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Integrating lateral expansion into models of peatland development in temperate New England

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Summary

1 As peatlands form they create a temporal archive of community development, allowing the reconstruction of vegetation dynamics through the analysis of sediments and the development of detailed chronologies of successional change. Peatland formation occurs through two mechanisms: (i) terrestrialization, when a water body fills with sediments and peat; and (ii) paludification, the conversion of dry land to peatland. In temperate regions, where high summer temperatures may limit peat accumulation, general models of peatland development suggest that allogenic factors such as climate change control peatland development and that terrestrialization is the primary mechanism of formation.

2 This study evaluates this widely accepted model by comparing the developmental histories of three peatlands within the same climate region in New England in order to: (i) describe the development and timing of successional events among peatlands; (ii) document the roles of paludification and terrestrialization as developmental mechanisms; and (iii) evaluate the importance of climate change vs. autogenic factors in peatland development in this temperate region.

3 Basin morphometry, sediment stratigraphies, and chronologies of community change determined through radiocarbon dating indicate that peatland development at each site involved terrestrialization followed by paludification, with no apparent influence of broad-scale climate change on the timing of these processes. Paludification was consistently initiated coincident with the consolidation of a shrub mat across each lake-basin, and was controlled in extent and rate by the topography of the adjoining uplands. The timing of stratigraphic changes varied among sites, suggesting that autogenic factors associated with the accumulation of peat rather than regional climate change controlled development. These results provide the foundation for a model of temperate peatland development driven by autogenic factors and caution against the use of temperate peatland development as a proxy for climatic reconstruction.

Key-words: allogenic control, autogenic control, climate, paludification, terrestrialization, peatland, stratigraphy, New England

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Introduction

As substantial reservoirs of organic carbon, peatlands are a significant component of the global carbon cycle (Gorham 1991; Warner *et al*. 1993; Gignac & Vitt 1994). According to current models, climate warming and ensuing changes in water balance may greatly alter the dynamics of carbon sequestration by initiating carbon inputs to the atmosphere through enhanced decomposition or conversely by increasing peat accumulation rates in locations receiving greater precipitation (Gorham 1991; Mäkilä *et al*. 2001). Yet, fundamental questions persist concerning the dynamics of peatland ecosystems. How much regional variation exists in peatland development and what factors control the differences and timing of successional changes? These and other issues may be addressed through detailed study of the archive of peatland development preserved in partially decomposed plant material.

Peatland vegetation dynamics may be reconstructed by characterizing sediments and developing detailed chronologies of successional changes. Peatland formation occurs through two mechanisms: terrestrialization,

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when a water body fills with sediments and peat, and paludification, when dry land is converted to peatland. Terrestrialization is identified by the presence of open-water sediments, such as silt or lake mud, underlying peat, whereas paludification is recognized by the presence of peat deposits directly over mineral soil (Solem 1986; Foster *et al.* 1988; Korhola 1992, 1994, 1995; Mäkilä 1997). Following paludification, basal peat deposits are younger towards the peatland edge where expansion has occurred.

Although paludification is a major mechanism of peatland formation world-wide (Heinselman 1970; Frenzel 1983; Gore 1983; Johnson 1985; Glaser 1987), general developmental models for temperate regions suggest that high summer temperatures limit peat accumulation above the groundwater table (Transeau 1903; Damman 1979), and that terrestrialization is the primary mechanism of peatland development. Nonetheless, a few studies suggest that paludification may also be important in temperate regions such as New England in the United States of America (USA) (Thorson & Webb 1991; Zebryk 1991). Identifying the relative importance of terrestrialization vs. paludification therefore remains a critical challenge in understanding the long-term dynamics of these important ecosystems.

Many studies in North America (Dachnowski 1922; Winkler 1988; Zoltai & Vitt 1990) and Europe (Korhola 1995; Hansen & Engstrom 1996; Hendon *et al.* 2001) suggest that peatland initiation and development are closely tied to regional climate change. If such allogenic factors control fundamental shifts in peatland development then changes in succession or the rate of peat accumulation would be expected to occur synchronously across broad regions. For example, in the deep basins of some New England peatlands, alternating layers of peat and aquatic sediments (gyttja) suggest multiple fluctuations in the water table that presumably reflect major climate changes (Thorson & Webb 1991; Newby *et al.* 2000; Almquist *et al.* 2001).

