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Hydrologic Recovery of Snow Accumulation and Melt Following Harvesting in Northeastern Ontario

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ABSTRACT

Hydrologic recovery is the restoration of the hydrologic characteristics of harvested forest sites to preharvest conditions, and is closely linked to sustainable forest management. We examine the hydrologic recovery of snow accumulation and melt in regenerating forest stands in the boreal forest of northeastern Ontario. Peak snow water equivalent in clearcuts was generally greater than that in regenerating and undisturbed stands; however, mean melt rates were largest in stands experiencing initial regeneration. This led to different rates of hydrologic recovery for these two properties, such that peak snow water equivalent had recovered to ~80% of that in undisturbed forest stands within ~15 years after harvesting, while there was less than 50% recovery of mean melt rates by that time. Hydrologic recovery in the boreal forest of northeastern Ontario may be more protracted than in other North American forest landscapes, and this must be considered when assessing the hydroecological consequences of forest harvesting in this region.

Keywords: boreal forest, snow accumulation, snowmelt, forest harvesting, canopy properties, hydrologic recovery.

INTRODUCTION

Black spruce-dominated forests in the low-relief landscape of northeastern Ontario are currently undergoing extensive harvesting, largely in the form of clearcutting. There is great interest in the hydroecological consequences of this harvesting for receiving waters. Snow accumulation and melt are important hydrologic events in this landscape. Impacts of forest harvesting on both processes are relatively well understood, largely on the basis of research conducted in other forest types. In general, clearcuts exhibit greater snow water equivalent (*SWE*) than nearby forested areas due to: (1) elimination of interception; (2) reduced sublimation of snowfall; and (3) redistribution of snowfall to clearcuts (Storck et al. 1999, Stegman 1996). This is accompanied by accelerated melt in clearcuts relative to undisturbed forest, due to increased energy inputs from shortwave radiation and turbulent fluxes (Murray and Buttle 2003). The combination of a rapid melt with greater total water input to the soil surface can produce major changes in infiltration, soil water mixing, groundwater recharge, and water and nutrient fluxes from harvested slopes to receiving wetlands, streams and lakes relative to those from undisturbed forest stands (Murray and Buttle 2005).

It is reasonable to expect that forest regeneration after harvesting will result in hydrologic recovery (*HR*) – the restoration of hydrologic characteristics to preharvest conditions (Hudson 2000). Information on the length of time required to achieve *HR* is an important aspect of sustainable forest management (Talbot and Plamondon 2002); yet, as Hudson (2000) notes, the effect of forest regeneration on changes in *SWE* and melt rate in harvested areas is not well known. Previous studies (Hudson, 2000, Winkler 2001, Talbot and Plamondon 2002) have addressed the relationship between forest regeneration and snow accumulation and melt; however, these projects

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were conducted in forest, topographic and climatic conditions that differ from those in northeastern Ontario. The degree to which these previous results can be applied to the current landscape is unclear. The purpose of this paper is to estimate *HR* of *SWE* and snowmelt in the black spruce-dominated forests of northeastern Ontario.

STUDY AREA AND METHODS

The study area is northeast of Cochrane, ON (49° 38’ N, 89° 00’W). Mean annual precipitation is ~800 mm, mean annual snowfall is ~285 cm, and mean annual evaporation is ~400 mm. The area is in the Northern Clay Section of the Boreal Forest Region (Rowe 1972), and forest cover is dominated by black spruce (*Picea mariana*). Forest stands are typical of undisturbed fire-origin boreal forest, ~95 years of age (Hazlett et al. submitted). Soils are largely poorly-drained orthic gleysols. The region is relatively flat, with elevations ranging from 235 m to 295 m a.s.l.

Snow surveys were conducted along 10 randomly oriented transects. The relatively flat terrain meant that aspect was not a major issue for snow accumulation or melt. Transects were selected to reflect the range in forest conditions in the area: recent clearcuts, regenerating sites of differing age, and undisturbed forest stands (Table 1). Maximum distance between sites was 22 km (Site 5 and Site 10).

