Water use efficiency of three green manure legume species as influenced by stand density
by Sharon Lee Pfaff

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Agronomy
Montana State University

Abstract:
The water use efficiencies of legume green manure species are needed to facilitate green manuring as a viable alternative to summerfallowing in semiarid environments. The objectives of this study were to determine the water use efficiency (WUE) of three legume species, Austrian winterpea [Pisum sativum ssp. arvense (L.) Poir. cv. Melrose], lentil (Lens culinaris Medik cv. Indianhead), and black medic (Medicago lupulina L. cv. George), in terms of dry matter production, canopy N accumulation and N2-fixation, and as influenced by stand density. The legumes and barley (Hordeum vulgare L. Bearpaw) were planted at three seeding rates in a split plot design at Logan, Montana, in 1993 and 1994. Cumulative evapotranspiration (ET), percent canopy closure, canopy biomass accumulation, canopy N accumulation, and stem length were measured over the two growing seasons. Legume dry matter production was unusually high in 1993, relative to 1994, due to an unusually cool wet growing season. Despite this, of the three legumes, Austrian winterpea consistently displayed the highest WUE in terms of canopy closure, canopy biomass accumulation, canopy N accumulation and N2-fixation, with comparisons made at each seeding rate. George black medic had similar performance to Austrian winterpea. Indianhead lentil consistently displayed lowest WUE of the three legume species at all seeding rates. No clear trends emerged in comparisons within species of the three seeding rates. During both years, the medium seeding rate (which is the standard recommended rate) often emerged as having highest WUE. It would appear this seeding rate has the optimum potential when these legume species are used as green manure. Plant height (stem length) and growth stage have been suggested as practical tools for farmers to use in estimating ET. In this study, plant height correlated well with cumulative ET for all three species both years. However, the slopes of the regression lines were quite different each of the two years. Growth stage was somewhat related to cumulative ET, but the relationship was not as distinct as plant height.

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APPROVAL

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This thesis has been read by each member of the thesis committee and has been found to be satisfactory regarding content, English usage, format, citations, bibliographic style, and consistency, and is ready for submission to the College of Graduate Studies.

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ABSTRACT

The water use efficiencies of legume green manure species are needed to facilitate green manuring as a viable alternative to summerfallowing in semiarid environments. The objectives of this study were to determine the water use efficiency (WUE) of three legume species, Austrian winterpea [*Pisum sativum* ssp. *arvense* (L.) Poir. cv. Melrose], lentil (*Lens culinaris* Medik cv. Indianhead), and black medic (*Medicago lupulina* L. cv. George), in terms of dry matter production, canopy N accumulation and N_2-fixation, and as influenced by stand density. The legumes and barley (*Hordeum vulgare* L. Bearpaw) were planted at three seeding rates in a split plot design at Logan, Montana, in 1993 and 1994. Cumulative evapotranspiration (ET), percent canopy closure, canopy biomass accumulation, canopy N accumulation, and stem length were measured over the two growing seasons. Legume dry matter production was unusually high in 1993, relative to 1994, due to an unusually cool wet growing season. Despite this, of the three legumes, Austrian winterpea consistently displayed the highest WUE in terms of canopy closure, canopy biomass accumulation, canopy N accumulation and N_2-fixation, with comparisons made at each seeding rate. George black medic had similar performance to Austrian winterpea. Indianhead lentil consistently displayed lowest WUE of the three legume species at all seeding rates. No clear trends emerged in comparisons within species of the three seeding rates. During both years, the medium seeding rate (which is the standard recommended rate) often emerged as having highest WUE. It would appear this seeding rate has the optimum potential when these legume species are used as green manure. Plant height (stem length) and growth stage have been suggested as practical tools for farmers to use in estimating ET. In this study, plant height correlated well with cumulative ET for all three species both years. However, the slopes of the regression lines were quite different each of the two years. Growth stage was somewhat related to cumulative ET, but the relationship was not as distinct as plant height.

Chapter 1

INTRODUCTION

Green manure crops have long been recognized by farmers as a beneficial component of a cropping system. Green manuring is one of the oldest practices known to agriculture, with written records of this practice dating back 3000 years or more to China (Allison, 1973). In the United States and Canada, green manure crops are commonly grown in higher rainfall, more humid areas, as they have many beneficial aspects: They act as a cover crop to decrease wind and water erosion; maintain soil organic matter and soil structure; improve soil fertility by adding nitrogen (in the case of N_2-fixing legumes); use excess soil water and thereby reduce leaching of soil nutrients and surface runoff; and break disease, insect and weed cycles (Power and Biederbeck, 1991). In addition to the above, green manure crops can reduce the formation and growth of saline seeps in semi-arid environments.

In the semi-arid Northern Great Plains states, traditional use of green manure crops has often resulted in negative impacts on the following cash crop (Army & Hide, 1959; Power, 1991). The climate in this region is characterized by relatively low humidity and precipitation, with almost one half of the annual precipitation falling as rain in April, May and June. Summer temperatures often reach a high of 100° F or greater with hot dry winds being common. For these reasons, potential evapotranspiration greatly exceeds growing season precipitation. Winters are characterized by extremely cold temperatures, with typically only a few inches of precipitation in the form of snow (Power and Biederbeck, 1991). Small grains are the most commonly grown dryland crop in this region, with an alternating fallow year being included. Not only does fallow allow for storage of soil moisture for the subsequent crop, but it also promotes mineralization and release of nutrients from soil organic matter and plant residues. Although these benefits have helped to stabilize crop yields, in many instances fallowing has proven not to be a sustainable system (Sims and Slinkard, 1991).

Continued oxidation and mineralization of organic matter has caused soil fertility to steadily decrease in soils under the crop-fallow system. It is estimated that soils in the Canadian Prairies and U.S. Great Plains have suffered soil organic matter losses of 40 to 60%, after being farmed under the crop-fallow system for the past 70 to 80 years (Campbell and Souster, 1982). Additions of chemical fertilizers under a continuous small grain rotation have been shown to maintain soil organic matter in the long term (Campbell et al., 1991), however, continuous cropping is not always feasible in the semi-arid Great Plains. Also, application of chemical fertilizers is becoming more costly, as the fossil fuels used to manufacture them become more scarce and expensive.

Fallowing is an extremely inefficient method of soil water capture and storage. Results from early studies in Montana indicated storage efficiency of fallow averaged 21% (Ford and Krall, 1979). Results from more recent studies conducted in Sidney, Montana, indicated an average storage efficiency of fallow under a stubble-mulch system averaged 31.6% (Tanaka and Aase, 1987). Rapid mineralization of organic matter also leaves nitrates vulnerable to leaching. Excess water leaches nitrates and other nutrients below crop rooting depths, causing potential groundwater contamination. If excess water is impeded from deep percolation by an impermeable layer in the soil profile, a saline seep often results (Sims and Slinkard, 1991). Legume green manure crops grown during the fallow period have great potential for correcting problems associated with fallow, especially in terms of using excess soil water and maintaining soil fertility. However, the challenge lies in managing the legume in such a way as to provide the optimum amount of nitrogen and other benefits, without unduly reducing the amount of water available to the subsequent crop. The objectives of this study were to determine the water use efficiency of three legume species in terms of dry matter production and N_2-fixation and as a function of stand density. Since Austrian Winterpea [*Pisum sativum* ssp. *arvense* (L.) Poir] has consistently displayed higher water use efficiencies than other species (Wright, 1993), it is postulated that it has the ability to close its canopy more quickly than some other legume species, thus limiting soil evaporation. Therefore, it is hypothesized that changing the stand density of the legume green manure crop from low to medium to high will more quickly achieve canopy closure, hence improve water use efficiency.

Chapter 2

LITERATURE REVIEW

Results from early studies in the Northern Great Plains showed no benefit from using legumes in crop rotations. This may have been primarily due to two factors. First, at the time of these early studies, soil organic matter levels had not yet been greatly depleted, therefore, N contributions by legumes would not have been as significant as in a depleted soil (Campbell et al., 1991). Secondly, green manure crops were not managed in such a way as to limit water use, which often depleted stored soil moisture reserves necessary for the subsequent crop (Army and Hide, 1959). The results of these studies, and the availability of inexpensive N fertilizer, appeared to discourage further research of green manure crops for a period of time. However, the energy crisis of the 1970's helped to renew an interest in the contributions of legumes to sustainable cropping systems (Mahler and Auld, 1989, Sims et al. 1985, Koala, 1982).

In recent years, researchers have made great strides toward incorporating legumes into cropping systems in semi-arid environments. These research efforts have been focused in three major areas: species adaptability (which includes water use efficiency), contributions to subsequent crops, and associated cultural practices.

Water use efficiency is defined as the amount of biomass produced per a given area for a unit of water evaporated or transpired (ET) for that area (Tanner and Sinclair, 1983). The soil evaporation component of ET is a purely physical process occurring primarily at the soil surface. During the growing season, evaporation from the soil surface is substantially reduced one to two days after wetting, and soil moisture below 20 to 30 cm is relatively safe from soil surface evaporation (Hanks, 1985). Plant transpiration is much more complex, being composed of both biological and physical processes. In water-limiting environments, transpiration is often more critical to total water use than soil evaporation. Transpiration efficiency for a given crop is relatively stable if climatic conditions are normalized for a given location and time of year (Ritchie, 1983). In 1958, de Wit (as reported by Hanks, 1983) demonstrated a strong correlation between biomass production and transpiration. Mathematically, he expressed this relationship as

$$Y = mT/ET_{max}$$

where Y = total dry matter mass per area, m = a crop coefficient (a constant related to crop performance of different crop species and varieties within species), T = transpiration, and ET_{max} = total potential evaporation from an open body of water. In reality, however, it is very difficult to separate transpiration from soil evaporation in a field situation. Water use efficiency based on ET is not as closely correlated to dry matter production as when based solely on T. Cultural practices can substantially alter ET by changing soil evaporation, weed transpiration, etc. (Tanner and Sinclair, 1983). However, ET is relatively easy to measure in the field and, for the purposes of this research, will be used as the basis for calculating water use efficiency.

Producers incorporating legumes into their cropping system need accurate information to select appropriate species. Response to temperature, biomass production, N_2-fixation, and water use efficiency are among the factors which need to be considered in species selection, along with seed availability and cost of establishment. Legumes used as green manure have been divided into three main groups, the small-seeded forage legumes, and medium-seeded and large-seeded grain legumes. In adaptation trials in Bozeman, Montana, small-seeded annual forage legumes performed quite well in biomass production and N_2-fixation, especially several varieties of clover and medic (Sims and Slinkard, 1991; Wright, 1993). However, small-seeded legumes have the disadvantage of needing shallow seedbed placement. If the upper surface layer is dry, they will not establish, and if planted deeper into moist soil, they often do not emerge, as can the large-seeded grain legumes. This is perhaps one reason why peas, lentils, and snail medic have emerged as the most adaptable legume species for green manuring in this region. In several field trials across a variety of dryland environments, researchers found that peas (*Pisum sativum* L.) consistently had the highest biomass production and N production of all legume species tested (Sims and Slinkard, 1991; Power, 1991; Zachariassen and Power, 1991; Bremer et al., 1988; Auld et al., 1982). Townley-Smith and associates (1993) also found this to be true, but determined lentils (*Lens culinaris* Medik) to be the most desirable green manure species. Even though lentils had only intermediate biomass and N production, the small seed size and low seeding rate made it a much more economical choice. Since green manure is not a cash crop, producers need to minimize inputs into this practice.

Maximum biomass production in a green manure crop is not always desirable, since legume species that exhibit the most rapid growth also tend to have the greatest water use (Zachariassen and Power, 1991). Researchers in several locations have found increases in small grain yields following incorporation of legume residues (Mahler and Hemamda, 1993; Welty et al., 1988, Koala, 1982) or even after production of a legume grain crop (Wright, 1990). However, maximum yields were obtained in winter wheat at Bozeman, Montana, when Indianhead lentils were terminated after using an intermediate amount of stored soil water (Sims and Slinkard, 1991). This research also shows that if legumes are terminated too early, little benefit from N_2-fixation may occur. Kucey (1989) and Wright (1993) found that it took peas approximately six weeks to begin fixing substantial amounts of N.

Results from several studies revealed that only 11 to 28% of mature legume residues were mineralized and taken up by the subsequent cereal crop (Mahler and Hemamda, 1993; Janzen et al., 1990). Bremer and van Kessel (1992) found approximately 40% of lentil green manure was mineralized, but only 19% was taken up by the subsequent wheat crop. They surmised that later seeding and incorporation would increase the amount of N made available to the following crop.

Other cultural practices which may govern the successful use of green manure crops include planting date and plant density. For maximum seed and biomass production, Sims and associates (1989) recommend that cool season legumes should be planted as early as equipment can be taken into a field. Warm season legumes should be planted to avoid the last killing frost. But, delaying planting too long substantially decreases legume yields.

Plant density of green manure crops as it relates to canopy closure and ET has received very little attention from scientists. Early researchers studying soil evaporation hypothesized that earlier canopy closure (narrower rows and greater plant densities) resulted in greater interception of solar radiation, and a reduction of soil evaporation (Alessi and Power, 1982). More recent research on a variety of crops indicates that this may be true in regions where the soil surface is kept wet by precipitation or irrigation. However, in regions where the soil surface is typically dry, and plants are dependant on stored soil moisture reserves, increased leaf surface area (greater plant densities) has resulted in increased transpiration and water use (Ritchie and Johnson, 1990). Increased dry matter production is usually the result of increased planting density; whether this results in higher water use efficiencies in terms of biomass production is not clear.

Chapter 3

METHODS AND MATERIALS

Site Description

A site near Logan, Montana (SE 1/4 of the SW 1/4 of Sec. 35, T2N, R2E) was selected because of its dryland characteristics, having coarse soils and low average annual precipitation (10-14 inches). Field plots were established May 11, 1993 and April 21, 1994 on Kalsted sandy loam (coarse loamy, mixed, borollic calciorthids). This site was broken out of native rangeland in the fall of 1992. The area for the 1994 experimental plots was planted to barley in 1993.

Experimental Design

Three legume species and a non N_2-fixing species, barley (*Hordeum vulgare* L. Bearpaw) were planted at a high, medium and low seeding rate in a split-plot design with four replications. Changing the stand density by varying row spacings had been considered, however, because of a lack of available equipment, this was not possible. Therefore, stand density was altered by changing plant density within the row. Unit plot size was 6.1 m x 3.1 m.

Before planting, the three legume species, Austrian winterpea [*Pisum sativum ssp. arvense* (L.) Poir. cv. Melrose], lentil (*Lens culinaris* Medik cv. Indianhead), and black medic (*Medicago lupulina* L. cv. George) were inoculated with the proper *Rhizobium* strain (Liphatech, Inc., Milwaukee, WI). Legumes and barley were seeded into a firm seedbed at the following rates: Austrian winterpea, 251, 168, and 83 kg/ha; Indianhead lentil, 119, 79, and 40 kg/ha; George black medic, 34, 22, and 11 kg/ha; barley, 169, 112, and 57 kg/ha. Row spacing in all plots was 25.4 cm.

Meteorological Observations

Precipitation and pan evaporation were collected weekly, using the system proposed by Sims and Jackson (1971). Collection site for weather data was located approximately 400 m from the study site. Pan evaporation data reported in this documents was adjusted with a pan factor of 0.55 (Jenson, 1974).

Soil Moisture Content

After planting, PVC access tubes were installed with a hydraulically-driven soil probe near the center of each plot. Soil moisture content was determined using a neutron moisture probe (model no. 503DR Hydroprobe, Campbell Pacific Nuclear, Pacheco, CA). The probe was calibrated at the site each year, by obtaining soil samples at 0.2 m increments to a depth of 1.8 m. Soil moisture content of these samples was determined gravimetrically and a regression equation developed to convert neutron probe readings to volumetric soil water content. Soil moisture content readings were taken in 0.2 m increments every 7 to 10 days during the growing season.

Soil, Biomass, Plant Height and Canopy Cover Sampling

Soil samples were obtained to determine initial pH, organic matter content, NO_3-N, phosphorus, and potassium. Monocalciumphosphate (0-44-0) fertilizer was applied at a rate of 145 pounds per acre.

Biomass samples were taken every 7 to 10 days. Within each plot, a 1 m row-strip was randomly selected and hand clipped to the soil surface to gather all above ground biomass. At the end of the growing season in 1994, when conditions turned very hot and dry, all species underwent leaf senescence. A portion of decaying plant materials could not be recovered, therefore recorded biomass levels dropped. To adjust for this, biomass and canopy N accumulation levels are reported as remaining at the point of peak performance.

