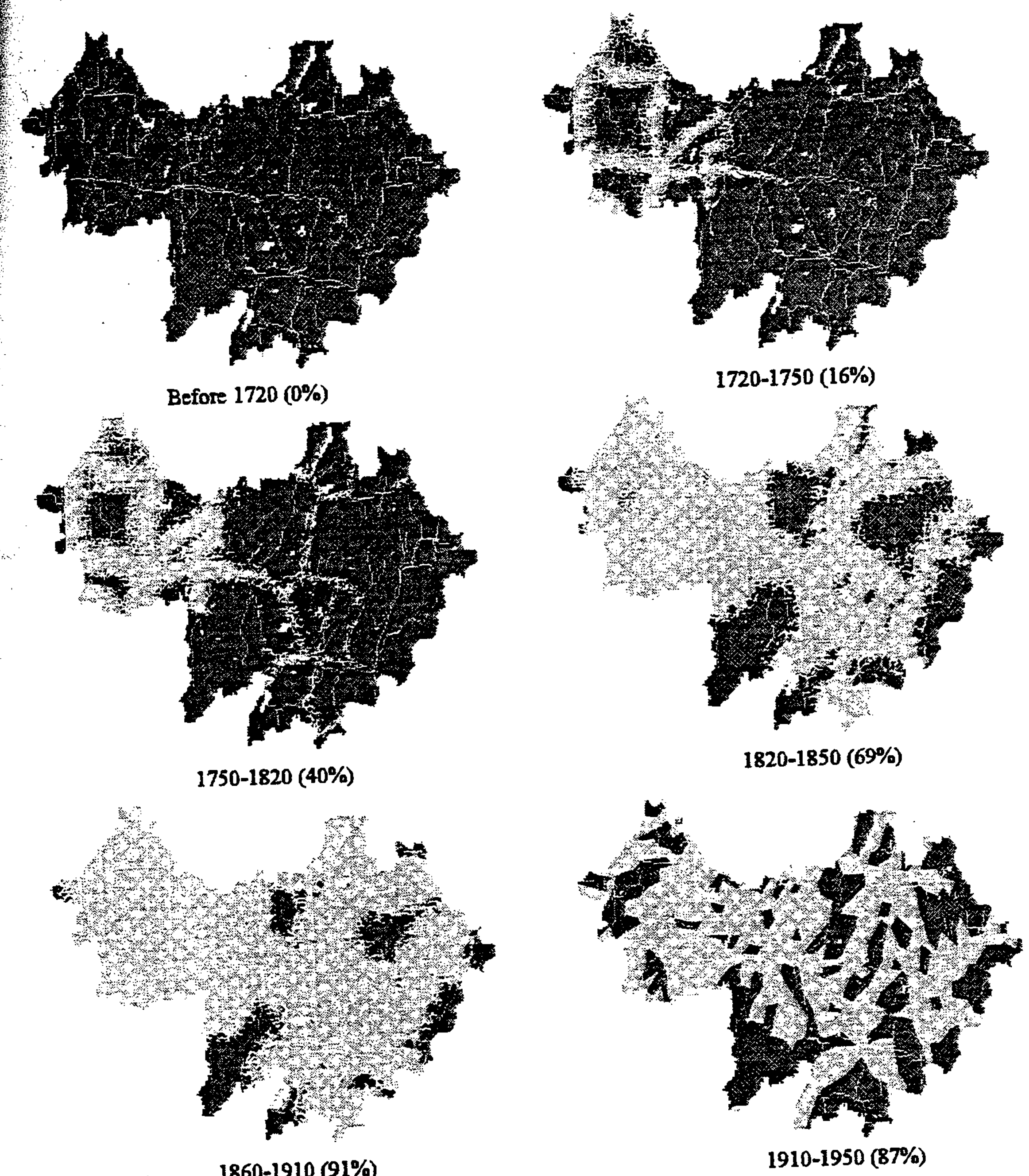


FIGURE 6: Predicted spatial and temporal distribution of settlement patterns in the Stony Creek watershed, Hudson River Valley, New York. Forested areas are represented with dark gray and settled areas with light gray. The (%'s) indicate percent settled land.