Table 1. Site characteristics.

						Forest composition (% of trees at site)					
Site	Year harvested	Trees ha^{-1}	Canopy height (m)	Basal area ha^{-1} (m^2)	Canopy density	Black spruce	White spruce	Balsam fir	Larch	White birch	Snags
1	2004	0	0	0	0.07	0.0	0.0	0.0	0.0	0.0	0.0
2	1997	0	0	0	0.00	0.0	0.0	0.0	0.0	0.0	0.0
3	1990	1947	1.7	0.73	0.09	0.0	98.6	1.4	0.0	0.0	0.0
4	1985	6421	1.8	5.91	0.01	99.2	0.0	0.0	0.8	0.0	0.0
5	1991	1552	2.4	2.21	0.03	93.3	0.0	6.7	0.0	0.0	0.0
6	1988	12474	3.2	10.78	0.22	42.6	19.8	37.6	0.0	0.0	0.0
7	1988	7316	3.3	12.77	0.36	43.9	12.9	42.4	0.0	0.0	0.7
8	–	5421	6.9	18.88	0.73	84.0	0.0	0.0	13.2	0.0	2.8
9	–	1579	16.0	33.17	0.80	8.3	1.7	50.0	0.0	13.3	26.7
10	–	1000	16.4	23.53	0.82	0.0	20.7	34.5	0.0	10.3	34.5

– indicates site was never harvested

Canopy gap fractions (*GF*) were measured at each transect using a LAI-2000 plant canopy analyzer (LI-COR Inc.) with a 45° view cap. Measurements were made on May 27, 2005 between 9 a.m. and 2:30 p.m. under overcast skies, at 1.25 m above the ground surface to avoid interference from understory vegetation and to estimate *GF* conditions immediately above the maximum snowpack surface elevation. Two above-canopy LAI-2000 readings were taken in a nearby clearing, while eight below-canopy readings were taken at each site (at the beginning and end of each transect and at each *SWE* measurement point). Canopy density was calculated as 1 – mean *GF* (Pomeroy et al. 2002). Leaf-out of larch and white birch had occurred prior to *GF* measurements, and estimated canopy densities would have been slightly greater than winter condition values at sites 8, 9 and 10. The year in which each site was harvested was determined using records from Abitibi Consolidated Ltd., in whose Forest Management Unit the sites are located.

Each transect was ~100 m in length. Snow depth was recorded every 5 m, while *SWE* (measured using a MSC snow tube) was sampled every 15 m. Surveys were conducted on roughly a two week interval from February 5 to March 26, and at roughly weekly intervals from March 26 to April 18. The same points were sampled during each survey. Peak *SWE* (SWE_{pk}, cm) was determined, while mean melt rate (*MMR*, mm d^{-1}) was estimated as the slope of the linear regression equation relating *SWE* to Day of Year (DOY) during the snowmelt period. We followed Hudson's (2000) method of estimating hydrologic recovery (*HR*) for SWE_{pk} and *MMR*:

$$HR(\%) = 100 - \left[\left(\frac{RI_x - RI_u}{RI_c - RI_u} \right) \times 100 \right] \quad [1]$$

where RI_x is the recovery index (either SWE_{pk} or *MMR*) for a given transect, and RI_u and RI_c are the recovery indices for undisturbed forest stands and recent clearcuts, respectively. This approach assumes a linear change in *HR* index between the recovery indices for 100% (undisturbed) and 0% (recent harvest) recovery states (Hudson 2000).

RESULTS AND DISCUSSION

Snow water equivalent

Snow water equivalent tended to be greater in recent clearcuts during the accumulation period, with the smallest *SWE* in mature forest stands (Figure 1). This was attributable to interception and subsequent sublimation of snowfall in forest stands, coupled with redistribution of snow to clearcuts (Murray and Buttle 2003). Nevertheless, there was large variability around these mean *SWE* values. We used Tukey's Honestly Significant Difference test (StatSoft Inc. 1995) to examine differences in *SWE* between the sites during the accumulation period (Table 2). There was no significant difference between *SWE* at Sites 1 and 2 ($p < 0.1$), while Site 2 had *SWE* consistently greater than at Site 9 and often greater than many of the other regenerating and undisturbed sites.