Plant height and percent canopy cover were obtained every 7 to 10 days. Plant height was determined by averaging heights (stem lengths) of three randomly selected plants within each plot. Canopy cover was determined by ocular estimations of canopy within 1 m of the access tube in each plot.

Stand density was also determined once all plants had fully emerged. Density was estimated by counting plants within three randomly selected 1 m row-strips and averaging the results within each plot.

Analyses of Soil and Biomass Samples

Initial soil samples were weighed and dried at 50° celsius in a forced-air oven. Analysis for pH, NO_3-N, phosphorus, soil organic matter, and potassium, was conducted by the Montana State University Soil Testing Laboratory. An automated cadmium reduction method (American Public Health Association, 1981) was used to determine NO_3-N concentration. The Olsen method (Olsen and Sommers, 1982) was used to determine phosphorus concentration using sodium bicarbonate as an extractant. The colorimetric method of Sims and Haby (1971) was used to determine soil organic matter content, and an extractable cation method (Knudsen et al. 1982) was used to determine potassium concentration.

Biomass samples were dried at 50° celsius in a forced-air oven. Dry matter samples were weighed, ground and a sub-sample analyzed for the total Kjeldahl nitrogen content

(Bremner and Mulvaney, 1982) by Montana State University Soil Testing Laboratory.

Estimating Legume N_2-fixation

An adjusted measure of fixation was obtained by the difference method (Henson and Heichel, 1984; LaRue and Patterson 1981). Canopy nitrogen of the non-fixing barley crop was subtracted from the canopy nitrogen content of the legumes. The nitrogen in the nonlegume was assumed to come strictly from the soil N pool. Secondly, it was assumed that differences between the growth patterns and root morphology of the nonlegume and legumes were not great enough to negate using this technique.

Statistical Methods

Data was examined statistically with the MSUSTAT statistical package. The analysis of variance, comparison of sample means using Student's t, and a general linear model were used to examine research results. Comparisons between regression lines were generated using the general linear model. Polynomial constants reported in regression equations were generated using mregress in MSUSTAT.

A relatively simple logistic equation, $y=a/(1+be^{-cx})$, with a,b, and c being constants, generally provides a suitable portrayal of vegetative growth (Milthorpe and Moorby, 1974). This equation was used to fit curves to crop performance data (means of four replications in all cases). Sigmaplot software (Jandel Scientific, San Rafael, CA) was used for logistic and polynomial curve fitting operations.

Chapter 4

RESULTS AND DISCUSSION

Appraisal of Crop Performance

The 1993 growing season was uncharacteristically cool and wet, with 27 cm of precipitation falling at the research site during the data collection period, May 20 to August 18. In contrast, the 1994 growing season advanced normally, with ample precipitation falling early, and conditions turning hot and dry during June and July. During the 1994 data collection period, May 1 to July 31, 12 cm of precipitation fell. (Graphs of 1993 and 1994 pan evaporation and precipitation can be found in the appendix.)

Stand densities for 1993 and 1994 are reported below (Table 1) for Austrian winterpea (AWP), Indianhead lentil (IHL), George black medic (GBM) and barley (BAR) at high (H) medium (M) and low (L) seeding rates. All species showed a marked drop in stand density at most seeding rates in 1994. This was especially evident in GBM. Heavy barley residues (due to excessive moisture in 1993) impeded proper seed placement of GBM, a small-seeded species, resulting in initially poor stand establishment across all seeding rates. This illustrates the advantage of using large-seeded species when it is difficult to maintain proper seeding depth. It should be noted, however, that the high GBM stand density in 1994 is quite near the low stand density of 1993. As will be seen in the following data, GBM was still able to expand its above ground canopy and remain competitive with the other two species, despite this disadvantage. In fact, GBM performed very similarly relative to the other two legume species both years, suggesting that GBM can maintain crop performance with lower stand densities.

Table 1. Stand density in plants/m^2 for 1993 and 1994 for AWP, IHL, GBM and BAR at three seeding rates.

	Species							
	AWP		IHL		GBM		BAR	
Seed rate	1993	1994	1993	1994	1993	1994	1993	1994
High	133	124	307	212	385	133	177	107
Med.	101	81	207	136	226	67	130	78
Low	51	46	87	88	110	46	74	51

Cumulative Evapotranspiration (ET)

Comparisons of cumulative ET between AWP, IHL and GBM at high, medium and low seeding rates, reveal only minor differences (Figs. 1 and 2). Maximum cumulative ET achieved was 26 cm in 1993, and 17 cm in 1994. George black medic consistently had slightly lower ET over time, during both years. Cumulative ET was similar for AWP and IHL, with IHL slightly exceeding AWP in 1993, and AWP being slightly higher in 1994.

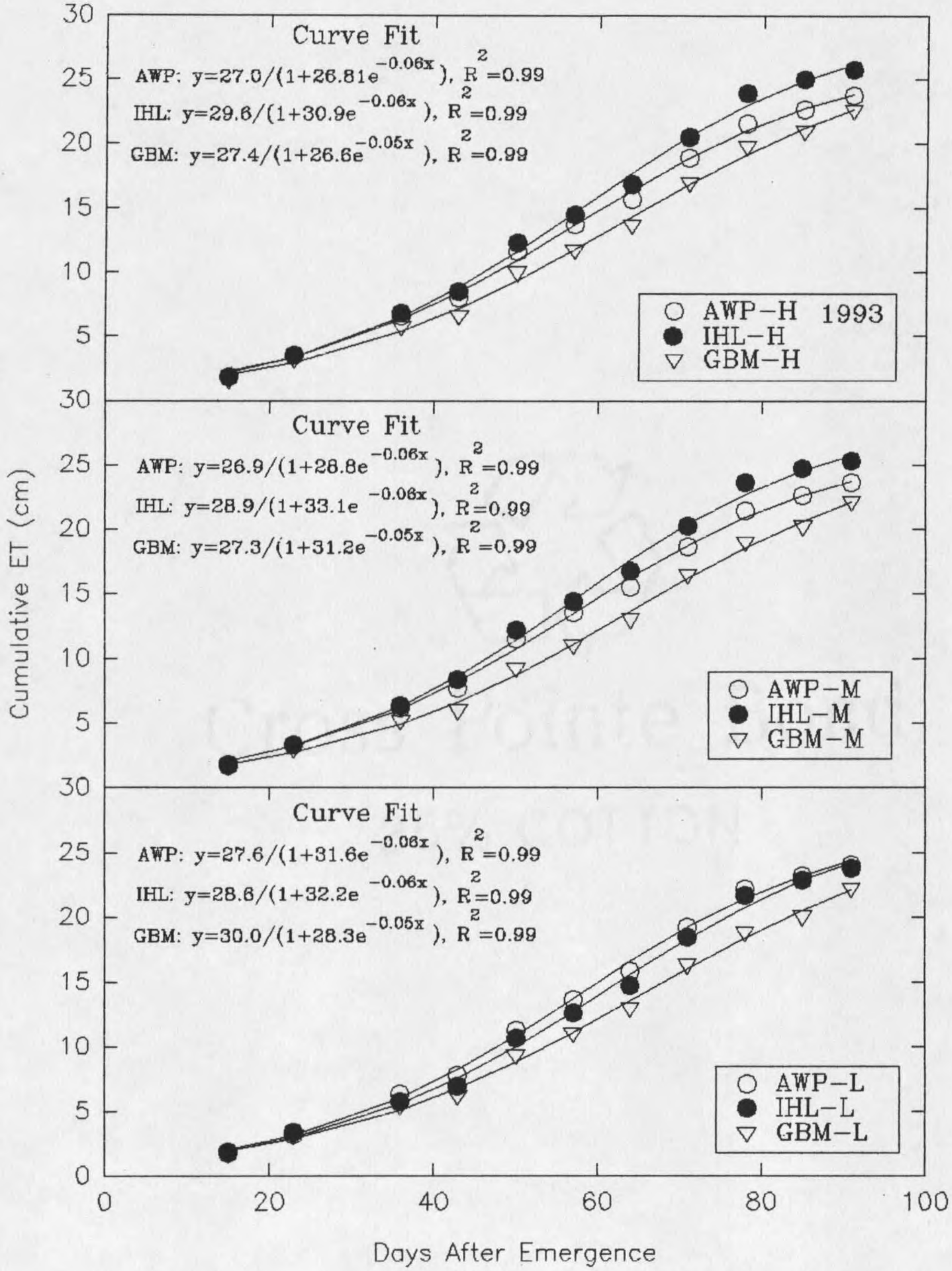

Fig. 1. Cumulative ET after emergence in 1993. Comparisons between AWP, IHL and GBM at each seeding rate.

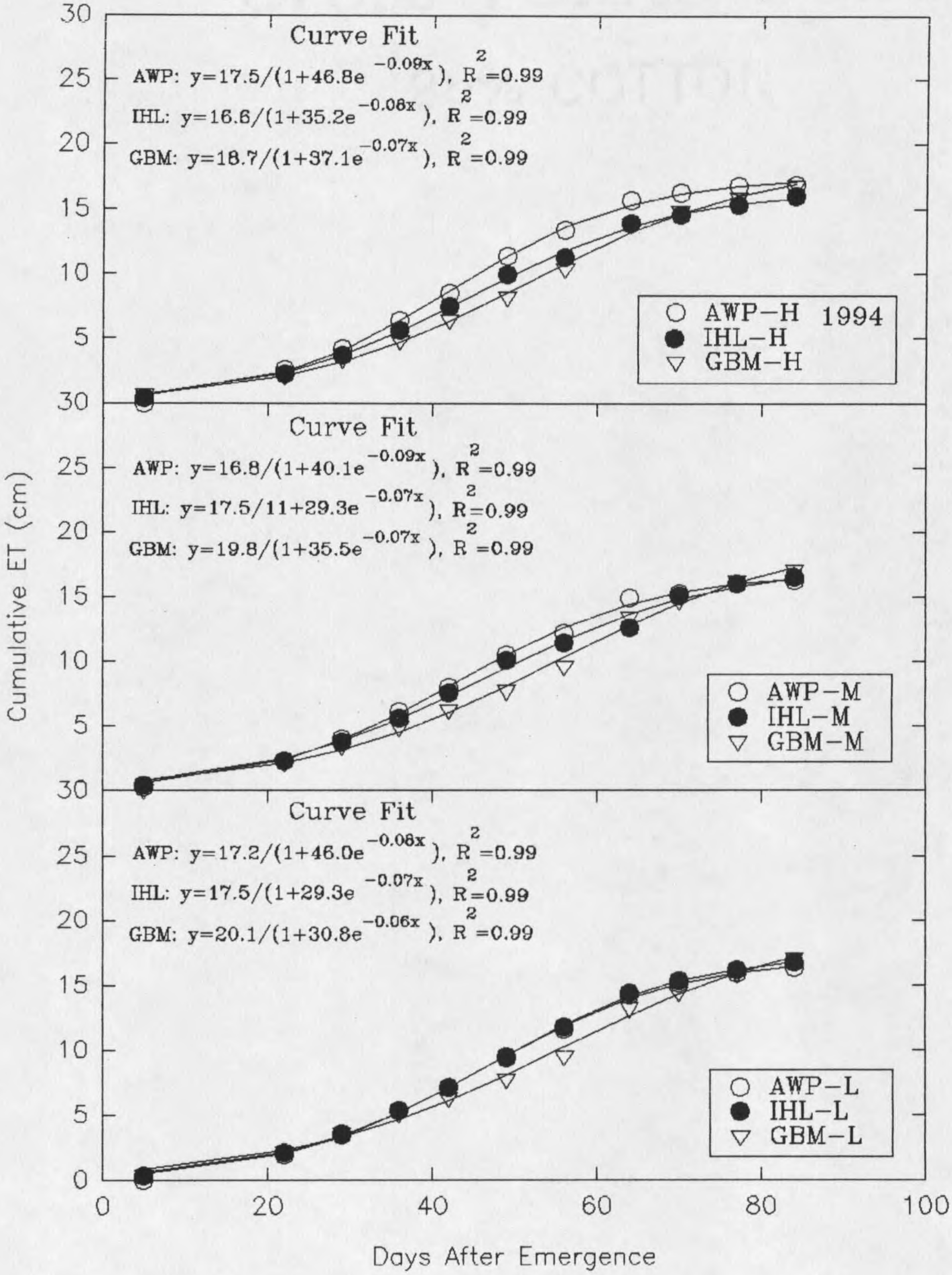

Fig. 2. Cumulative ET after emergence in 1994. Comparisons between AWP, IHL and GBM at each seeding rate.

Within species comparisons of AWP, IHL, and GBM cumulative ET generally did not vary significantly between high, medium and low seeding rates in 1993 or 1994. This similarity between seeding rates has been explained as follows: Under the lower seeding rates, there is less leaf surface area, therefore, less transpiration, and greater exposure of the soil surface to evaporation. The opposite being true for the higher seeding rates (Loomis, 1983).

There were two minor exceptions to this trend. In 1993, IHL under the low seeding rate used slightly less water than higher seeding rates. In 1994, a similar but still minor separation of curves occurred in AWP.

The 1993 soil profile volume water content data did not reveal any clear depletion trends because of heavy rainfall throughout the growing season.

Analysis of 1994 soil profile volume water content data (Figs. 3, 4 and 5) provide insight into cumulative ET differences between species. During days 5 to 42 after emergence, AWP and IHL clearly had higher depletion of soil water than GBM. Interestingly, during this time, GBM gathered more moisture from the 40 to 80 cm depths than from the surface 40 cm. Based on this and biomass data reported later, it would appear that GBM spent this time in downward development of its root system, while IHL aggressively developed above ground canopy, drawing on moisture closer to the surface to accomplish this. Indianhead lentil drew more

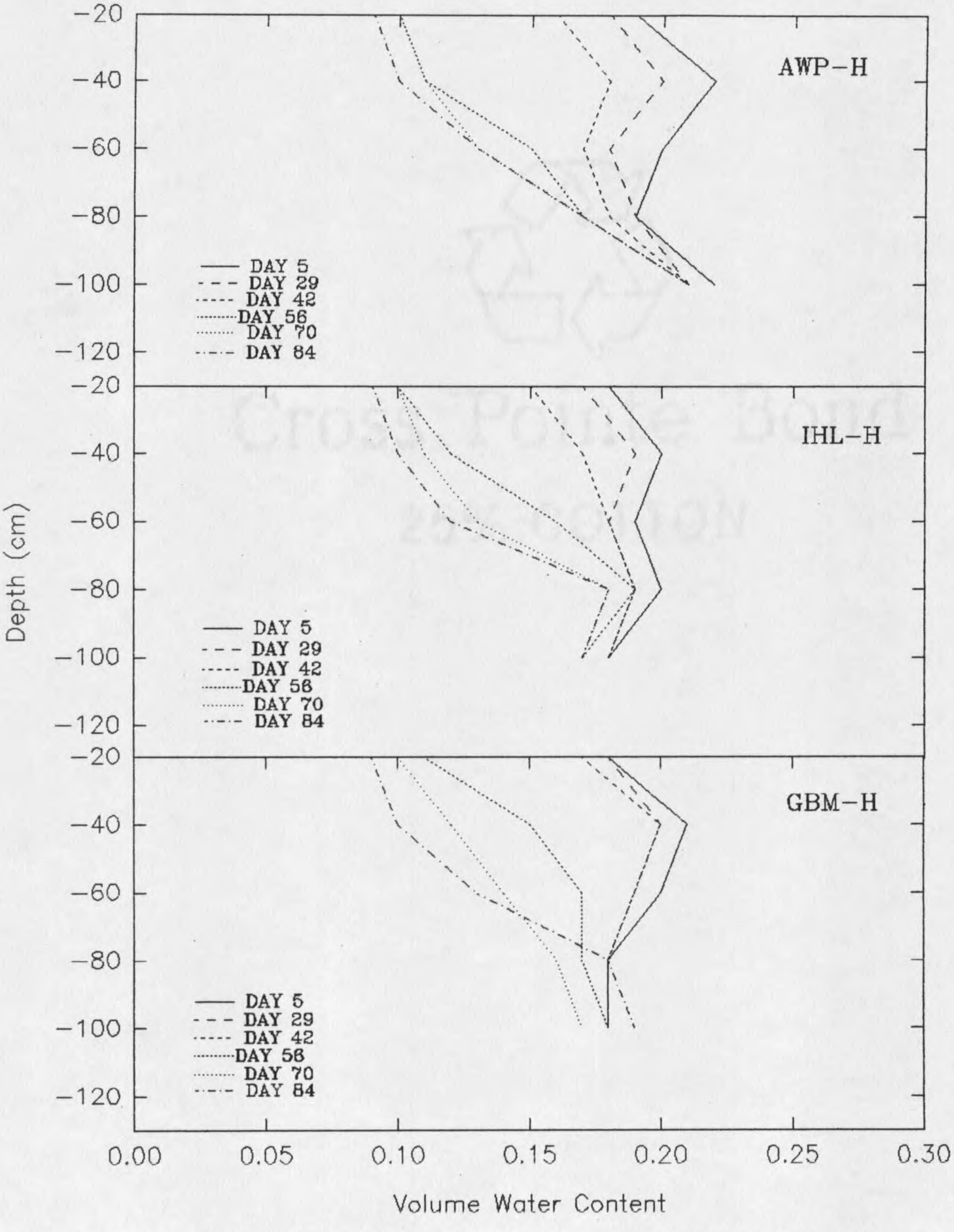

Fig. 3. Soil water content after emergence in 1994. Comparisons between AWP, IHL and GBM at high seeding rate.