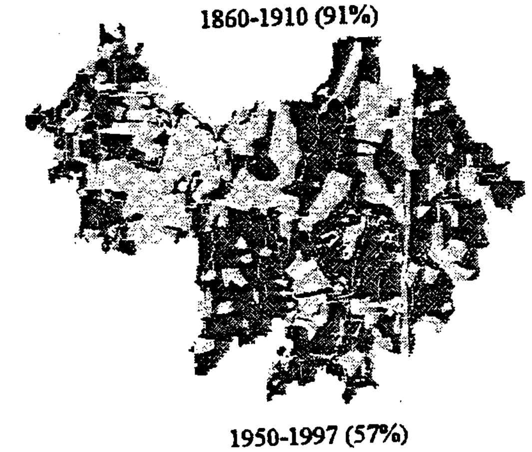


FIGURE 7: Predicted spatial and temporal distribution of settlement patterns in the Saw Kill watershed, Hudson River Valley, New York. Forested areas are represented with dark gray and settled areas with light gray. The (%'s) indicate percent settled land.

slope steepness, slope length, and rainfall erosivity. We used a constant R value because long-term meteorological data are not available before 1900. Although interannual variation in climate may have affected our predictions, the relative response of the watersheds is clear. For a detailed discussion of the MSLE parameters for the Stony Creek and Saw Kill watersheds see Reichheld and Barten (1992) and Fraser and Barten (1995).

The VM factor is the ratio of soil loss from land managed under specified conditions to the corresponding loss from bare soil. Hence, the values range from 0 for well protected, heavily vegetated land to 1 for bare soil. Table 3 lists the VM factors selected from USDA Soil Conservation Service (1975) tables for this study.

Settled lands in both the Stony Creek and Saw Kill watersheds for the period 1720-1820 were represented by a single VM factor. A value of 0.23 was selected based on historical references indicating that most of the cleared lands during this time were used for wheat production.

The inclusion of data by town in the 1875 State Census of New York allowed for the separate calculation of VM factors for settled lands in the watersheds in the time interval from 1820-1910. The VM factor used to represent the Transition Period and the Dairy and Manufacturing Period was based on the values in Tables 2 and 3. A weighted mean VM factor was calculated for the Stony Creek and Saw Kill watersheds. The 1875 census reported approximately half the plowed areas were used for corn and the remainder for oats, yielding a mean of 0.31 for tilled areas. The "Other" category in the *improved* lands section - farmhouse, kitchen garden, barn, outbuildings, and walkways - was represented with a single factor of 0.20. The "Other" category listed for *unimproved* lands - wetland areas, rock outcrops, and small ponds - was assigned a value of 0.

The average VM factor for settled areas calculated for the Population Growth Period of 1910-1950 was retrospectively estimated with the proportion of each land use characterized in the 1995 land cover-land use layer. Again, the percentages of different land use categories were determined for the Stony Creek and Saw Kill watersheds, multiplied by the appropriate VM factors, then summed to yield a composite VM factor for settled lands. The values of 0.34 for plowed lands and 0.10 for developed areas from

TABLE 3: A summary of Vegetation Management (VM) factors for soil erosion estimates in the Tivoli Bays watersheds, Hudson River Valley, New York.

Forested Land	0.002
Settled Land	
Improved	
Plowed Land	
1720-1820	0.23
1820-1910	0.31
1910-1997	0.34
Pasture Land	0.1
Mown Land	0.06
Orchards	0.003
Other	0.2
Unimproved	
Woodlot	0.002
Other	0

Reichheld and Barten's (1992) Saw Kill study were used for both watersheds. A value of 0.06 was used to represent pasture and mown agricultural areas. This value was derived by averaging the previously selected value for pasture (0.10) and mown (0.013) areas. This VM factor for open field areas dominated by perennial vegetation is the same as that used in Howarth et al. (1991) for pasture areas. Orchards and tree farms were assigned a value of 0.003 (Brooks et al. 1997).

For the Modern Era (1950 to present), the same VM factors were used as the 1910-1950 time period. These VM factors were applied directly to the land use categories created in the 1995 land use layer. Since the GIS layer for this time period includes the actual location of settled lands (pasture, crops, and developed areas), an average VM factor was not needed.

Annual soil erosion was multiplied by the number of years in each time period and summed to estimate cumulative soil erosion for each of the eight time periods. Annual soil erosion ranged from 100 to 4,400 Mg in the Stony Creek watershed and from

300 to 10,400 Mg in the Saw Kill watershed. Table 4 shows the annual and cumulative soil erosion.