Alternatively, numerous studies have documented that autogenic processes operating within the ecosystem are important drivers of peatland development (Clymo 1984; Foster *et al.* 1988; Foster & Jacobson 1990; Almquist-Jacobson & Foster 1995; Bunting *et al.* 1996; Bunting & Warner 1998). For example, lateral peatland expansion may be initiated when the water table rises due to the accumulation of partially decomposed peat with low hydrological conductivity (Ivanov 1981; Clymo 1984; Noble *et al.* 1984; Futyma & Miller 1988; Johnson *et al.* 1990). Clearly, sorting the relative role of allogenic and autogenic factors in controlling fundamental ecosystem processes is essential for both reconstructions of climate and forecasts of future changes.

In the current study, we compare the developmental histories of three peatlands within the same climate zone in order to: (i) determine similarities of developmental pathways and the timing of successional changes among peatlands; (ii) document the relative importance of paludification as a developmental mechanism in temperate peatlands; and (iii) investigate the roles of climate change vs. autogenic factors in driving peatland development.

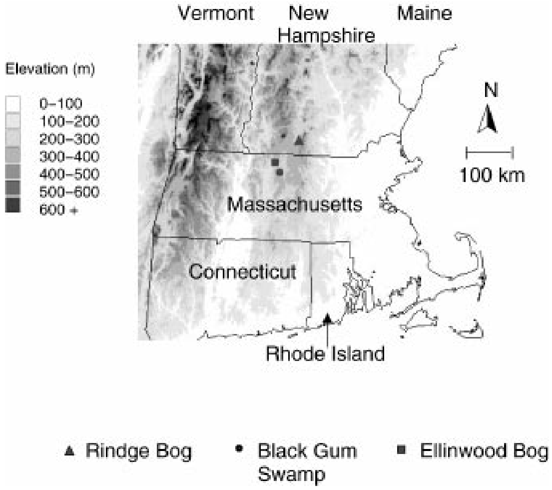

Fig. 1 Study site locations in New England, USA.

Methods

STUDY AREA

The study focused on three approximately 10-ha peatlands in central New England (Fig. 1) that currently support similar forest communities dominated by red spruce (*Picea rubens*), Eastern hemlock (*Tsuga canadensis*) and red maple (*Acer rubrum*). Located in the Central Uplands physiographic region of New England (Motts & O'Brien 1981), this moderately rugged area is characterized by north–south ridges and valleys and Palaeozoic bedrock of granite, gneiss and schist. Upland soils are moderate to well drained, acidic, sandy-loams formed in glacial till, with poorly to excessively drained soils in glacial outwash in some valleys and basins. Elevation ranges from 220 m to 410 m a.s.l. and regional deglaciation occurred approximately 14 500 cal YBP (Ridge *et al.* 1999). The regional climate is cool temperate and humid, with a mean July temperature of 20 °C and a mean January temperature of −7 °C. The annual precipitation of 110 cm is evenly distributed throughout the year (Rasche 1953). The regional upland vegetation is characteristic of the transition hardwood-hemlock-white pine forest region (Westveld 1956).

Sites were selected for similar vegetation and isolation from other peatlands, waterbodies and permanent stream systems. Black Gum Swamp, at an elevation of 365 m a.s.l. in Petersham, Massachusetts, occupies an irregularly shaped basin, drains to the south-west, and has a small mineral island in the north-centre. Rindge Bog in Rindge, New Hampshire, at an elevation of 335 m a.s.l., is a roughly triangular basin with an intermittent inflowing stream from the south and a larger intermittent stream draining to the north. Ellinwood Bog in Athol, Massachusetts, at an elevation of 258 m a.s.l. is roughly circular, with streams entering from the south and the south-east, no visible drainage and mineral islands scattered in a north–south band. All sites have pronounced hummock-hollow topography.

BASIN MORPHOMETREY AND STRATIGRAPHY

At each peatland, north–south and east–west transects were established at 25-m intervals, with grid points installed with an accuracy of ±1 m. Peatland margins, defined by the presence of peat and muck, were mapped and sediment depths were probed at each grid point. As the hummock-hollow topography produces height variation up to 75 cm, measurements were consistently made from a topographically low area close to the sample point. From these data, basin morphometrey was interpolated using SURFER (Golden Software 1994).