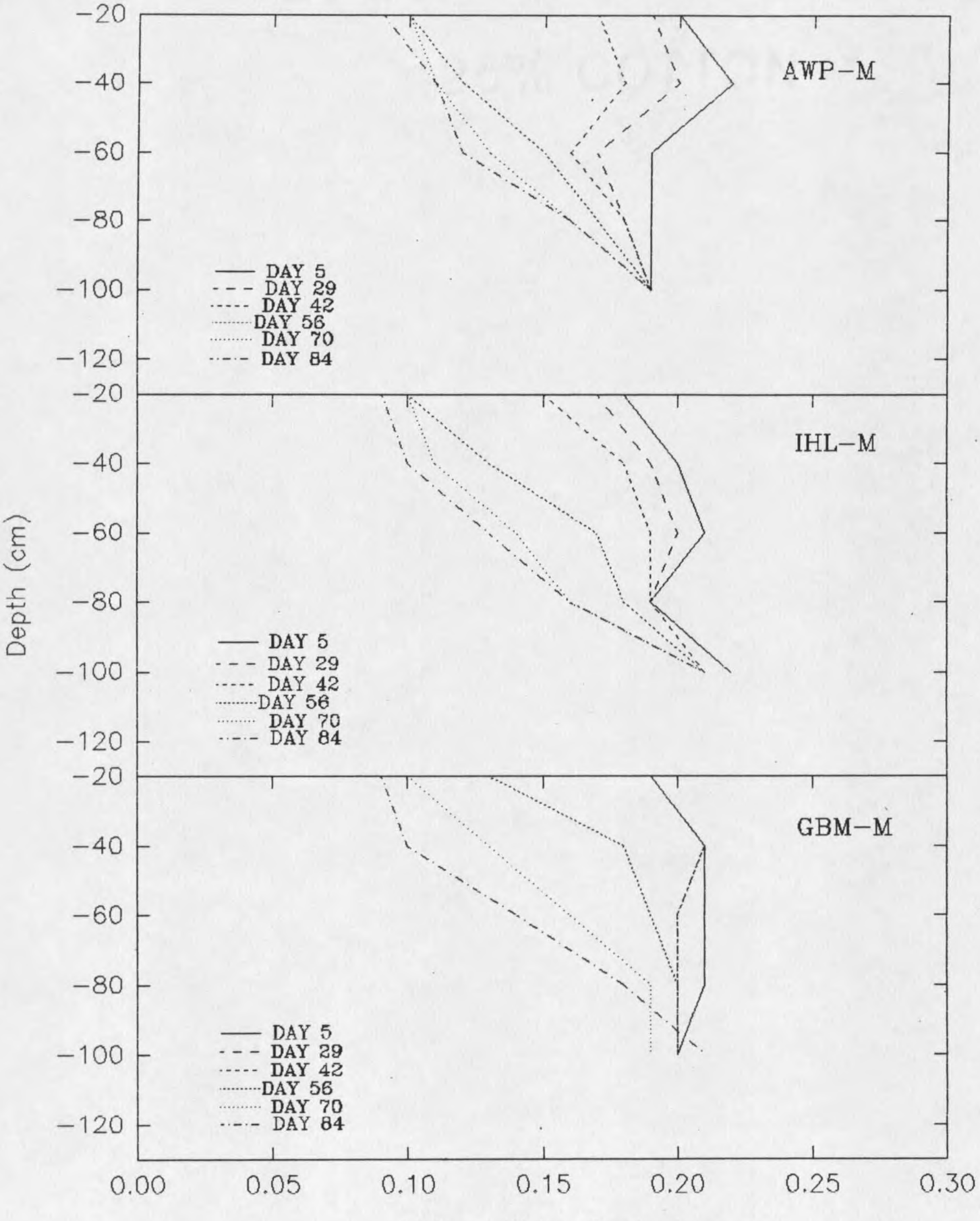

Fig. 4. Soil water content after emergence in 1994. Comparisons between AWP, IHL and GBM at medium seeding rate.

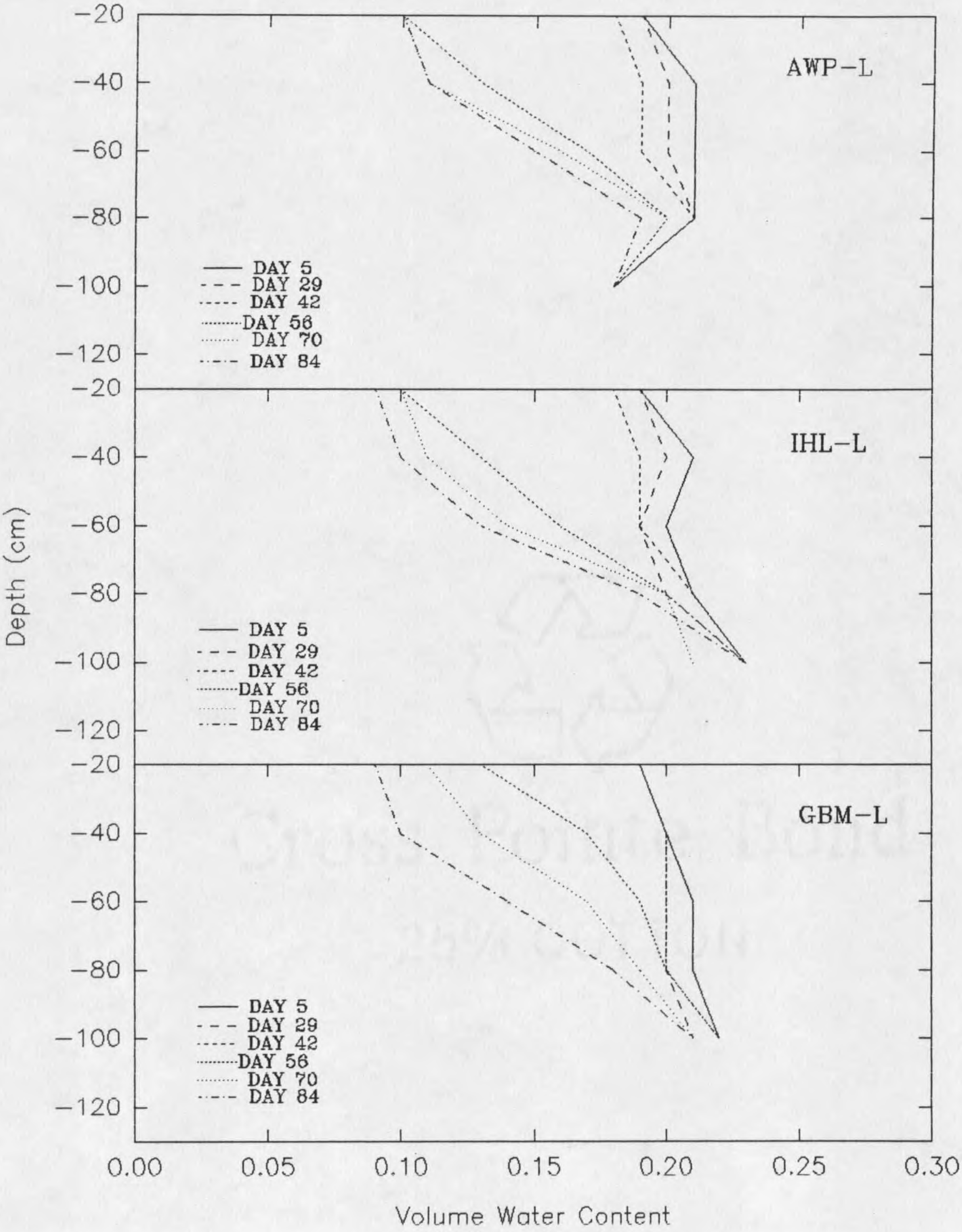

Fig. 5. Soil water content after emergence in 1994. Comparisons between AWP, IHL and GBM at low seeding rate.

water out of the surface 50 or 60 cm than did AWP and GBM. Austrian winterpea growth apparently involved both downward root development and canopy growth, thereby drawing water more uniformly from the surface down to 80 cm. After day 42, water depletion proceeded rapidly under GBM, until it was at the same level as the other two species.

In general, more water was drawn from deeper depths under the higher seeding rates, as compared to the low. It would also be expected that a higher percentage of depletion under the low seeding rates in the 0-30 cm depth was partitioned into surface evaporation rather than transpiration (Hanks, 1985).

Percent Canopy Cover

Crop canopy was measured in this study because of its close relationship to ET. When the soil surface is wet, as in 1993, evaporation is a critical component of ET, and the ability of the crop canopy to shade the soil surface can influence the amount of water that is partitioned between evaporation and transpiration. A heavier canopy will shade the soil surface, reduce soil surface temperatures, thus reducing evaporation, and leaving more moisture available for transpiration. When the soil surface is dry, as in 1994, evaporation is not as critical, although a heavier canopy may still reduce transpiration by reducing the amount of radiant heat coming from the soil surface, increasing

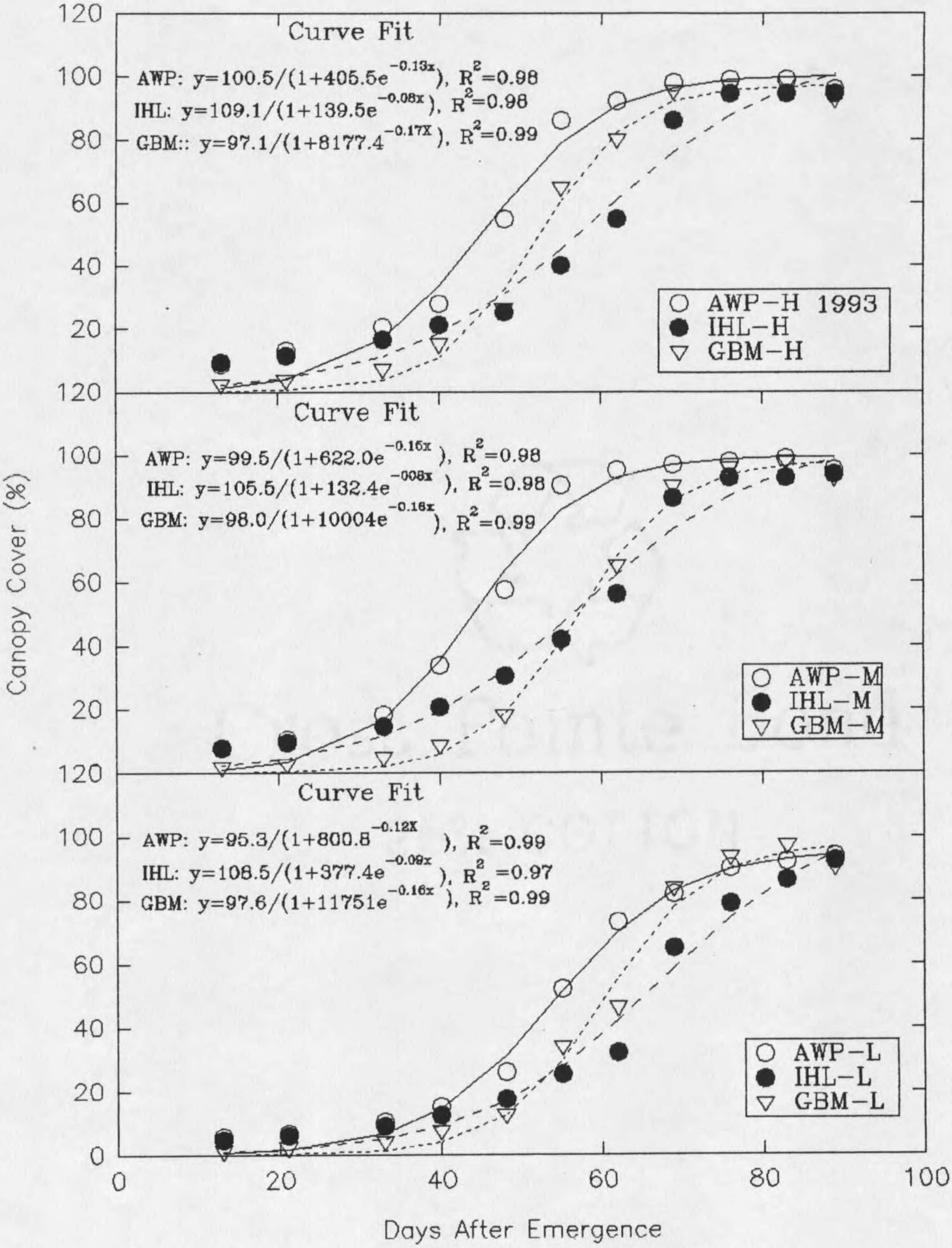

Fig. 6. Canopy cover after emergence in 1993. Comparisons between AWP, IHL and GBM at each seeding rate.

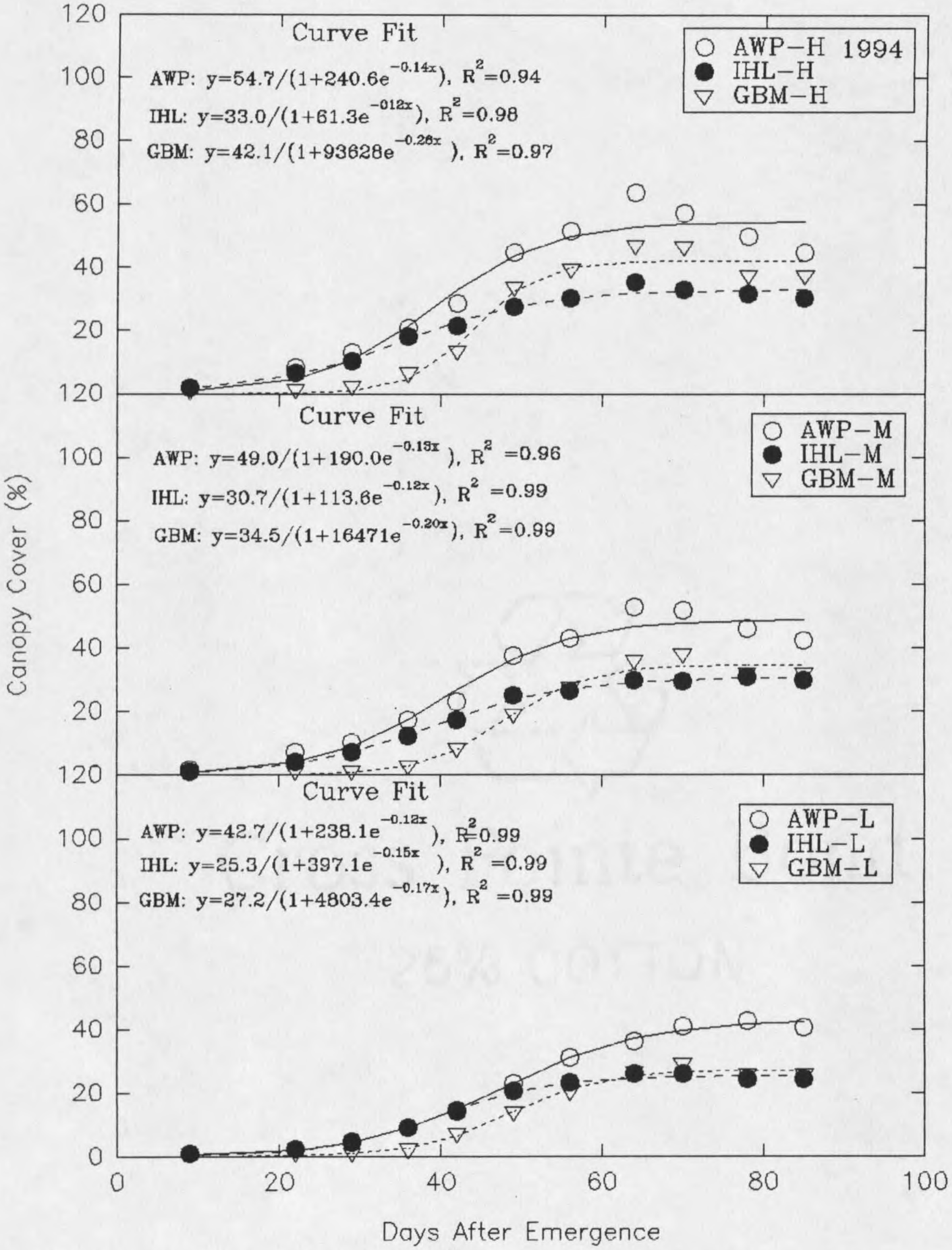

Fig. 7. Canopy cover after emergence in 1994. Comparisons between AWP, IHL and GBM at each seeding rate.