Estimated annual soil erosion was consistently greater in the Saw Kill watershed. Furthermore, the two-fold difference in soil erosion was uniformly greater than the 1.2X difference in watershed area. This reflects cumulative differences in the interaction of land use with soil and terrain characteristics.

TABLE 4: A summary of soil erosion in the Tivoli Bays watersheds, Hudson River Valley, New York.

Watershed	Annual Soil Erosion (Mg/year)	Annual Soil Erosion per Unit Area (Mg/ha)	Duration (years)	Total Soil Erosion per Time Period (Mg)
Stony Creek				
1683-1720	100	0.02	37	3,700
1720-1750	500	0.09	30	15,000
1750-1820	1,700	0.31	70	119,000
1820-1860	2,200	0.40	40	88,000
1860-1910	4,200	0.75	50	210,000
1910-1950	4,400	0.79	40	176,000
1950-1997	2,000	0.36	47	94,700
Total	15,100			705,700
Saw Kill				
1683-1720	300	0.05	37	11,100
1720-1750	1,000	0.18	30	30,000
1750-1820	3,000	0.54	70	210,000
1820-1860	6,500	1.17	40	260,000
1860-1910	10,400	1.87	50	520,000
1910-1950	6,300	1.13	40	252,000
1950-1997	3,100	0.56	47	145,700
Total	30,600			1,428,800

Sediment Delivery

Only a portion of soil eroded in a watershed reaches the stream network and outlet. There are numerous opportunities for sediment deposition in small depressions, wetlands, densely vegetated riparian areas, behind small dams, etc. To account for storage effects most studies have relied on logarithmic functions to estimate sediment delivery ratio as a function of watershed area (ASCE 1975). However, as noted by Howarth and others (1991) in an earlier study of the Hudson River watershed, it would be preferable to use a method that represents the influence of site-specific watershed characteristics.

In a related project, we developed and tested a spatially explicit delivery model (SEDMOD) to predict the landscape-scale movement of nonpoint source pollutants via overland flow. The prototype model was tested with soil erosion-sediment delivery predictions on the 43 km^2 Little Beaver Kill watershed in the nearby Catskill Mountains (Fraser et al. 1996). An ongoing study is using the model to predict transport of fecal coliform bacteria from livestock areas to streams in a system of 12 sub-watersheds of the Saw Kill (Fraser and Barten 1995; Fraser et al. in press; Pinney and Barten 1997). In this project, we used SEDMOD to estimate sediment delivery to the Tivoli Bays from 1683 to present. The algorithm uses a digital terrain model to determine the flow-path from every grid cell to the nearest stream. Up to six parameters (flow-path gradient, shape [convex, planar, concave], surface hydraulic roughness, stream proximity, soil texture, and overland flow index) are used to derive a dimensionless delivery ratio (sediment delivered/soil eroded; range = 0 to 1) for each 30 meter grid cell. The soil erosion layer is multiplied by the result, a delivery ratio layer, to predict a net sediment delivery layer for the watershed. This operation was repeated for all eight time periods; results are summarized in Table 5 and Figure 8. As a consequence of their similar area and terrain characteristics, the Saw Kill and Stony Creek watersheds have a nearly identical total delivery ratio of 0.18. Hence, overall patterns of sediment delivery with respect to time parallel the trends described earlier for soil erosion.

TABLE 5: A summary of sediment deposition in the Tivoli Bays watersheds, Hudson River Valley, New York.

Watershed	Duration (years)	Annual Sediment Delivery (Mg/year)	Total Sediment Delivery per Time Period (Mg)
Stony Creek			
1683-1720	37	20	700
1720-1750	30	100	3,000
1750-1820	70	320	22,400
1820-1860	40	420	16,800
1860-1910	50	770	38,500
1910-1950	40	790	31,600
1950-1997	47	340	16,000
Total		2,760	129,000
Saw Kill			
1683-1720	37	60	2,200
1720-1750	30	180	5,400
1750-1820	70	540	37,800
1820-1860	40	1,210	48,400
1860-1910	50	1,920	96,000
1910-1950	40	1,070	42,800
1950-1997	47	550	25,900
Total		5,530	258,500