Peatland stratigraphy was described for every sample point at Black Gum Swamp (n = 146) and Ellinwood Bog (n = 139) and for all but 17 points (n = 142) at Rindge Bog. Peat and sediment samples were extracted using a Russian corer with a 50 × 5 cm chamber. Boundaries between different sediment types were rounded to the nearest 5 cm.

In the field, sediments were assigned to major types characterized by dominant matrix, macrofossils and colour. As the study sought to determine broad patterns of peatland development, minor variations in degree of decomposition or macrofossil composition were not recorded. Although transitions among sediment types were often clear and abrupt, the length of gradual transitions was recorded. Representative samples of the major sediment types were washed, sieved and examined under a light microscope (up to 3×) to identify macrofossil constituents (Levesque *et al*. 1988).

RADIOCARBON DATING

Basin morphometry and stratigraphies were used to select samples for radiocarbon dating, which were taken along two perpendicular transects running from the deepest portion of each basin to the upland. Transects were located on gentle slopes and samples were distributed to obtain both basal peat and gyttja. At Rindge Bog and Ellinwood Bog samples were also taken along the length of a core from a deep basin, whereas a comparable core had previously been dated at Black Gum Swamp (Zebryk 1991).

A total of 41 samples were collected and wrapped in plastic film wrap and aluminium foil. In the laboratory, each sample was scraped to expose uncontaminated sediments and 2–5 g subsamples were removed. Samples were dried for 6–12 h at 105 °C and sealed in plastic bags for AMS radiocarbon dating at the Radiocarbon Laboratory at the University of Arizona. Results were calibrated using Calib version 4.1 (Stuiver *et al*. 1998) and are reported as calibrated years before present (cal YBP).

Results

BASIN MORPHOMETRY AND STRATIGRAPHY

Basin depth is defined as the depth of organic sediments (peat or gyttja) to till or clay. Basin morphometry is consistent with surrounding topography and varies gradually with few abrupt changes. Black Gum Swamp has a deep basin in the north-eastern corner with a maximum depth of 6.5 m and small, shallow basins less than 2 m deep throughout the south-western lobe. Rindge Bog is dominated by a large steep-sided central basin with a maximum depth of 7.5 m. Ellinwood Bog is dominated by a large basin on the western side and has a small, steep-sided basin 5.7 m deep in the north-east.

Four stratigraphic sequences were observed: wood peat on till; wood peat over shrub peat; wood peat over gyttja; and wood peat and shrub peat over gyttja. Two dominant peat types were identified. Wood peat contained large wood fragments with small twig and sedge fragments. Shrub peat contained abundant small diametre (up to 1 cm) ericaceous wood fragments within a matrix of decomposed *Sphagnum* and fern rhizomes. This material was very coarse, medium brown, better preserved than the wood peat, and consistently found between wood peat and lake sediments (gyttja) in deep basins. The transition from shrub peat to wood peat was often gradual, occurring over 25–35 cm. Gyttja varied considerably in colour and texture. It was always found below peat and above till or clay and was typically medium brown with increasing amounts of macrofossil fragments near the boundary with the overlying peat. At greater depths, gyttja was grey/green with no visible macrofossils. Light to dark grey clay lined the deepest basins.

Stratigraphic patterns were highly consistent among and within sites, with an overall pattern from the bottom to the top of each peatland of mineral soil–gyttja–shrub peat–wood peat. There were no 'reversals' in stratigraphy. The amount of peat preserved increased with basin depth; wood peat was the surface deposit at all sites and was highly decomposed near the surface. Shrub peat was found only in deep basins. The shallowest areas had basal deposits of wood peat directly on till while intermediate depths had wood peat over gyttja with abundant macrofossils. In deep basins, wood and shrub peat overlie gyttja. Clay occurs at the bottom of the deepest basins.