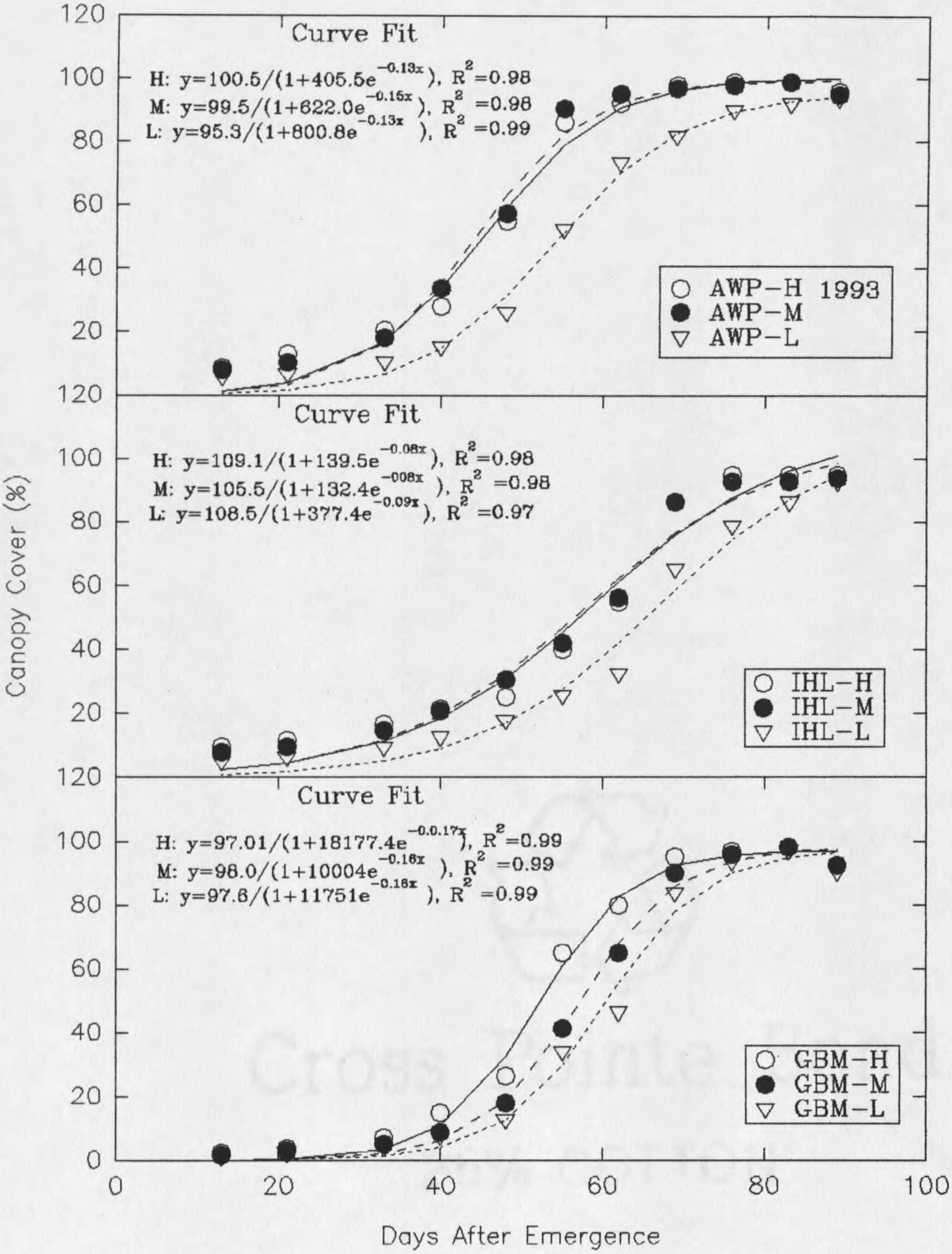

Fig. 8. Canopy cover after emergence in 1993. Comparisons between seeding rates for AWP, IHL and GBM.

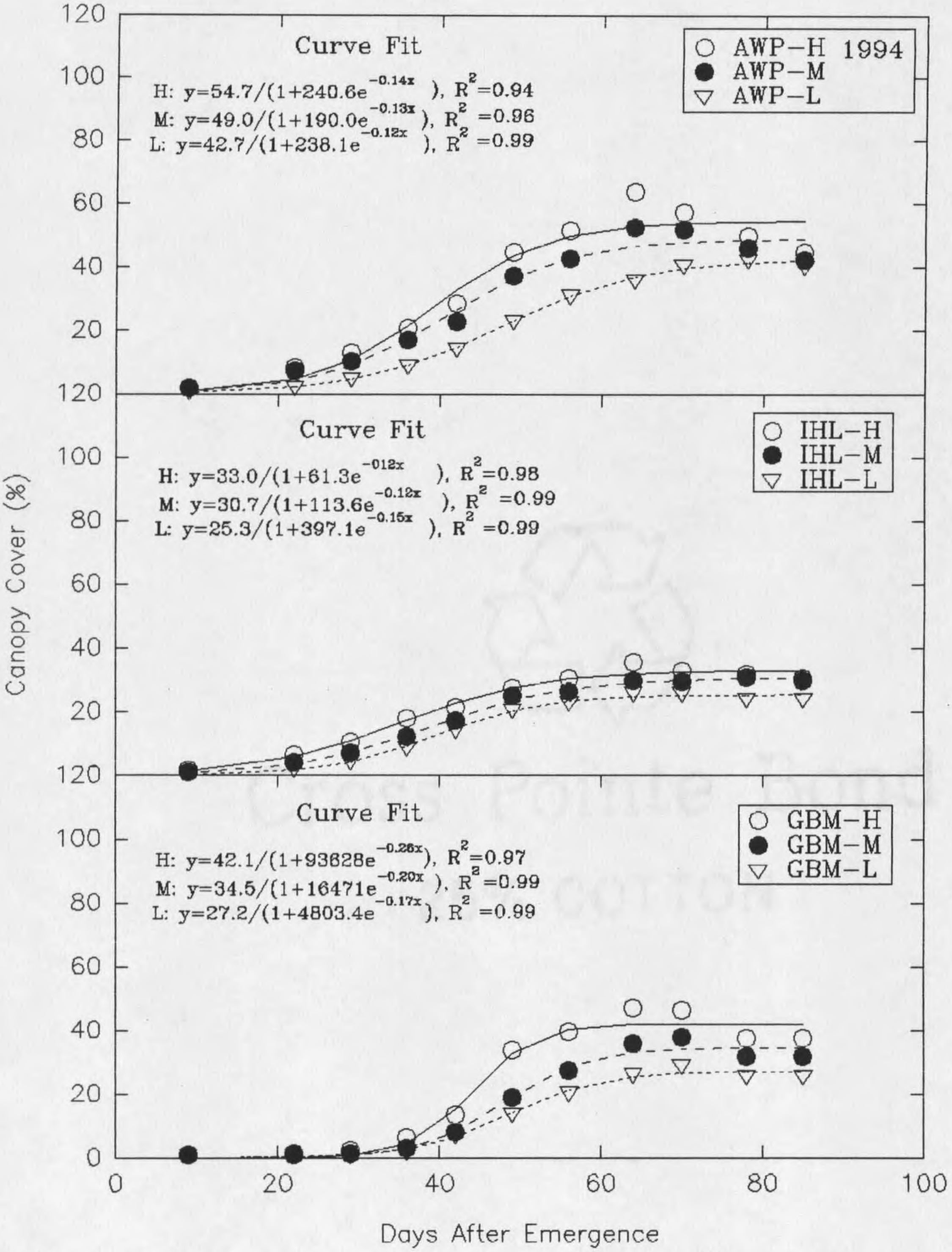

Fig. 9. Canopy cover after emergence in 1994. Comparisons between seeding rates for AWP, IHL and GBM.

leaf surface temperatures and thus transpiration (Loomis 1983; Ritchie, 1983).

Comparisons of percent canopy cover between species reveal, during both years and over all seeding rates, canopy development for AWP and IHL was similar in area but not pattern, for approximately the first 40 days (Figs. 6 and 7). After this, AWP clearly was the most aggressive species in canopy development.

George black medic had much slower canopy closure early in the growing season, probably using early season metabolites to develop a deep root system instead. By day 40, however, GBM underwent rapid canopy closure, quickly equaling and often exceeding IHL performance.

With adequate moisture in 1993, all species were able to reach almost 100% canopy closure. In 1994, percent canopy ranged from a low of 30% in the low seeding rate of IHL and GBM, to a high of 60% in AWP at the high seeding rate. The geometry of the bare, exposed soil varied between species. The erect growth of IHL resulted in large, uniform blocks of exposed soil between rows; whereas the prostrate and viney growth of AWP and GBM resulted in a mosaic pattern of shaded and exposed soil.

Comparing seeding rates within species reveal that, generally, 1993 and 1994 growth curves are graduated down from high to medium to low seeding rates in all species

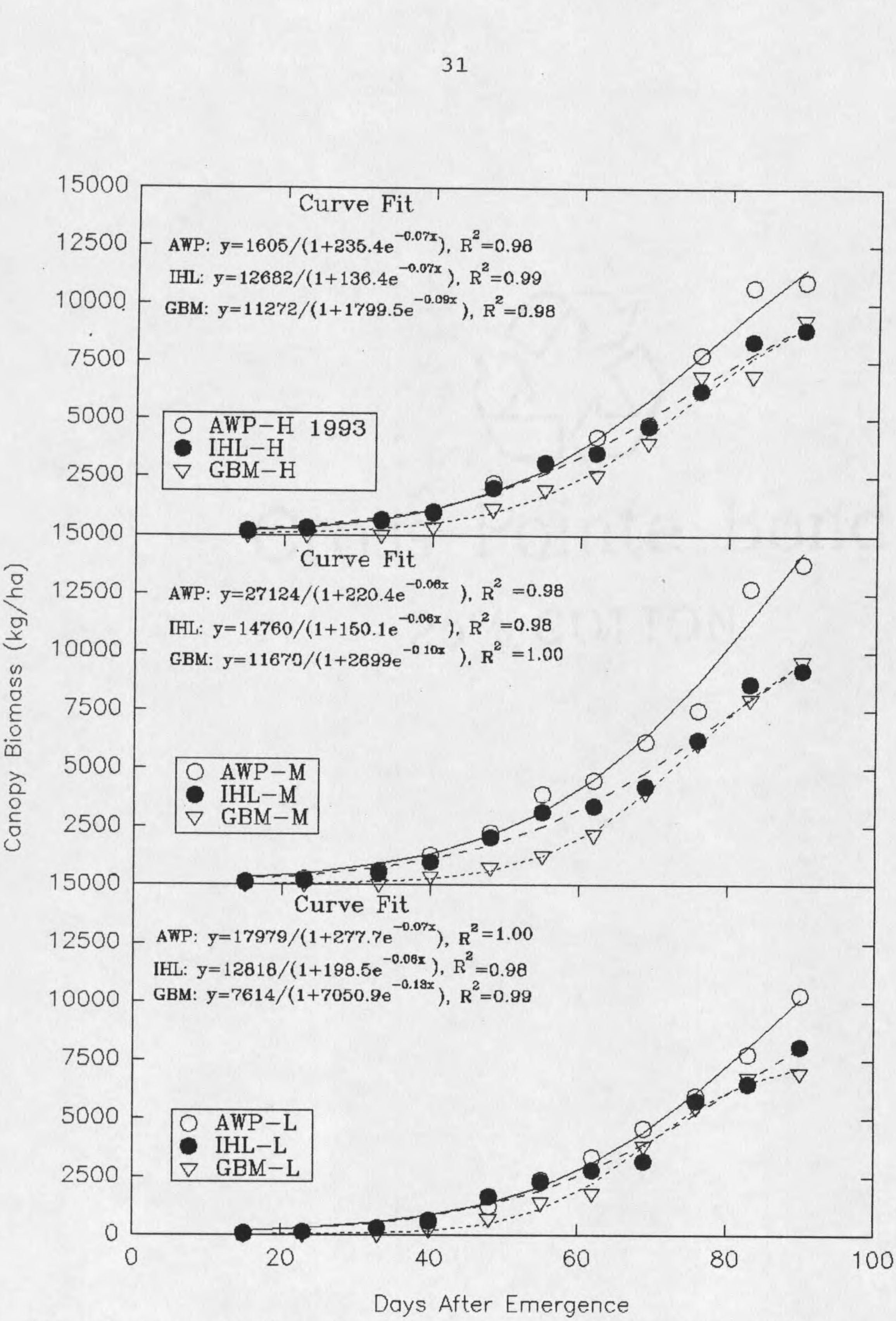

Fig. 10. Canopy biomass after emergence in 1993. Comparisons between AWP, IHL and GBM at each seeding rate.

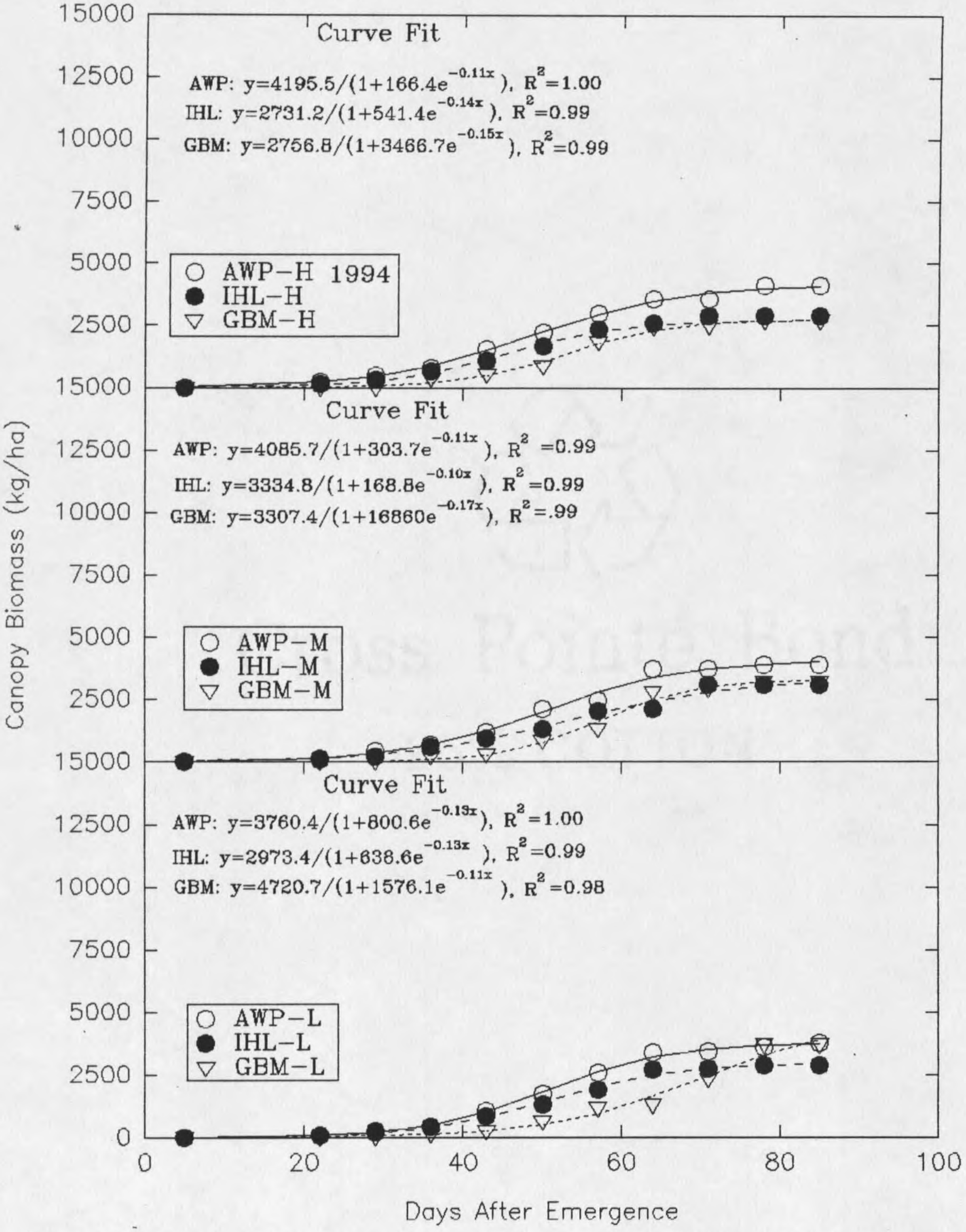

Fig. 11. Canopy biomass after emergence in 1994. Comparisons between AWP, IHL and GBM at each seeding rate.