The *SWE* data suggest that the forest sites lost their snowcover within a few days of the clearcut sites. Enhanced melt at the clearcut sites relative to the forest sites may have been countered by greater pre-melt *SWE* in the clearcuts, resulting in a near-simultaneous loss of snowcover across the sites. Murray and Buttle (2003) found a similar pattern for forest and clearcut sites on a north-facing slope in a hardwood forest in central Ontario.

Snow water equivalent on DOY 68 (March 9, date of SWE_{pk} in the two clearcut sites) in undisturbed forest stands ranged from 0.61 (Site 9) to 0.81 (Site 8) of the mean clearcut *SWE*. This suggests seasonal snow interception losses from 19 – 39% of above-canopy snowfall; however, these values are probable overestimates due to snow redistribution to the clearcuts. Figure 2 compares the ratio of *SWE* in regenerating and undisturbed sites (S_f) to the mean *SWE* in the clearcut sites (S_c). There was a relatively poor correlation between S_f/S_c and canopy density prior to SWE_{pk} in the clearcut sites, and many points fell below the range of S_f/S_c vs. canopy density values measured by Pomeroy et al. (2002) for boreal forest sites in western Canada. There was a much stronger relationship between S_f/S_c and canopy density on DOY 68, and the data follow the general trend observed by Pomeroy et al. (2002). This indicates that the influence of canopy density on *SWE* accumulation is most pronounced at the time of SWE_{pk} in open areas. It also suggests that the relative differences in *SWE* between harvested, regenerating and undisturbed sites at SWE_{pk} in northeastern Ontario may apply across a large portion of Canada's boreal forest.