At Black Gum Swamp in areas up to 100 cm deep and in one case to a maximum depth of 165 cm, wood peat occurs directly on mineral soil or till (Fig. 2a). In the southern basins, the typical stratigraphy is 85–100 cm of wood peat over macrofossil-rich gyttja. In the deep northern basin, wood peat or wood peat and shrub peat overlay gyttja. With increasing basin depth, the

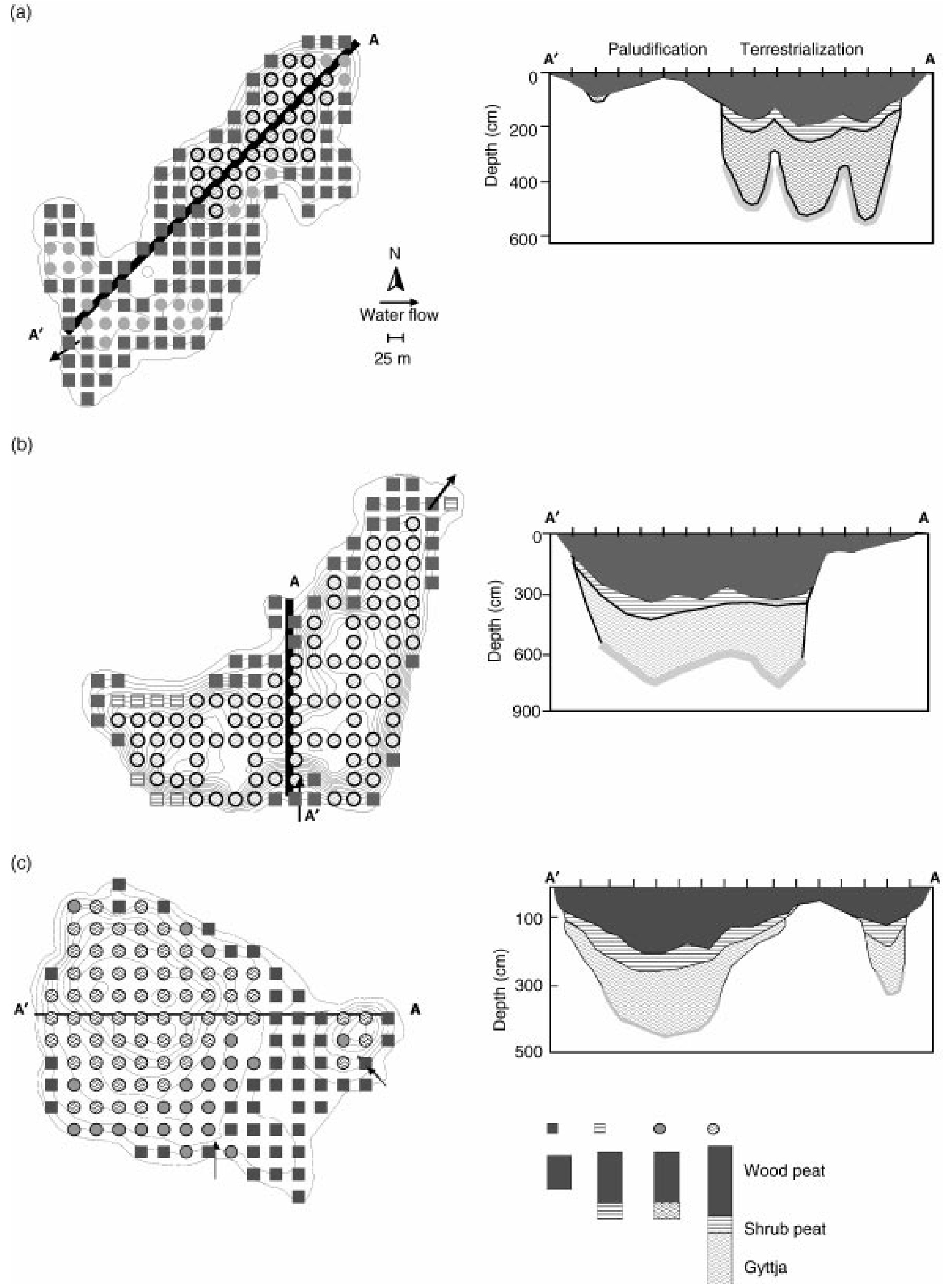

Fig. 2 Stratigraphy of each cored sample point with site cross-section. (a) Black Gum Swamp. (b) Rindge Bog. (c) Ellinwood Bog. Depth contour intervals 50 cm.

thickness of wood peat increases and gyttja occurs at greater depths. Shrub peat is found only in the deep northern basin. Clay occurs where basin depth exceeds 300 cm.