(Figs. 8 and 9). The exception to this trend occurred in 1993 in AWP and IHL, where high and medium canopy closure was nearly the same.

Above Ground Biomass Production

Comparisons of biomass production between species (Figs. 10 and 11) reveal AWP clearly held an advantage over IHL and GBM. Although AWP and IHL maintained similar production during the early part of the growing season, AWP rapidly began to out-produce IHL at all seeding rates, as the season progressed. This trend became evident about day 60 in 1993, the cool, wet year, but expressed itself about day 40 in 1994, the hot dry year.

As seen here and intimated from water use data presented earlier, GBM had low early season biomass production compared to AWP and IHL. Not until later in the season, when temperatures increased, did it begin to rapidly commence canopy development. By days 60 to 70, GBM was at similar production levels to IHL, but was never able to reach AWP levels.

In 1993, biomass production levels peaked at approximately 14,000 kg/ha for AWP, and 8,750 kg/ha for IHL and GBM, at the medium seeding rate. In 1994, peak production occurred at approximately 4,100 kg/ha (29.3% of 1993 production) for AWP at the high seeding rate, and 3,000 kg/ha (34.3% of 1993 production) for IHL and GBM at medium and high seeding rates respectively.

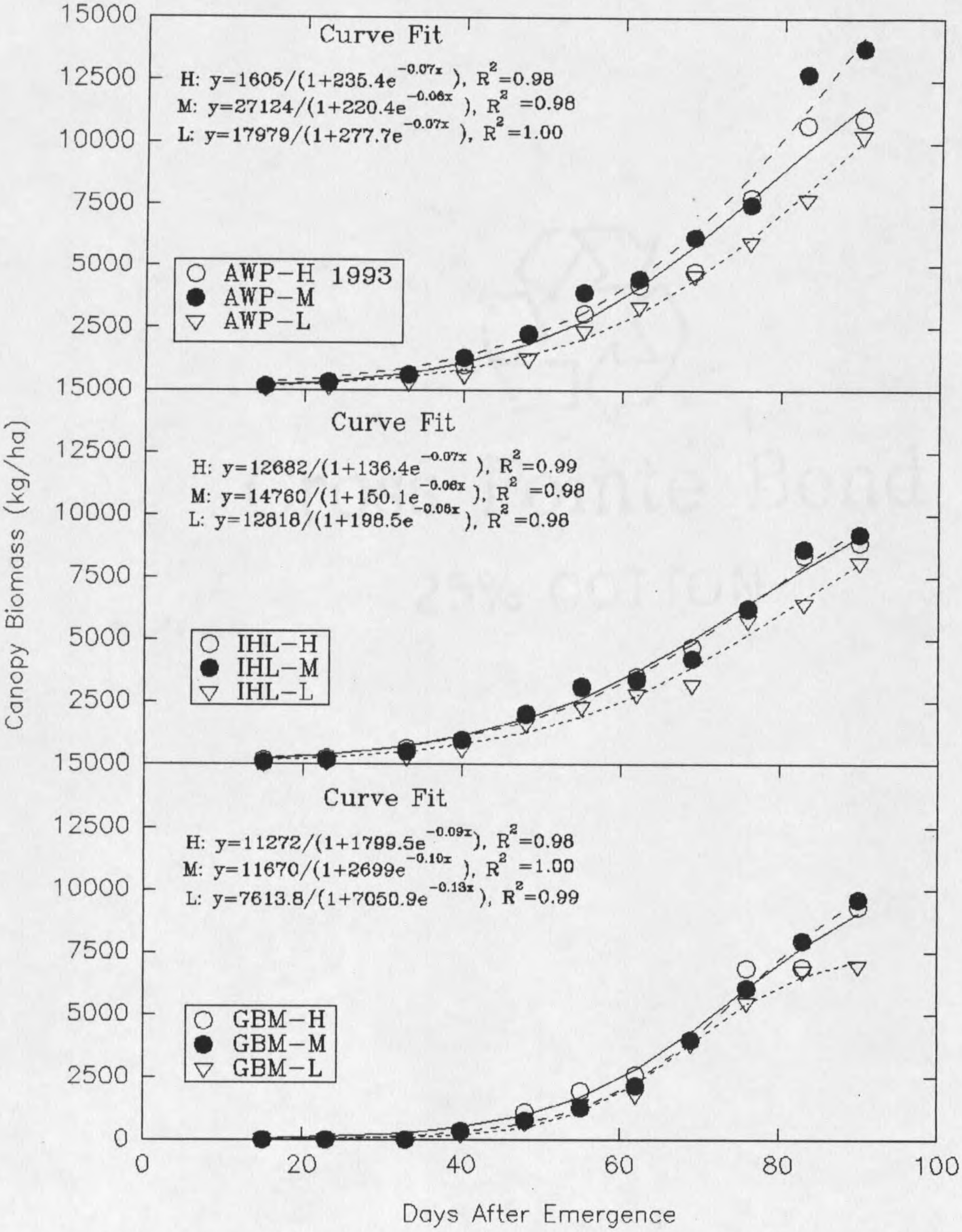

Fig. 12. Canopy biomass after emergence in 1993. Comparisons between seeding rates for AWP, IHL and GBM.

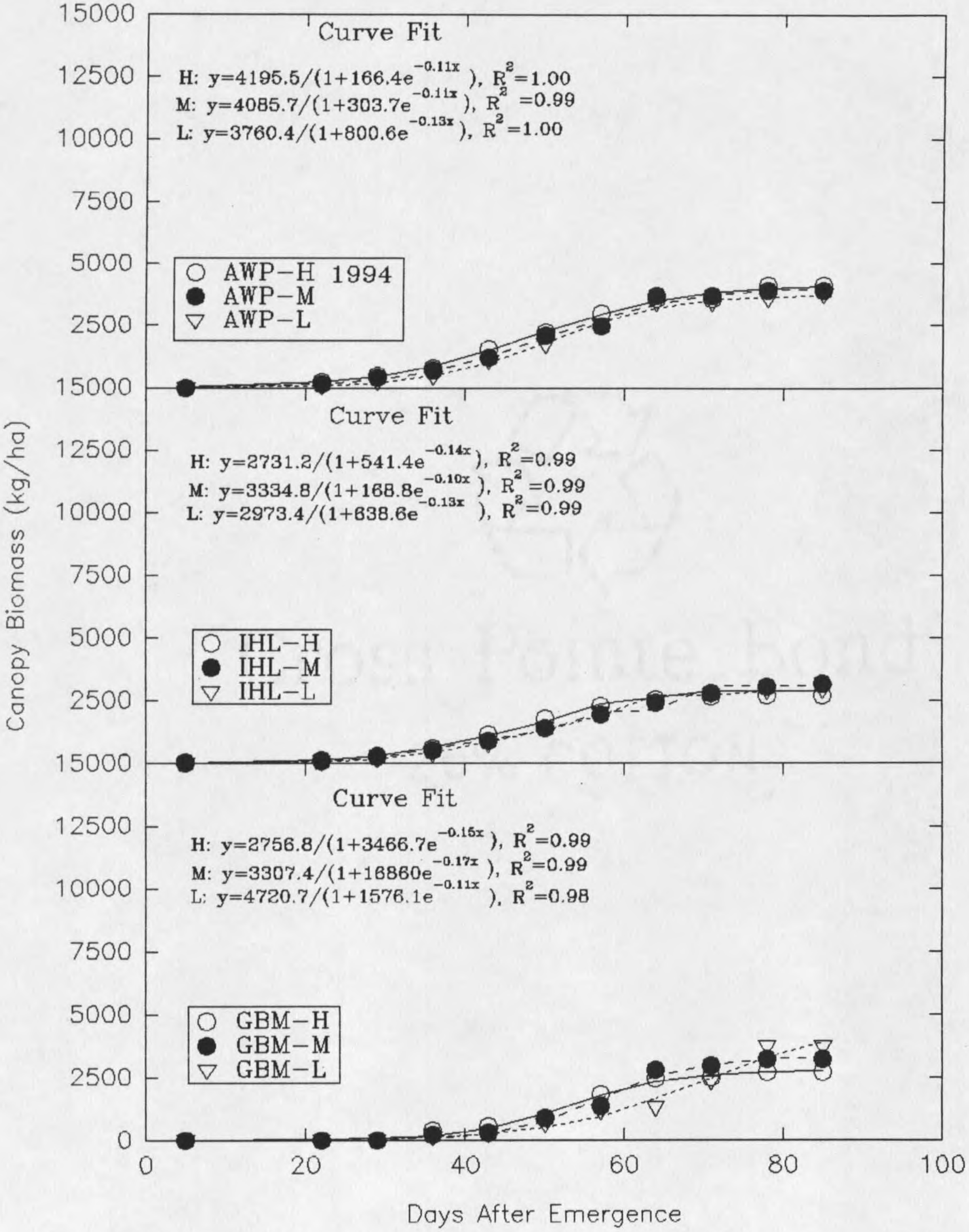

Fig. 13. Canopy biomass after emergence in 1994. Comparisons between seeding rates for AWP, IHL and GBM.

Seeding rate comparisons within species in 1993 (Figs. 12 and 13) revealed under medium seeding rate, biomass production was similar to or even exceeded that of the high seeding rate, for all three species. The low seeding rate production level was only slightly below the other two. During this excessively cool, wet growing season, AWP had the greatest distribution between seeding rates, while GBM appeared to have the least. The narrowness of the range of performance between seeding rates in 1993 is somewhat surprising. With ample moisture, the high seeding rate should have been able to maintain superior production. Apparently, increased competition for light and nutrients kept production near that of the medium seeding rate. As seen in the canopy closure data above, the low seeding rate was not able to achieve complete canopy closure as rapidly as the other two rates. Because the soil surface was often wet in 1993, more water was likely partitioned to evaporation under the sparser canopy of the low seeding rate. This was one factor which could have held back production levels at the low seeding rates.

In general, for all species in 1994, there was very little difference in biomass production over all seeding rates. After day 60, the medium rate production nearly equaled that of the high rate in AWP, while both medium and low surpassed that of high in IHL and GBM. In 1994, a hot dry year where the soil surface remained relatively dry throughout the growing season, soil evaporation was not as critical. Having stored soil moisture reserves later in the season eventually gave the medium and low rates an advantage over the high. In the case of GBM, with its presumed deeper rooting system, the low rate was even able to surpass the medium rate at the end of the season.

To generalize, optimum biomass production occurred at the medium seeding rate in all species, during an excessively wet and a relatively dry (normal) growing season.

Total Canopy Nitrogen (N) Accumulation

Species differences become more apparent with canopy N comparisons (Figs. 14 and 15). Both years, AWP had a distinct early season advantage over the other two species, which it maintained for the rest of the season. Canopy N continued to increase in all species at a steady rate in 1993. However, in 1994, IHL canopy N quickly leveled off after approximately day 50, while AWP continued to steadily increase for several more days. Initially, GBM canopy N accumulated slowly, but began to rapidly increase about day 40, exceeding IHL canopy N between day 50 and 60, and approaching that of AWP by the end of the season. The ability of peas to maintain higher canopy N levels than IHL has been reported in other green manure studies. In a recent study in Saskatchewan, which included another variety of field peas (*Pisum sativum* L. 'Trapper') and IHL, field

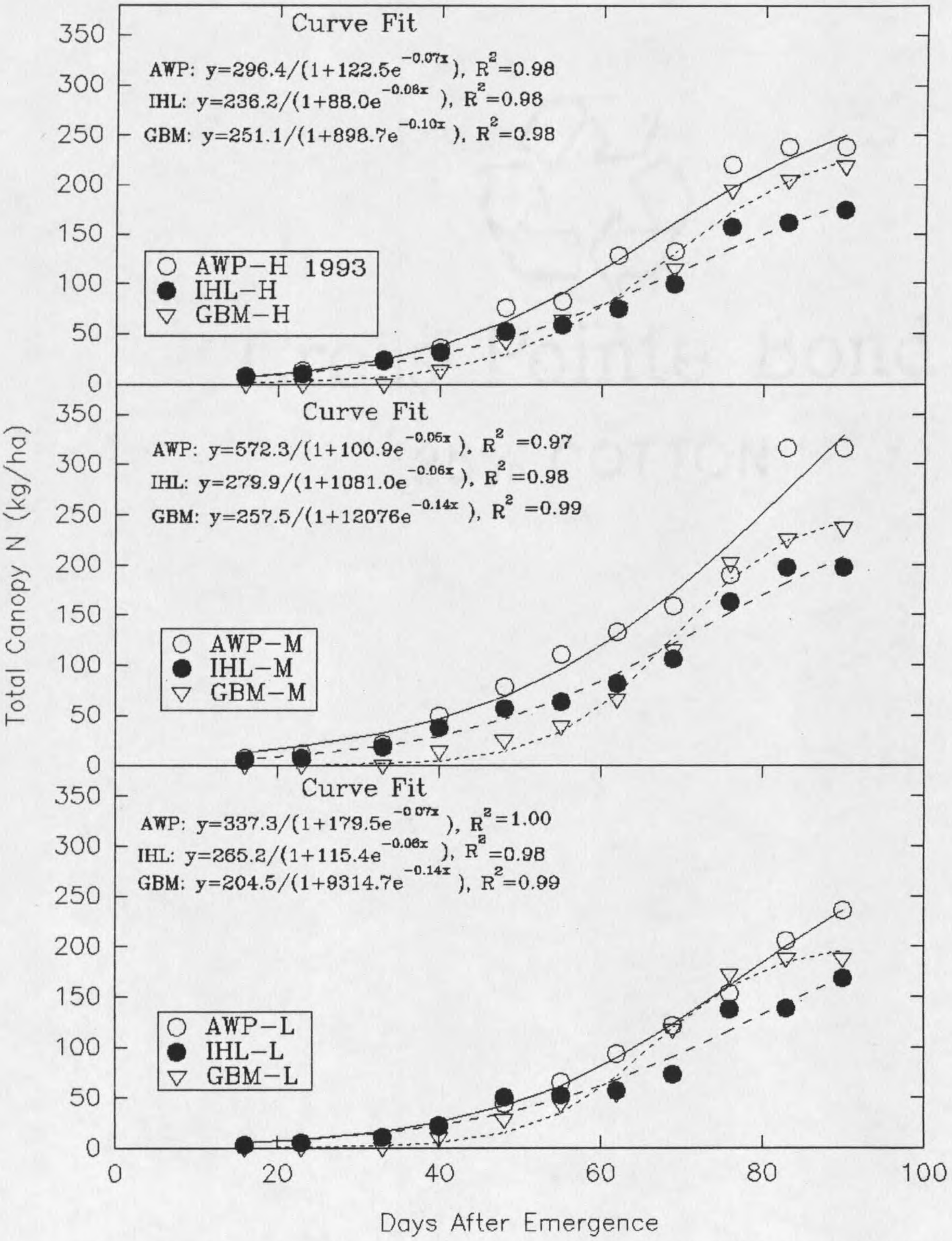

Fig. 14. Canopy nitrogen accumulation after emergence in 1993. Comparisons between three species at each seeding rate.