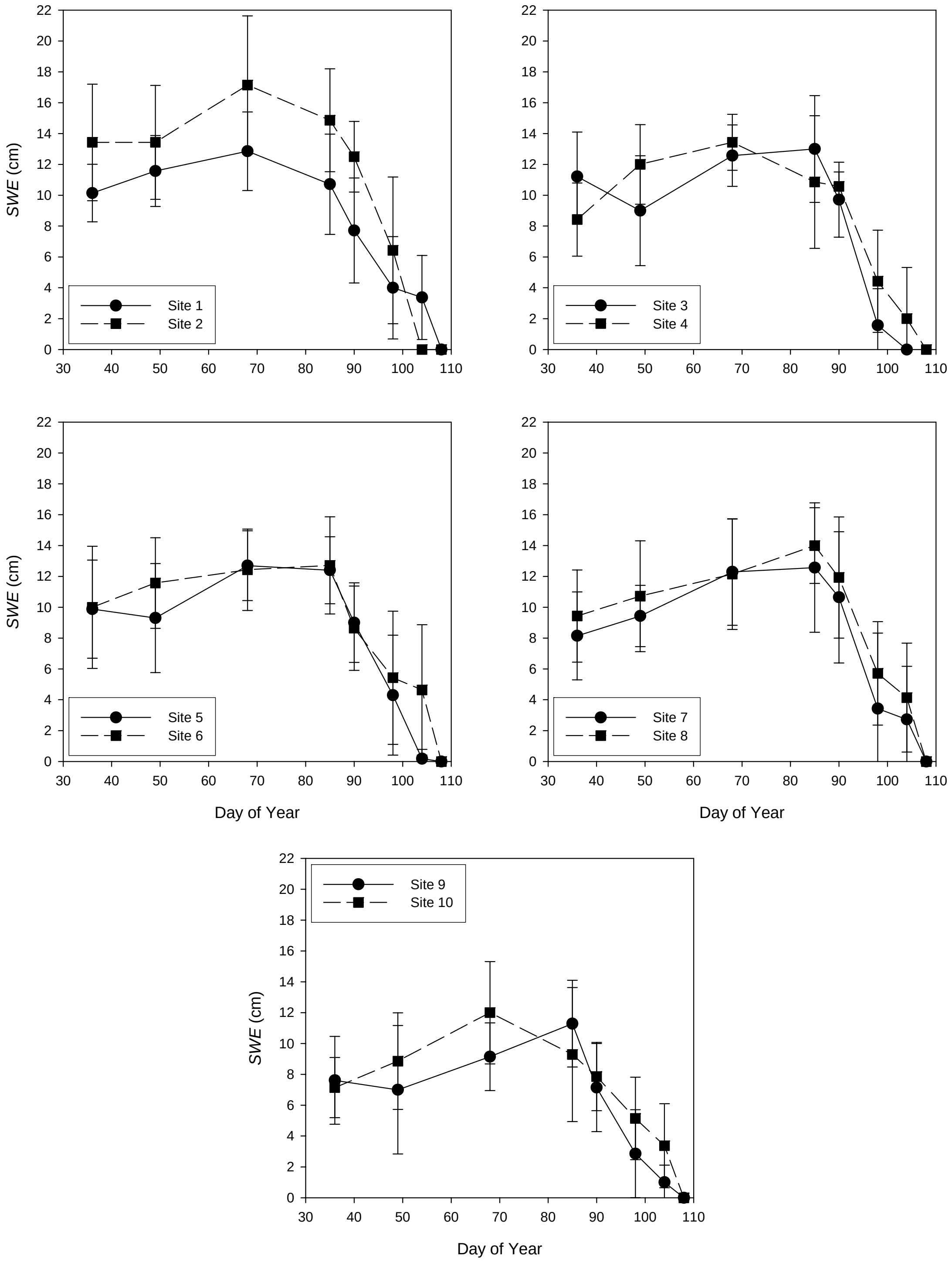

Figure 1: Mean *SWE* (± 1 SD) during late winter – spring at the study sites.

Table 2. Instances when Site 2 *SWE* was significantly greater than *SWE* at other sites during the accumulation period.

	Date of survey		
Significance level	DOY 36	DOY 49	DOY 68
p < 0.05	2 > 9, 10	2 > 9	2 > 9, 10
p < 0.1	2 > 4, 5, 7, 9, 10	2 > 9	2 > 5, 6, 7, 8, 9, 10

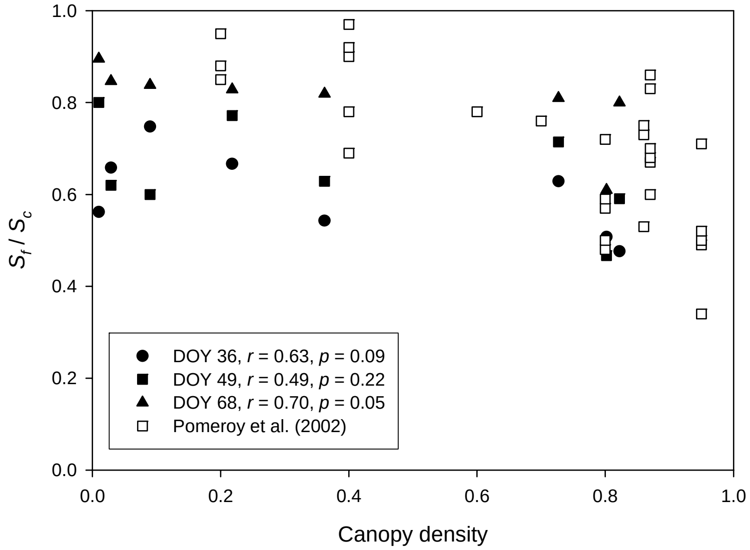

Figure 2: Ratio of forest (S_f) to mean clearcut (S_c) *SWE* as a function of canopy density.