At Rindge Bog (Fig. 2b) wood peat and shrub peat form basal peat deposits. There is a range of 15–165 cm of wood peat deposited on mineral soil. Basal shrub peat 25–110 cm deep occurs under wood peat. The deep central basin has a consistent pattern of clay beneath gyttja, shrub peat and wood peat. With increasing basin depth, the amount of wood peat increases and the transition to gyttja deposits occurs at deeper levels. Clay occurs where basin depth exceeds 500 cm.

At Ellinwood Bog (Fig. 2c) wood peat up to 140 cm deep forms the basal deposit in a shallow zone around the perimeter of the site and along the shallow area between basins. South-west of this shallow area, towards the intermittent inflow, 60–135 cm of wood peat occurs over gyttja. In the two deep basins, the typical stratigraphy is a minimum of 110 cm of wood peat and shrub peat over gyttja. In the smaller eastern basin, macrofossils are present throughout the gyttja. Clay occurs where the depth exceeds 300 cm.

Macrofossil concentrations in the gyttja are consistently related to basin depth. In shallow areas, typically less than 2 m in depth, the gyttja contains many macrofossils. In deep basins, macrofossils are

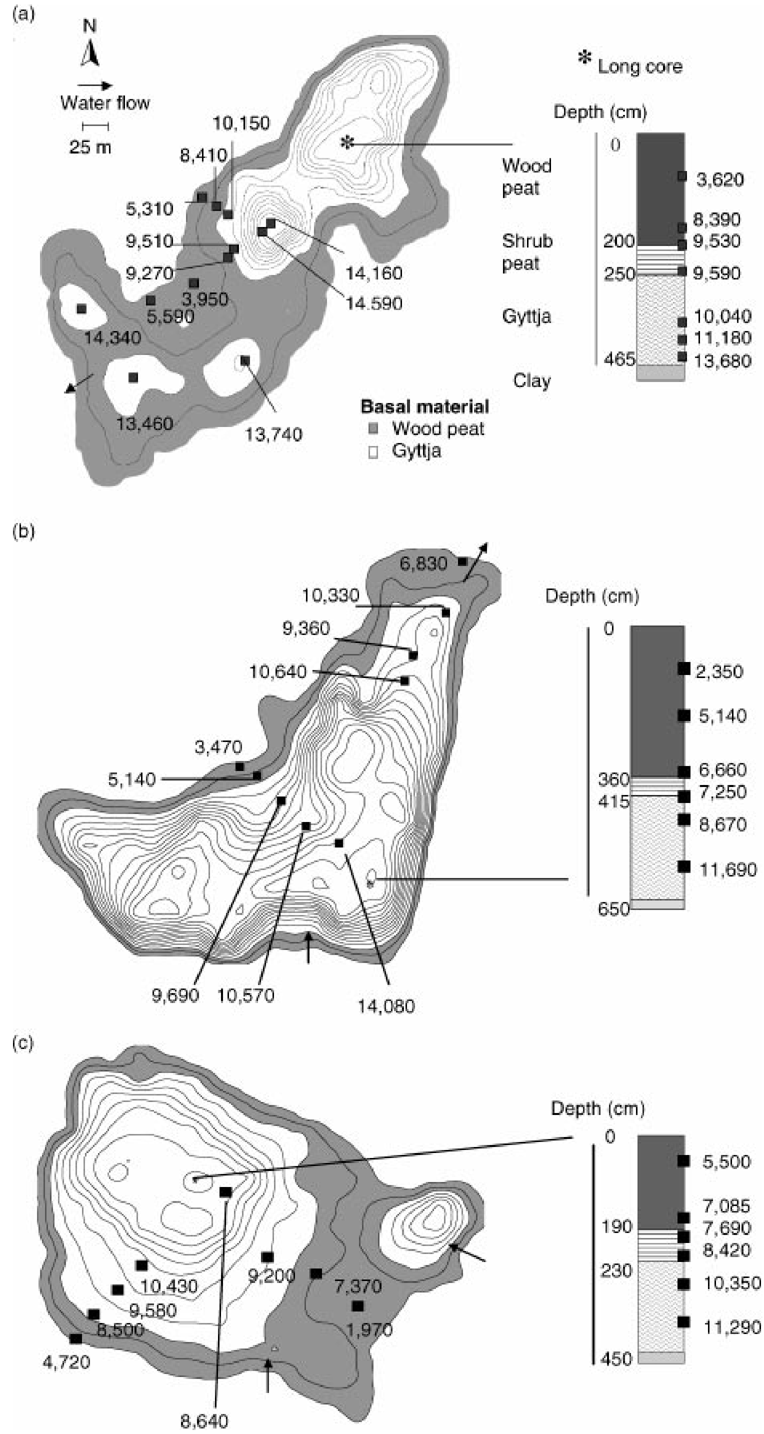

Fig. 3 Calibrated radiocarbon dates rounded to the nearest decade. (a) Black Gum Swamp. (b) Rindge Bog. (c) Ellinwood Bog. Depth contour intervals 50 cm.

abundant directly beneath peat deposits but decrease with depth. In locally deep areas in otherwise shallow basins, macrofossils are present throughout the gyttja.

RADIOCARBON DATING

At Black Gum Swamp (Fig. 3a) the basal gyttja sediments date from 14 590 cal YBP to 9510 cal YBP (data available from Harvard Forest Archives; Anderson 2001). In the centre of the deep northern basin, gyttja accumulated until at least 9600 cal YBP and was followed by an abrupt transition to shrub