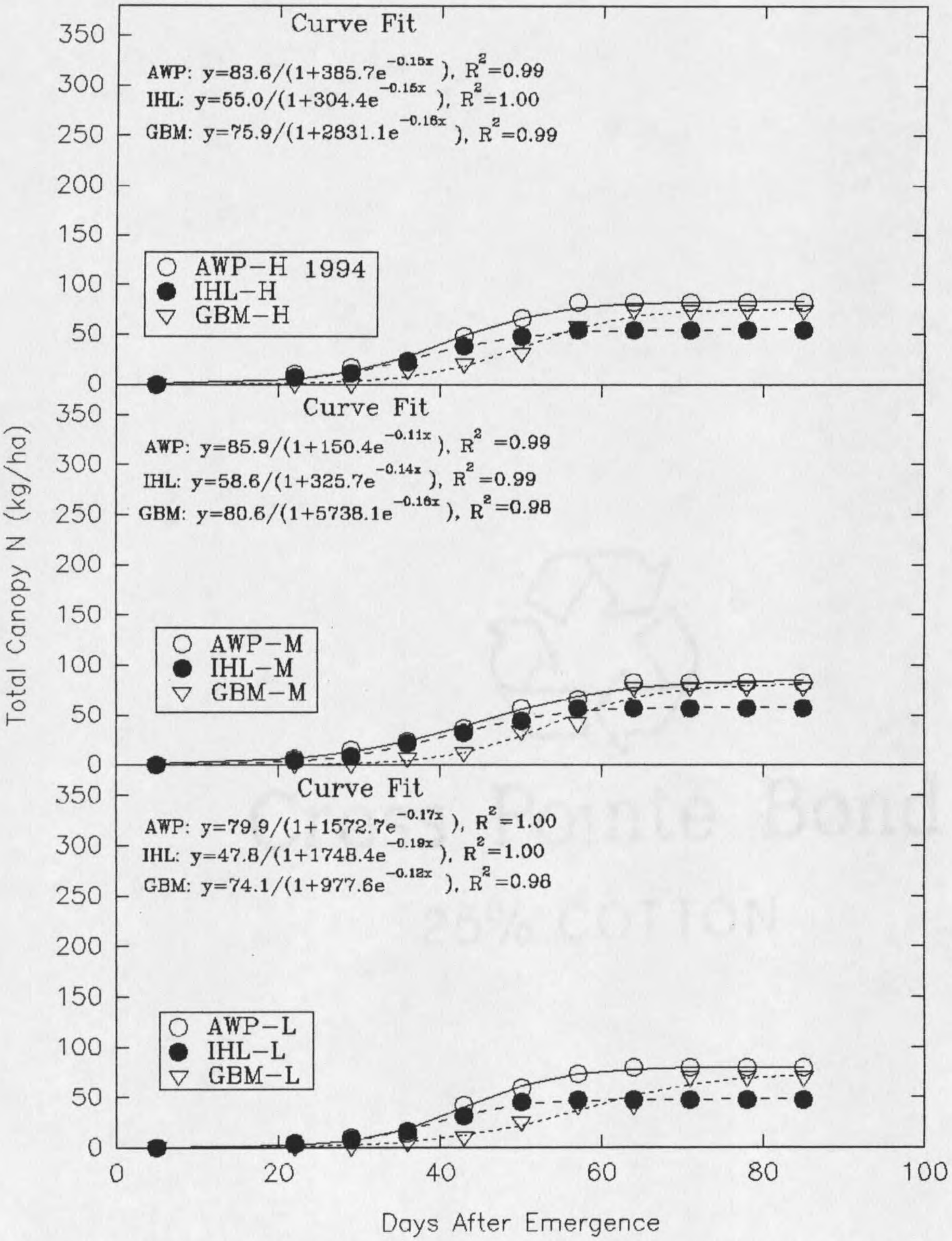

Fig. 15. Canopy nitrogen accumulation after emergence in 1994. Comparisons between three species at each seeding rate.

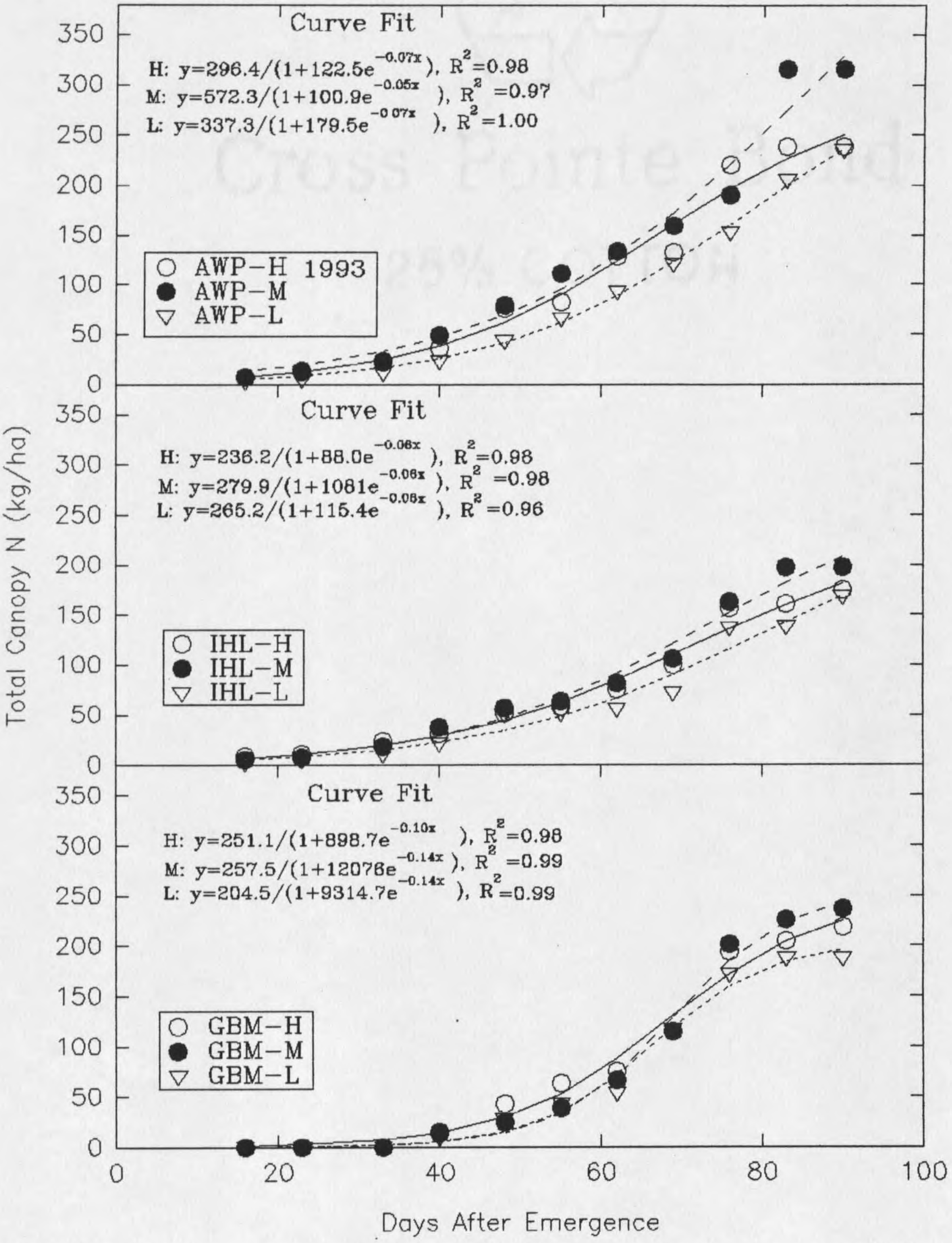

Fig. 16. Canopy nitrogen accumulation after emergence in 1993. Comparisons between seeding rates for AWP, IHL and GBM.

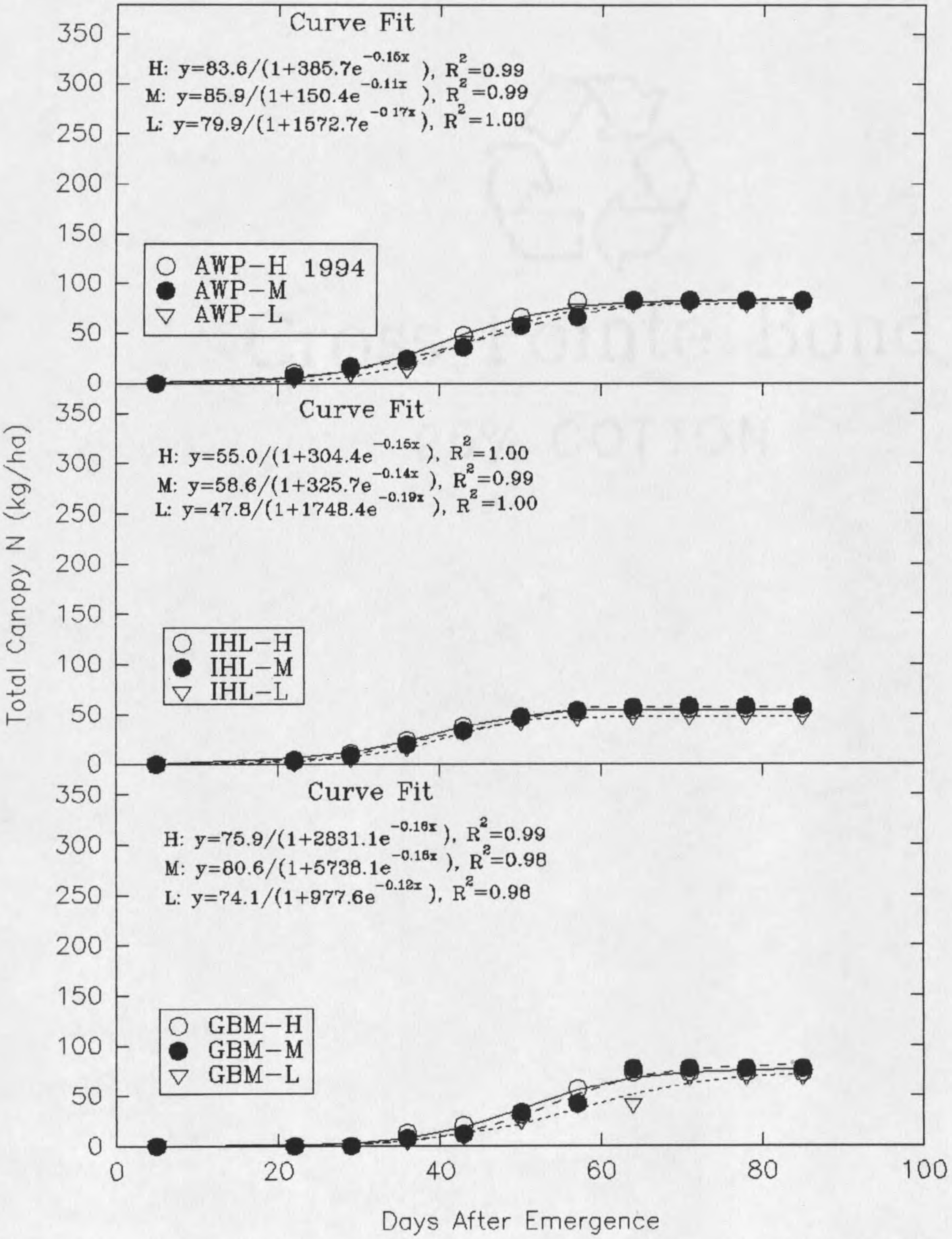

Fig. 17. Canopy nitrogen accumulation after emergence in 1994. Comparisons between seeding rates for AWP, IHL and GBM.

peas had greater dry matter production and canopy N accumulation than did IHL (Townley-Smith et al., 1993).

Peak N production in 1993 occurred at approximately 320 kg/ha for AWP, 240 kg/ha for GBM and 190 kg/ha for IHL at the medium seeding rate. In 1994, peak N production was only approximately 82 kg/ha for AWP and GBM, and 50 kg/ha for IHL at the medium seeding rate.

Since canopy N and biomass production are so closely correlated, within species comparisons of seeding rates show very similar results (Figs. 16 and 17) to biomass data (Figs. 12 and 13). During both years, medium seeding rate canopy N levels equaled and generally exceeded high seeding rates. Low seeding rates had lowest canopy N across all species, even in 1994. High plant populations apparently were able to maintain more canopy N, despite the increasing biomass production in the low seeding rate plots later in the season. In general, maximum canopy N production occurred with the medium seeding rate in all species.

N_2-fixation

Figure 18 illustrates canopy N accumulation by barley in comparison to the three legume species for 1993 and 1994. Using the difference method, N_2-fixation is assumed to be that part of the legume N accumulation at a given time which exceeds the N accumulated by barley. The reader is reminded that the difference method merely provides an estimate of N_2-fixation by legumes and is not totally accurate. High

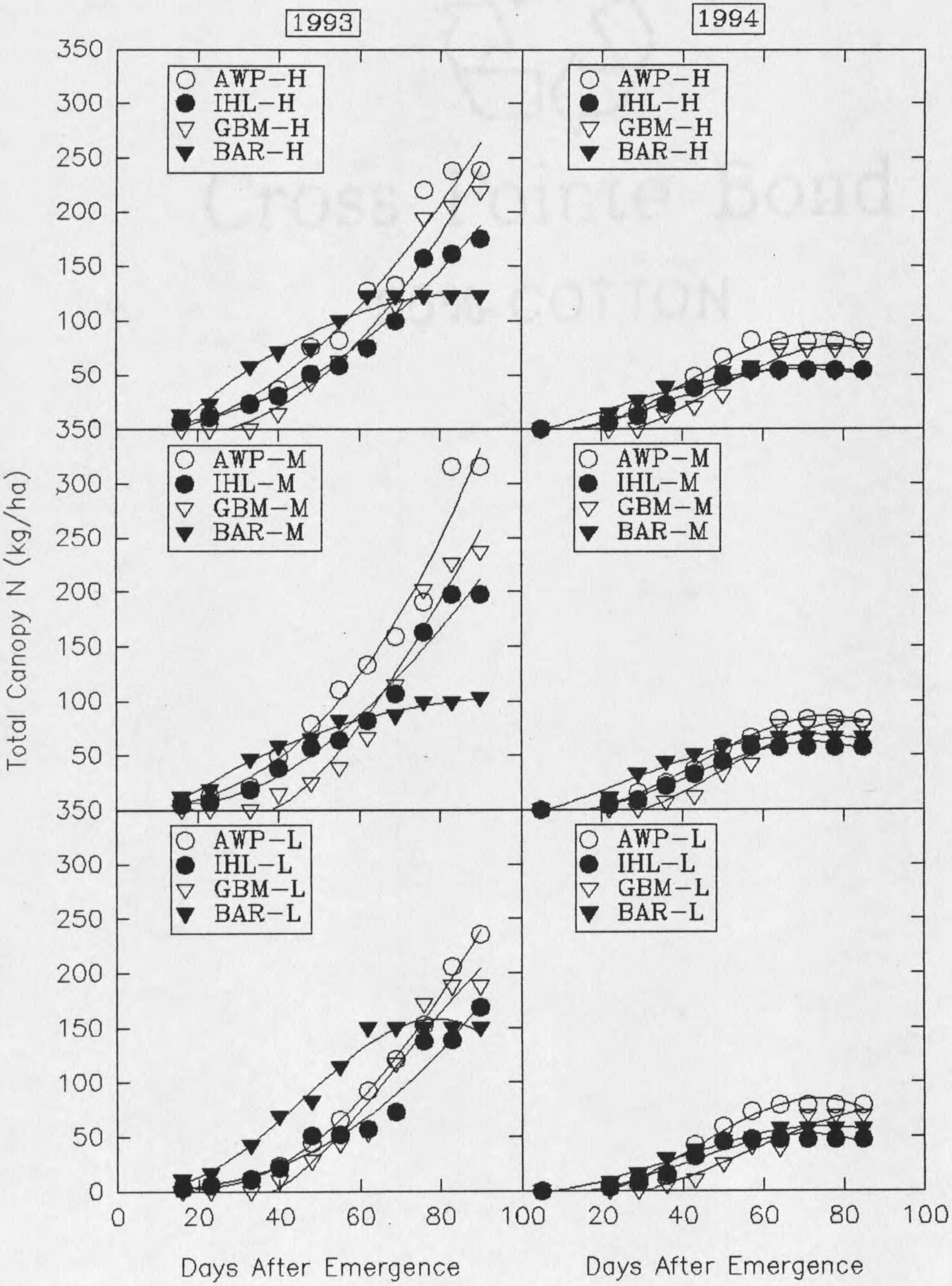

Fig. 18. Total canopy N accumulated after emergence in 1993 and 1994. Comparisons between AWP, IHL, GBM, and BAR.

levels of NO_3-N in the soil are known to inhibit nodulation and/or N_2-fixation by legumes. Also, the level of NO_3-N which inhibits these processes varies from species to species.