SUMMARY AND CONCLUSIONS

Our results lead us to reject the null hypothesis and raise a number of additional questions. Our primary hypothesis was that greater amounts of settlement over time in the Stony Creek watershed led to elevated levels of soil erosion and sediment delivery to Tivoli North Bay. Our historical research indicates that the Stony Creek watershed did, in fact, have higher percentages of settlement. However, this did not translate to larger amounts of soil erosion. It appears that physiographic characteristics of the watersheds that affect soil erosion (slope length, slope steepness and soil erodibility) interacted with

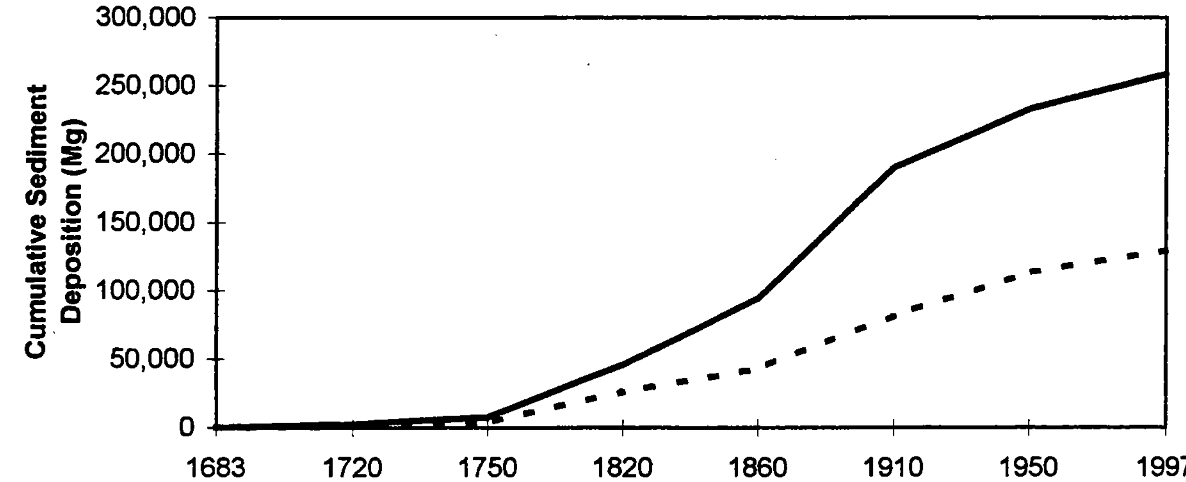


FIGURE 8: Estimated cumulative delivery to Tivoli South Bay (solid line) and Tivoli North Bay (dashed line) from 1683 to present, Hudson River Valley, New York.

the changing patterns of land use to generate greater rates of soil erosion in the Saw Kill watershed.

The greater rate of soil erosion in the Saw Kill watershed demonstrates that it is not necessarily the magnitude of a force that has the largest effect on a system, but often the location of the force. We predicted that the amount of clearing would be directly related to the amount of soil erosion in these watersheds. This theory has been widely documented in the literature (Davis 1976; Judson 1968; Meade 1969). Yet our research indicates that the location of forest clearing and settlement has an even greater influence on soil erosion than just an increase in open land. This underscores the importance of site-specific analysis and management of watersheds.

Many other factors also may have contributed to differences in the form of the bays. These include: (1) three acres of land reputedly subsided into Tivoli North Bay (Carey and Waines 1986); (2) large quantities of sawdust, crop residues and fine sediment may have been contributed by a sawmill, gristmill and brickyard that were operated on the banks of Tivoli North Bay; (3) small dams on the Saw Kill may have trapped sediment and reduced sediment delivery to Tivoli South Bay (Carey and Waines 1986); (4) the construction of the railroad in 1851 altered the tidal exchange with the river and may have caused less sediment to be deposited in Tivoli South Bay; and (5) the increased sediment trap efficiency of Tivoli North Bay as the marsh vegetation became established.

Our results shift the focus of sediment studies from differences in land use and watershed characteristics to other attributes of the ecosystem. They include, but are not limited to, (1) sediment routing along the Saw Kill and Stony Creek, (2) tidal exchange with the Hudson River, and (3) net sediment deposition in the Tivoli Bays. A combination of field, laboratory, and modeling research will be needed to further our understanding of the Tivoli Bays.

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