peat followed by wood peat. At the time of this transition, wood peat formed on mineral soil in the 50–100 cm contour interval. Wood peat accumulated on mineral soil in the 0–50 cm contour interval from at least 5590 cal YBP until approximately 4000 cal YBP, and continued to accumulate in the centre of the peatland until at least 3620 cal YBP.

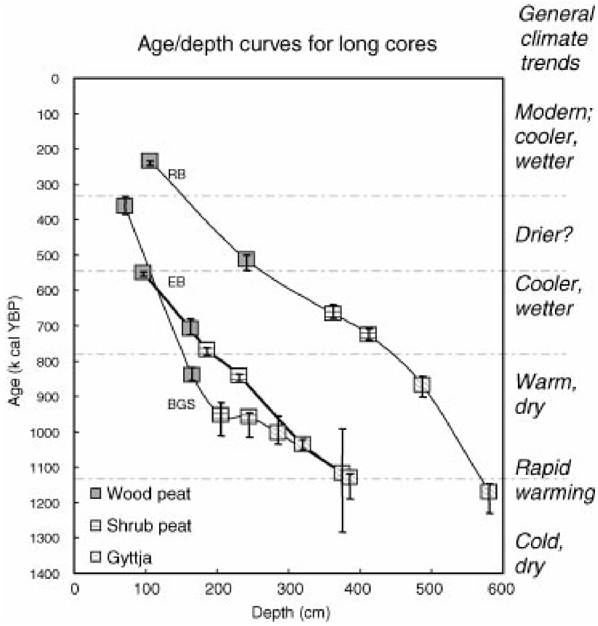

Fig. 4 Age/depth curves for long cores from each site with general climate trends based on Newby *et al.* (2000). BGS = Black Gum Swamp; RB = Rindge Bog; EB = Ellinwood Bog. EB samples are outlined in black and connected by a heavier black line. Error bars = ± 2 standard deviations from the median calibrated age. Lowest gyttja samples from each core are not included.

Rindge Bog (Fig. 3b) has basal gyttja dates ranging from 14 080 to 9360 cal YBP. In the deep basin, gyttja dates until 7250 cal YBP, when there was a distinct transition to shrub peat. Shrub peat formed until 6660 cal YBP, and graded into wood peat, which accumulated in the deep basin until at least 2350 cal YBP. By 6830 cal YBP, wood peat formed on mineral soil at the edge of the shallow northern lobe. On the steeper north-western edge, wood peat accumulated on mineral soil until at least 3470 cal YBP.

Ellinwood Bog (Fig. 3c) has basal gyttja dates up to 8500 cal YBP. In the centre of the western basin, open water conditions persisted until at least approximately 8420 cal YBP, when there was a sharp transition from gyttja to shrub peat. Shrub peat accumulated until at least 7690 cal YBP and graded into wood peat, which accumulated until at least 5500 cal YBP. Wood peat was deposited on mineral soil until at least 4720 cal YBP on the south-western edge and until 1970 cal YBP on the shallow eastern bench. One basal date on wood peat of 12 870 cal YBP is assumed to be contaminated (Anderson 2001).