Soils data for 1993 and 1994, are reported in Tables 2 and 3 below. Having been freshly broke out of sod, soil NO_3-N was very low at planting in 1993. Although an effort was made to maintain these low levels in the 1994 plot area by planting barley in 1993, NO_3-N levels had increased significantly by 1994. Mineralization of soil N was no doubt enhanced by the wet growing season of 1993. Healthy pink nodules were observed by day 15 on the three legume species in 1993, and by day 23 in 1994, indicating that N_2-fixation was taking place. Thus, an unknown portion of the N accumulated by the legumes prior to day 40 to 50 probably was derived from N_2-fixation. Wright (1993) found that, although both barley and legumes accumulated N from the soil N pool, at the end of the season legumes had taken less N out of the soil pool than had barley. This indicated substantial N_2-fixation had occurred.

Table 2. 1993 soil NO_3-N, P, K, organic matter, and pH at at time of planting.

Depth (cm)	NO3-N (mg/kg)	P (mg/kg)	K (mg/kg)	O.M. (%)	pH
0 - 15	1.73	5.33	421	1.53	8.5
15 - 30	0.63	2.47	367	0.97	8.5
30 - 45	0.30	1.3	372	0.78	8.7

Table 3. 1994 soil NO_3-N, P, K and organic matter at time of emergence.

Depth (cm)	NO3-N (mg/kg)	P (mg/kg)	K (mg/kg)	O.M. (%)
0 - 15	15.5	11.7	356	1.5
15 - 30	9.9	---	---	---
30 - 45	4.8	---	---	---

Differences between 1993 and 1994 barley canopy N (Fig. 19) are a little less dramatic than were the differences for the legume canopy N accumulation curves. This is likely due to earlier seed set and maturity in barley, as compared with the legumes. However, had the 1994 soil NO_3-N remained at the same low level as in 1993, 1994 barley canopy N levels may have been even lower.

In general, in 1993, legume canopy N exceeded that of barley around day 50 to 60 (Fig. 20), with the earliest instance around day 50, noted with the AWP medium seeding rate. Negative values were considered to be zero. Differences between legume performance are the same as those discussed in the previous section on legume canopy N accumulation. Peak performance occurred at the medium seeding rate for all species, where AWP led with approximately 225 kg/ha, GBM at almost 150 kg/ha and IHL at 100 kg/ha.

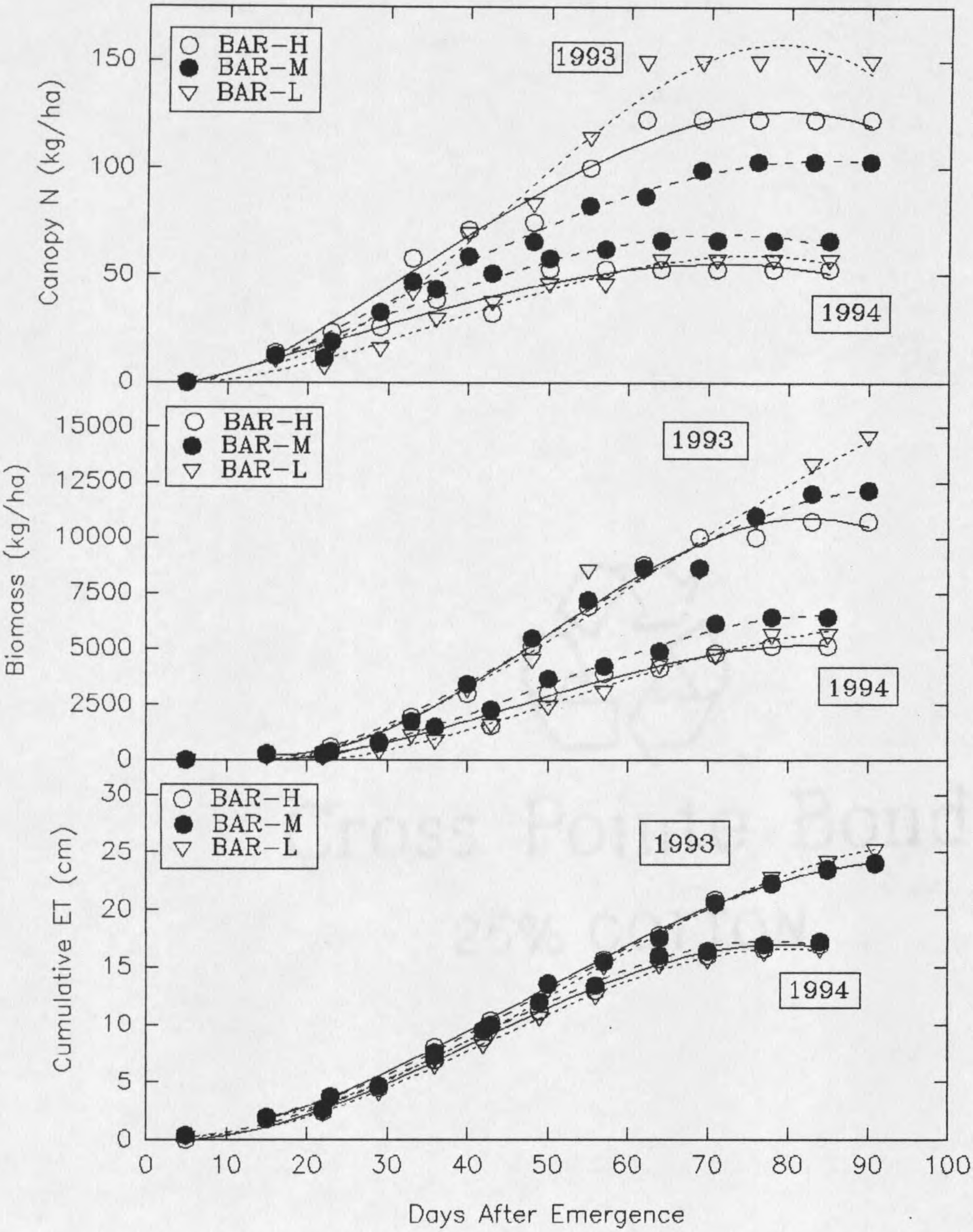

Fig. 19. Cumulative ET, biomass and canopy N accumulation after emergence for barley in 1993 and 1994.

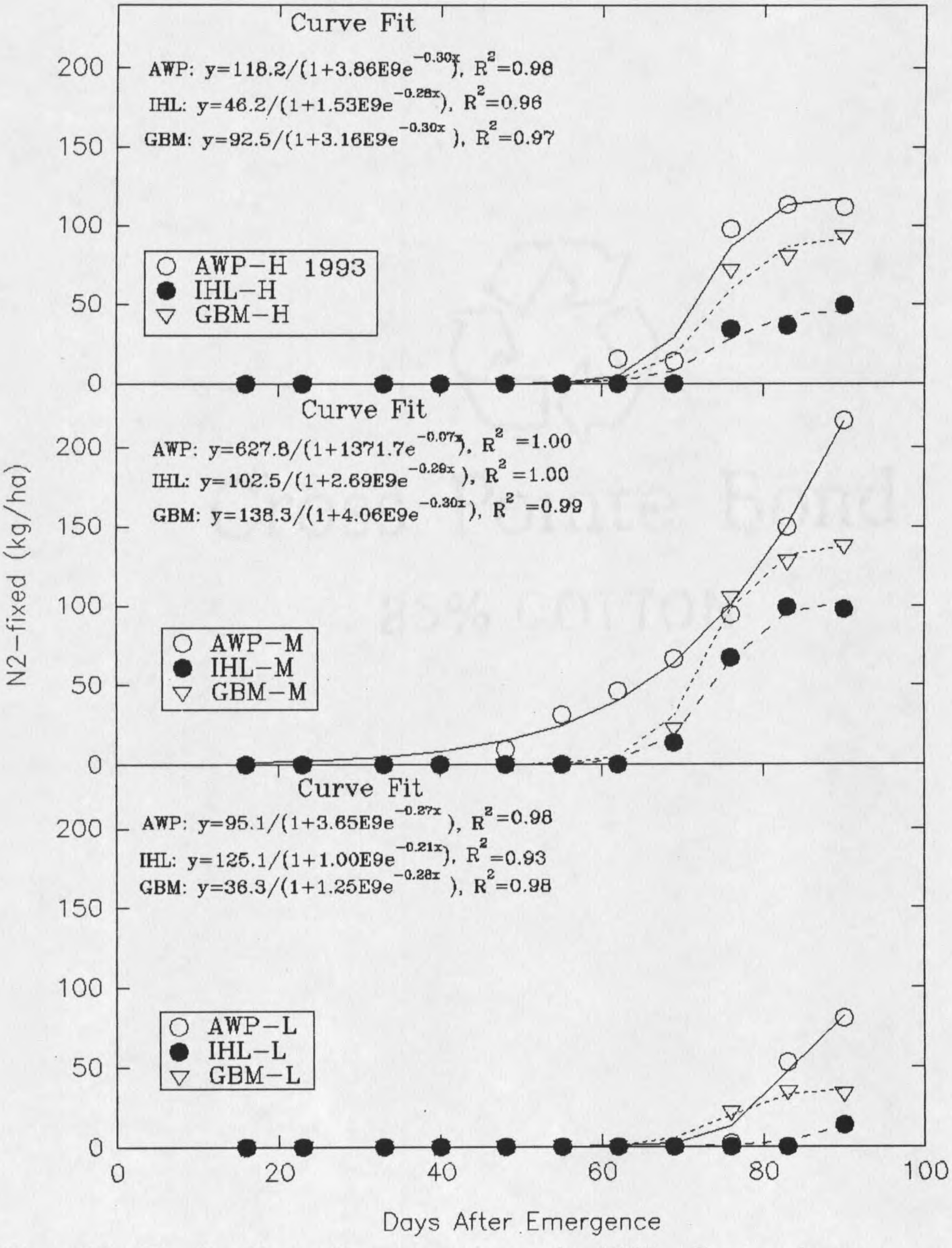

Fig. 20. N_2–fixation after emergence in 1993. Comparisons between AWP, IHL, and GBM at each seeding rate.

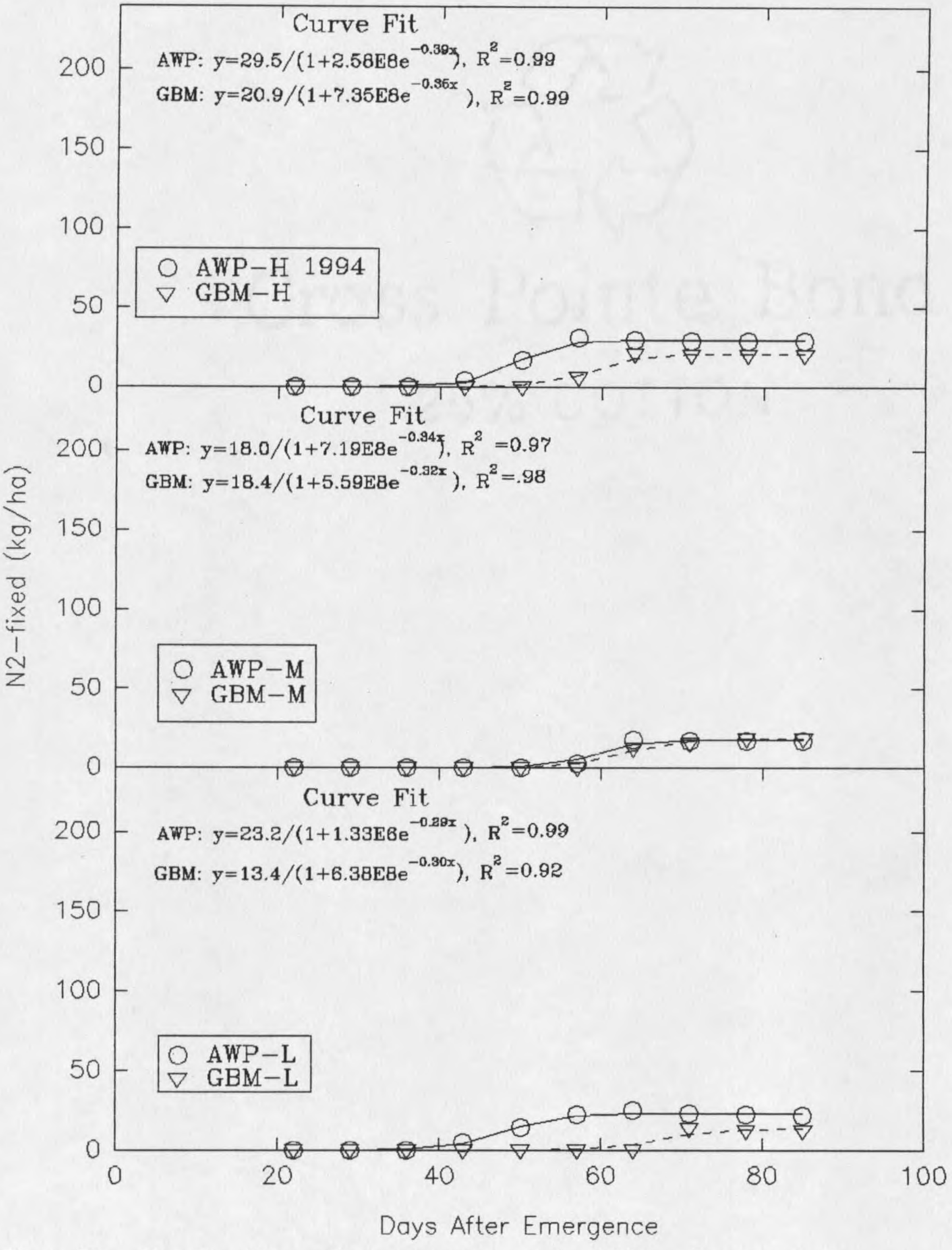

Fig. 21. N_2-fixation after emergence in 1994. Comparison between AWP and GBM at each seeding rate.

In 1994, (Fig. 21) legume canopy N exceeded barley N between day 40 and 50. Performance was very similar for all seeding rates in AWP and GBM, and reached a plateau of only 25 kg/ha. Indianhead lentil had very similar performance to barley, but was never able to exceed barley levels in 1994.

Although there are inherent problems with using the difference method to calculate N_2-fixation, it does give a graphic illustration of the advantages of using a legume crop for green manure, rather than one that is not able to fix nitrogen.