Mean melt rate

Mean melt rates were determined for the DOY 85 to 104 (March 9 to April 14) period in order to ensure inter-site comparability in the results. There was a significant linear relationship between *SWE* and DOY ($p < 0.05$) at all sites (Table 3). The largest *MMR* was for Site 3, while the smallest was for Site 10. The relationship between *MMR* and canopy height and density showed an increase in *MMR* with initial regeneration, followed by a decrease in *MMR* to values equal to or even less than those measured in the clearcut sites (Figure 3). Potential reasons for this include increased longwave radiation and sensible and latent heat fluxes to the snowpack surface as saplings and shrubs begin to emerge above the snow.

Table 3. Mean melt rate estimates for each site.

Site	Year harvested	Mean melt rate (mm d^{-1})	Standard error of the estimate (mm d^{-1})	r^2
1 + 2	1 – 2004; 2 – 1997	5.9	1.1	0.837
3	1990	7.3	1.0	0.962
4	1985	5.1	0.9	0.947
5	1991	6.4	0.1	0.999
6	1988	**4.2**	0.9	0.915
7	1988	5.7	1.1	0.936
8	–	5.6	0.7	0.969
9	–	5.4	0.7	0.969
10	–	**3.2**	0.1	0.999

– indicates site was never harvested

Underlined mean melt rates are significantly less than that for Site 3 at the p = 0.1 level; bolded and underlined mean melt rates are significantly less than that for Site 3 at the p = 0.05 level.

Vegetation at Site 3 was ~1 m above the snowpack surface on the date of SWE_{pk}, and Price and Dunne (1976) noted that the increase in surface roughness length as vegetation protrudes above the snowpack surface can lead to a marked enhancement of turbulent fluxes. Pomeroy et al. (this volume) found that while there was no substantial difference in the latent heat flux from snow under shrubs on the Canadian tundra relative to open areas, there was a significant increase in sensible heat and longwave fluxes to the snowpack under shrubs. Pomeroy et al. (this volume) indicated that the enhanced snowmelt under shrub canopies was largely attributable to the greater downward net longwave flux. The increase in available energy for melt likely more than compensates for the reduction in incoming shortwave radiation caused by shading from the emerging canopy. As the stage of tree regeneration advances, *MMR* decreases due to the role of the canopy in restricting incoming shortwave radiation through shading and reducing turbulent fluxes by decreasing wind speeds over the snowpack surface (Price 1988).

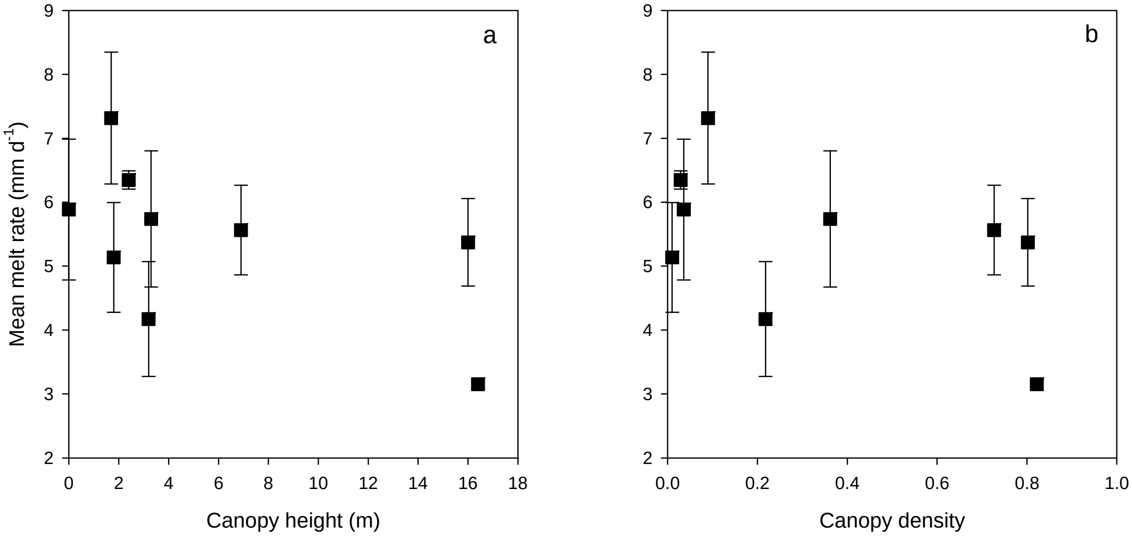

Figure 3: Mean melt rate (± 1 SE of the estimate) vs. canopy height (a) and density (b). Data for the clearcut sites have been averaged.