Age/depth curves for the cores from the deep basin of each site vary considerably (Fig. 4). At Black Gum Swamp accumulation rates may have slowed during the formation of the bog mat, but with the large error bars for these samples this interpretation is not conclusive. At Rindge Bog and Ellinwood Bog there was little variation in accumulation rates.

Discussion

By comparing the histories and timing of successional events at three peatlands in the same climatic region, we were able to assess the timing and importance of terrestrialization vs. paludification in peatland development in central New England. Our results confirm that terrestrialization and paludification were both involved in peatland formation. However, differences in rates and timing of stratigraphic changes among sites suggest that autogenic processes and local topography exert greater control over development than regional climate change. Parallels in the pattern of development among the sites suggest that autogenic development may be generally important in the region and indicate the need for caution in using peatland development as a proxy for climatic reconstructions in temperate regions.

DEPOSIT AND SEDIMENT INTERPRETATIONS

Peat deposits are identified in this study as representing physiognomic vegetation types, with wood peat developing from swamp forests and shrub peat resulting from an ericaceous bog mat and other shrub vegetation. The transition from gyttja to shrub peat was consistently sharp, supporting the interpretation that the shrub peat represents the expansion of low woody vegetation over shallow water and lake sediments. The transition from shrub to wood peat was typically gradual, suggesting a lengthy successional process involving a range of shrub and forest communities. These interpretations are consistent with results from macrofossil studies of nearby peatlands as well as models of bog mat formation (Swan & Gill 1970; Kratz & DeWitt 1986; Zebryk 1991).

DEVELOPMENTAL HISTORIES AND DRIVING FORCES

While overall developmental patterns were consistent at the three sites, the timing of successional events varied substantially. Lake-infilling and terrestrialization were the initial mechanisms of peatland formation. In the deepest basins clay grades upward into organic-rich sediments generated by an open-water environment. Accurate dating of the onset of gyttja deposition is hampered by anomalously old basal dates that may be caused by contamination from older carbon in soils or by the incorporation of non-atmospheric carbon in aquatic organisms (Olsson 1979; Ridge *et al.* 1999). Over time, terrestrialization occurred, with lake sediments gradually filling the basins, shrub vegetation encroaching across the sediments and shallow water, and a swamp forest ultimately developing on the stabilized peat surface. At all three sites, the open shrub mat apparently lasted less than 1000 years before swamp forest gradually dominated (Fig. 4). In moderately deep basins swamp forest developed directly on gyttja without any evidence of an intermediate shrub stage.

Basin depth and size appear to be major factors in determining the timing of sediment changes during terrestrialization. Terrestrialization occurred 1000 years earlier in the small basin at Black Gum Swamp than at a larger basin of similar depth at Ellinwood Bog. Rindge Bog, the deepest and largest basin, was covered by a floating mat 2000 years after Black Gum Swamp. Overall, the three age/depth curves are relatively smooth, with no synchronous changes in peat stratigraphy or accumulation rates during terrestrialization that might indicate regional climatic control over accumulation rates (Fig. 4).

Paludification is indicated at all three sites by the presence of up to a metre or more of wood peat deposited directly on mineral soil or till without a layer of intermediate gyttja, and by the sequence of radiocarbon dates indicating progressively younger basal samples away from the lake basins. Lateral expansion appears to have initiated at different times at the three sites, but in each case occurred subsequent to terrestrialization. Variation in timing among sites suggests that lateral expansion, like overall peatland development, was more strongly influenced by autogenic factors than regional climate change. The extent of peatland expansion varied substantially in this topographically complex landscape. Due to the steepness of the surrounding hillsides, paludification at Rindge Bog accounts for approximately 25% of the current extent of the peatland. In contrast, at Black Gum Swamp, with its shallow slopes and multiple basins, paludification increased the size of the peatland approximately 40% and joined several smaller basins into one extensive peatland. Expansion may still be occurring in the south-eastern shallow lobe of Ellinwood Bog where the youngest basal sample is found.

MODEL OF FORESTED PEATLAND DEVELOPMENT

A model of forested peatland development in temperate New England is presented (Fig. 5). After deglaciation, lakes occupied depressions and clay focused into deeper basins (a). With time, lake sediments (gyttja) became increasingly organic and focused into the deeper section of large basins. In smaller basins, gyttja mixed with macrofossils from emergent and adjoining vegetation, forming a layer of macrofossil rich gyttja. Marginal shrub mats formed on the edge of the larger basins (b). Organic matter falling from the bottom of the mat mixed with gyttja and was deposited as gyttja with abundant macrofossils. At the edges of deeper basins, the shrub mat became grounded and a swamp forest slowly established (c). Wood peat began to accumulate under the swamp forest as the shrub mat grew and continued to expand and solidify (d). As the smaller basins became shallower due to in-filling, the swamp forest covered the basins and wood peat began to accumulate (c–d). The transition from shrub mat to closed swamp forest canopy was slow and gradual.

As peat with low hydrological conductivity accumulated, inflowing surface and ground water pooled at the margins of the peatland, resulting in a local rise in the water table and a decrease in rates of decomposition. This led to the accumulation of peat on previously forested upland sites and resulted in the lateral expansion of swamp forests (d–e). Lateral expansion could continue until further increases in the water table water are precluded when water levels reach a drainage outlet or the climate changes.

Conclusions

This study documents the lateral expansion of peatlands as a result of paludification in New England and demonstrates that terrestrialization alone is not an adequate model for temperate peatland development. Similar developmental pathways among sites suggests that autogenic peatland development may be a regionally important process, with the extent of paludification largely determined by local topographical constraints. With little evidence for synchronous shifts in peat stratigraphy or accumulation rates, our results suggest that temperate peatlands may be inappropriate proxies for regional climate reconstructions.

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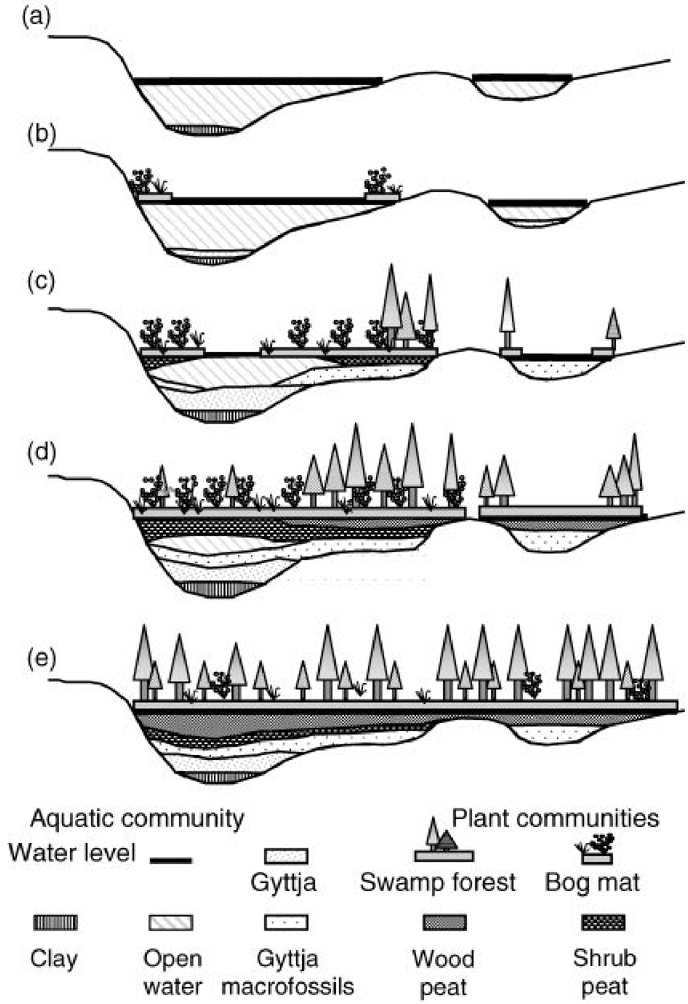

Fig. 5 Model for forested peatland development in central New England. The events in the two basins are not assumed to be synchronous. Letter C is based on Kratz & DeWitt (1986).

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