Hydrologic recovery

Hudson (2000) combined *SWE* and *MMR HR* values when examining variations with canopy height and canopy density, and assumed a similar response in the *HR* of these two hydrologic characteristics. He found that a Chapman-Richards equation of the form:

$$HR(\%) = 100(1 - e^{-bX})^{c} \qquad [2]$$

provided a good fit to *HR* results from coastal British Columbia forests, where *X* is a stand structure variable (e.g. canopy height, canopy density), and *b* and *c* are curve-fitting parameters. This curve type has the virtue of approaching 100% *HR* asymptotically with increasing *X*. However, our data suggest that the *HR* of SWE_{pk} and *MMR* do not behave similarly. The Chapman-Richards best-fit equation indicates rapid increase in SWE_{pk} *HR* with initial regeneration, followed by a more gradual increase (Figure 4a, b). A SWE_{pk} *HR* of ~80% is reached with a canopy height of ~7 m and a canopy density of ~0.4; Hudson (2000), in comparison, found 80% *HR* for SWE_{pk} for a canopy height of ~10 m and a canopy density of ~0.6 in a coastal British Columbia forest. We found negative values of *HR* of *MMR* during initial stand regeneration (Figure 4c, d), in contrast to Hudson (2000). This was attributed to an increase in melt rate with early stand growth (discussed above). Canopy height explained a greater proportion of the variation in SWE_{pk} and *MMR HR* values than canopy density, in contrast to Hudson's (2000) observation that *HR* could be predicted equally well by canopy height and canopy density. Figure 4e presents results from Talbot and Plamondon (2002) for a balsam fir forest north of Quebec City, which have been re-expressed in terms of *HR*. These data also showed incidences of negative *HR* values during initial stand regeneration, and suggest that our results may apply elsewhere in the boreal forest. This issue deserves further study. Our *MMR HR* vs. canopy height data had much greater scatter than those from Talbot and Plamondon (2002), which may reflect inter-site variations in forest composition in our study (Table 1).

CONCLUSIONS

It appears that we cannot simply assume that forest regeneration promotes a progressive and simultaneous restoration of all hydrologic characteristics. Our results indicate that SWE_{pk} *HR* reaches ~80% of preharvest values within ~15 years after harvesting. Conversely, *MMR* values suggest that snowmelt rates may actually increase above melt rates in recent clearcuts during the initial stages of stand regeneration, and do not drop significantly below those observed for Site 3 (harvested in 1990) until at least 14 years after harvesting (Table 3). The Chapman-Richards curve in Figure 4a estimates that 50% recovery of *MMR* occurs when canopy height approaches 16 m, which is similar to that of unharvested stands (Table 1). This compares to 50% recovery of melt rates when average canopy heights reach ~4 m in coastal British Columbia forests (Hudson 2000) and in balsam fir forests in Quebec (Talbot and Plamondon 2002). There is a large amount of uncertainty in the Chapman-Richards curve estimate of the canopy height associated with the 50% *MMR HR*, given the curve's relatively poor fit to the data. Nevertheless, our results suggest that the hydrologic recovery of snowmelt rates in the boreal forest of northeastern Ontario may be more protracted than that in other forest landscapes in North America. This needs to be considered when assessing the hydroecological consequences of forest harvesting in this region.

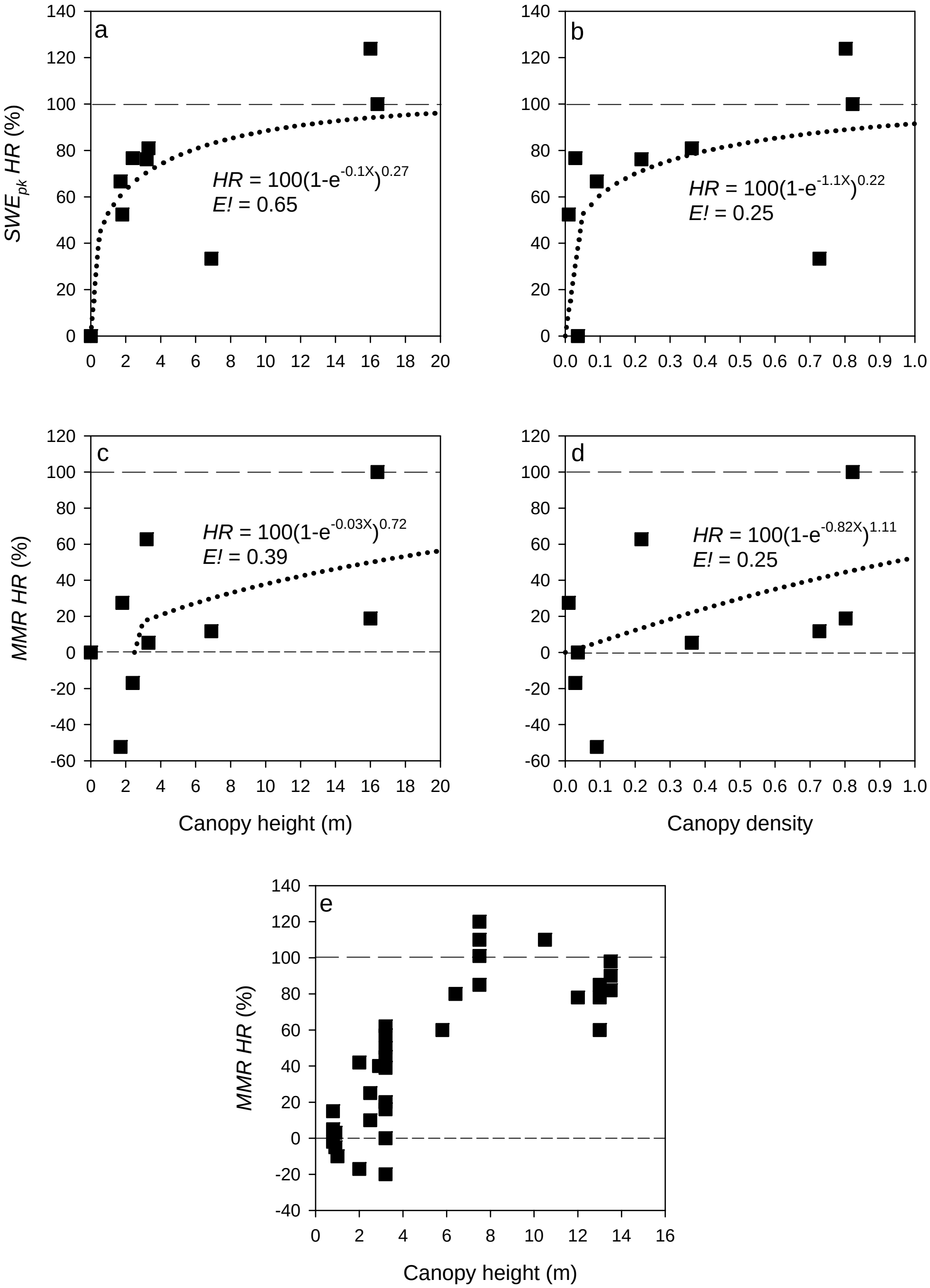

Figure 4: Hydrologic recovery of *SWEpk* and *MMR* vs. canopy height (a, c) and canopy density (b, d) in this study; hydrologic recovery of *MMR* vs. canopy height (e) in a balsam fir forest near Quebec City (Talbot and Plamondon 2002). *E!* in (a–d) indicates Nash-Sutcliffe model efficiency for best-fit Chapman-Richards curves.

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