Water Use Efficiency

In Terms of Cumulative ET vs. Percent Canopy Cover

Data shown here and in following water use efficiency (WUE) comparisons were fit to polynomial equations which were statistically compared for coincidence. Regressions displayed in the following figures which have the same letter are considered coincident at the p=0.05 level. In general, in 1993 (Fig. 22) AWP and GBM had similar WUE. Indianhead lentil usually had lowest WUE. One explanation for this may be that IHL has a more open upright canopy, as compared to the more dense, prostrate growth habit of AWP and GBM. Thus, the IHL canopy allows for greater evaporation at all seeding rates. Biederbeck and associates (1993) came to a similar conclusion in a green manure study which included black lentil (*Lens culinaris* Medikus) and a

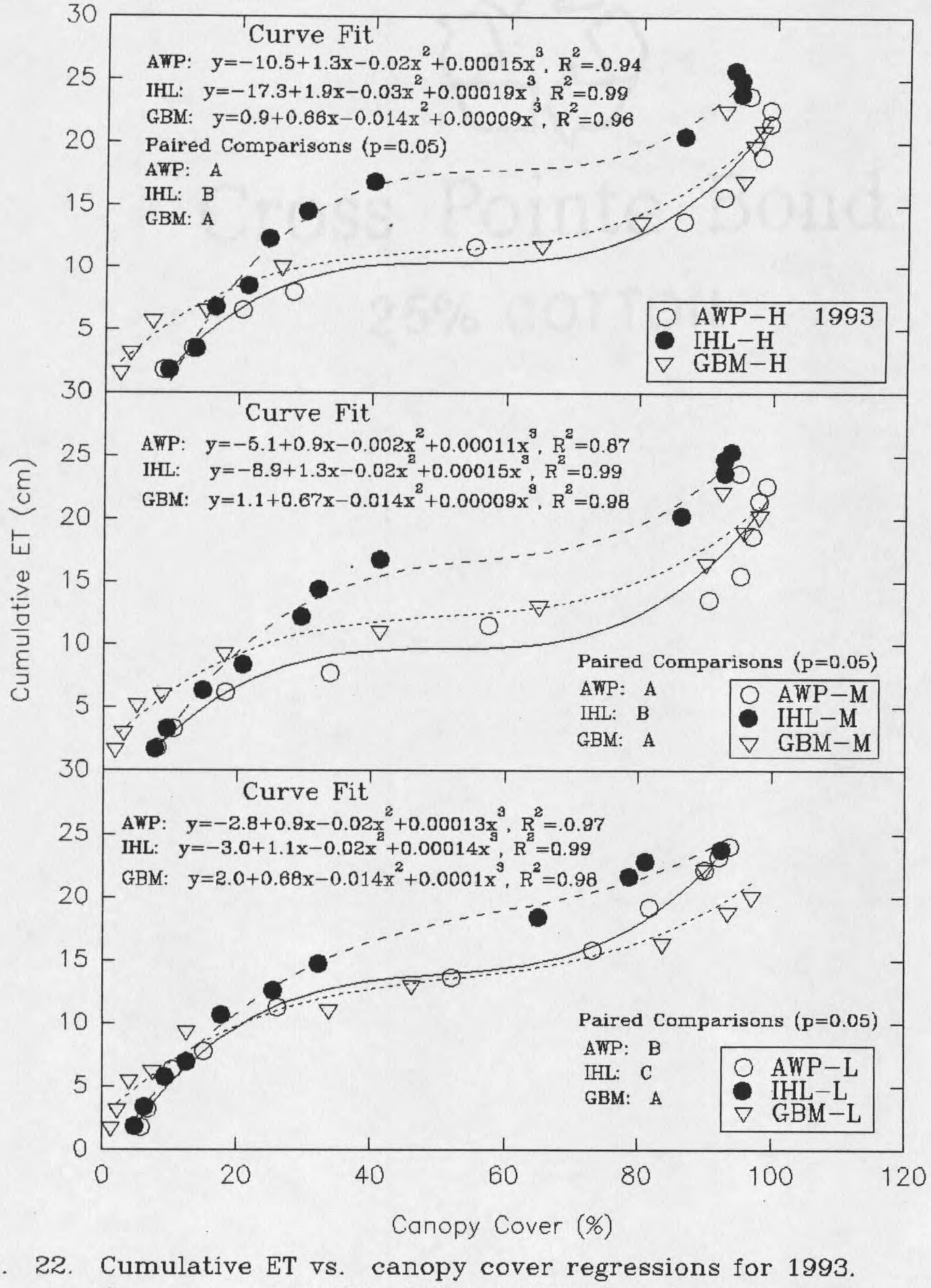

Fig. 22. Cumulative ET vs. canopy cover regressions for 1993. Comparisons of AWP, IHL and GBM at each seeding rate.

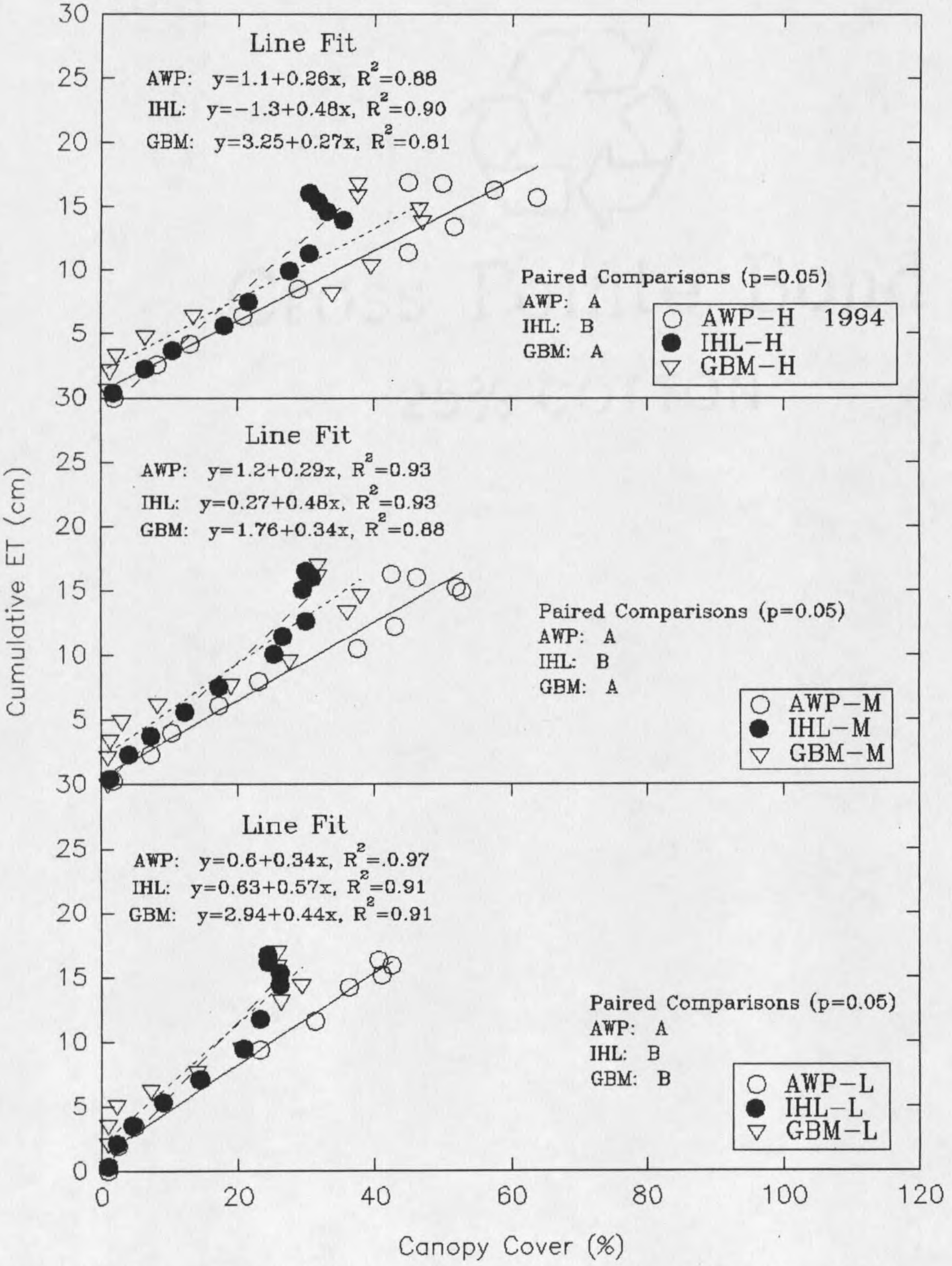

Fig. 23. Cumulative ET vs. canopy cover regressions for 1994. Comparisons of AWP, IHL and GBM at each seeding rate.

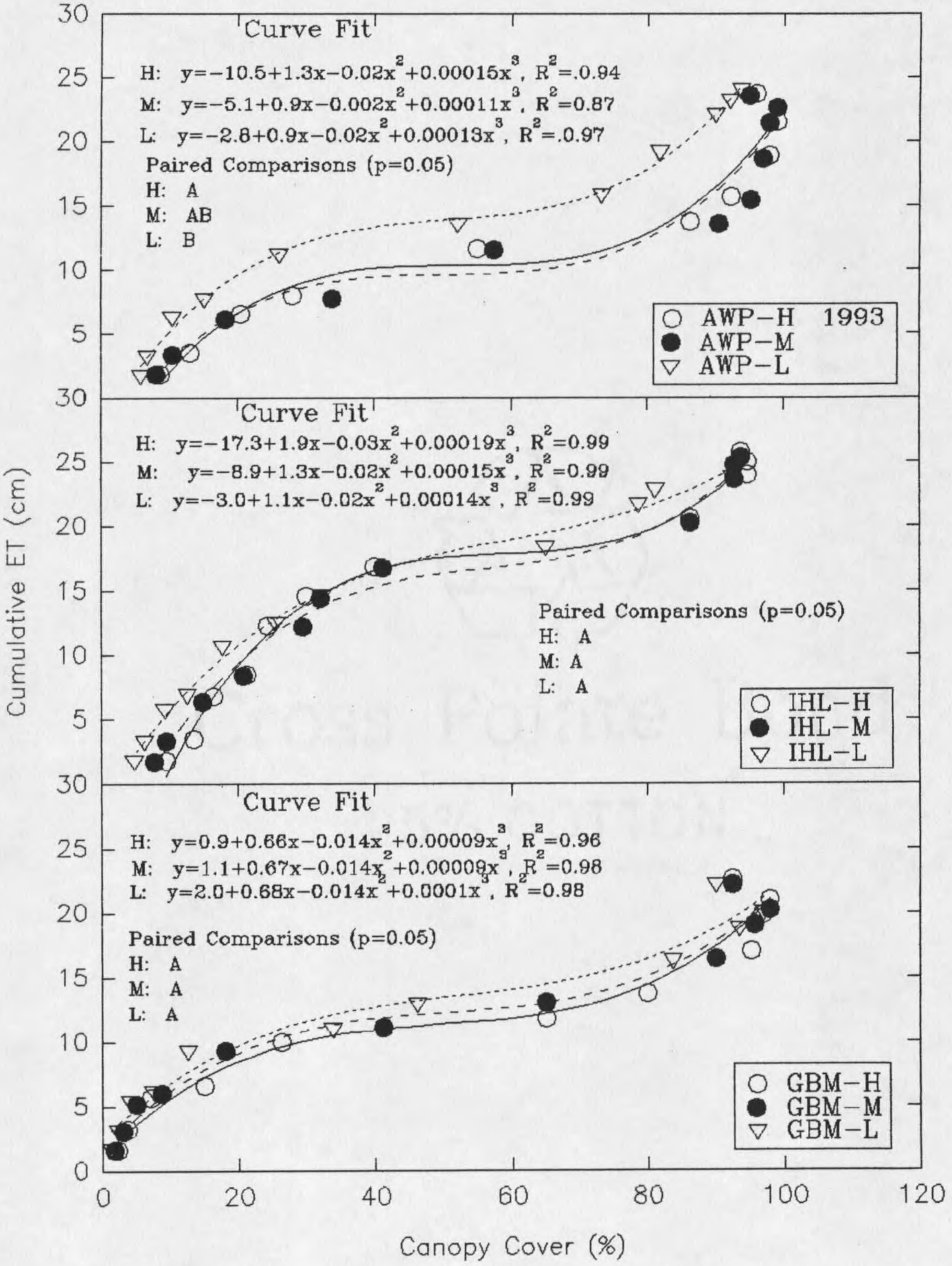

Fig. 24. Cumulative ET vs. canopy cover regressions for 1993. Comparisons between seeding rates for AWP, IHL and GBM.

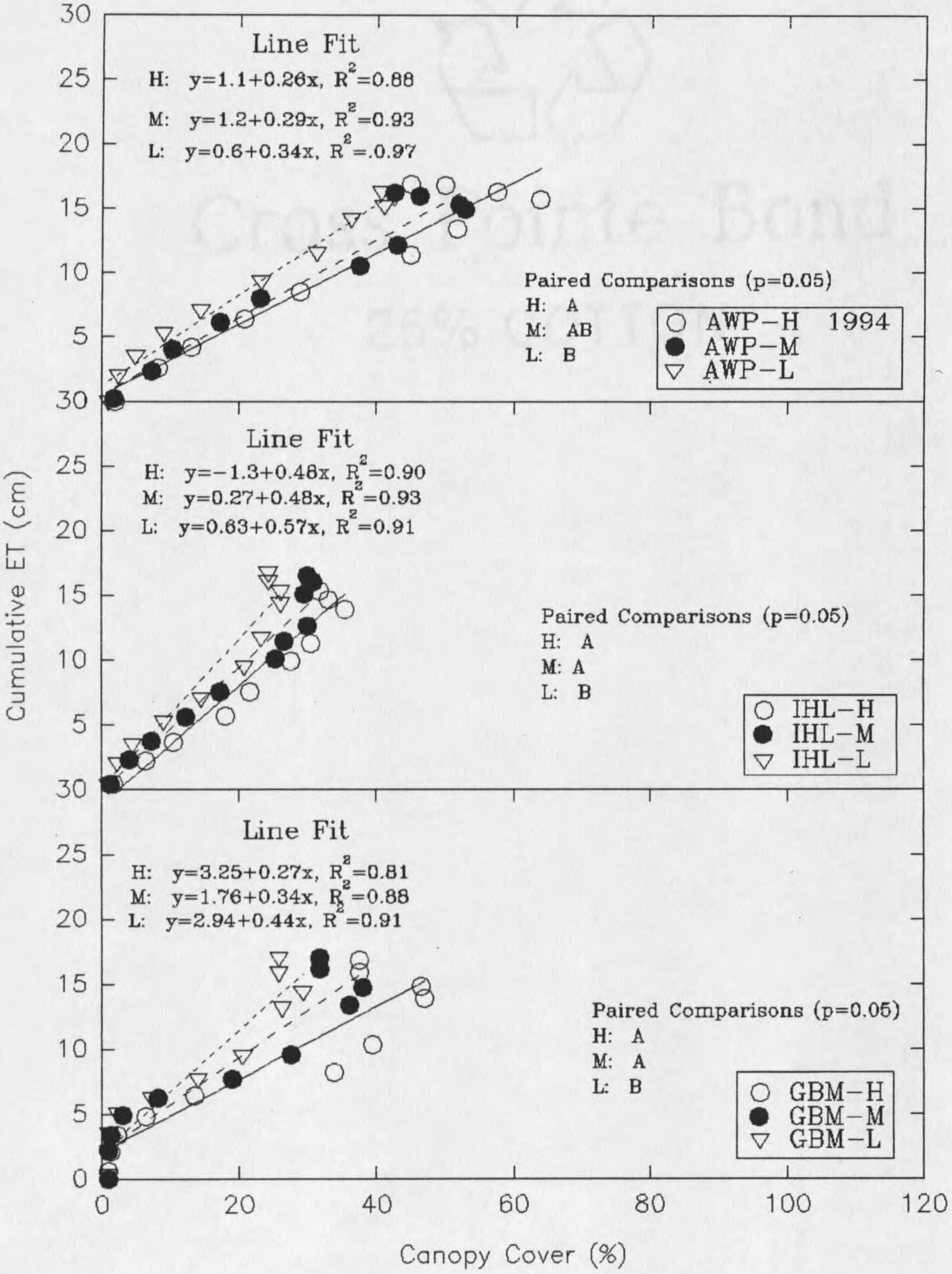

Fig. 25. Cumulative ET vs. canopy cover regressions for 1994. Comparisons between seeding rates for AWP, IHL and GBM.

feedpea (*Pisum sativum* L.). They measured stem length and canopy height, and calculated the degree of decumbency. Their conclusion was that the lentil has an erect growth habit, while the feedpea has a more prostrate growth habit. This allowed the feedpea to provide more ground cover, and thus more soil protection.

During the first 20 days after emergence, GBM appeared to have lower WUE due to greater evaporation, however, this quickly changed after GBM commenced canopy growth.

The same trends were true in 1994, (Fig. 23). However, distinctions were not quite as obvious, possibly because evaporation was not as critical. Statistically, there was no advantage between AWP and GBM at high and low seeding rates, but AWP had higher WUE at low densities.

It was postulated that higher stand densities should have higher WUE. In terms of canopy cover, this often appears to be true for all species between the high and low seeding rates and often the medium and low rates (Figs. 24 and 25). The low seeding rate appeared to have left more soil exposed and had higher evaporation.

Medium and high seeding rates were often coincident at the 5% level. If there was similar evaporation for both seeding rates, one explanation for this may be that increased seedling mortality in the high rate caused population levels to decrease to near those of the medium rate, hence, transpiration was similar.

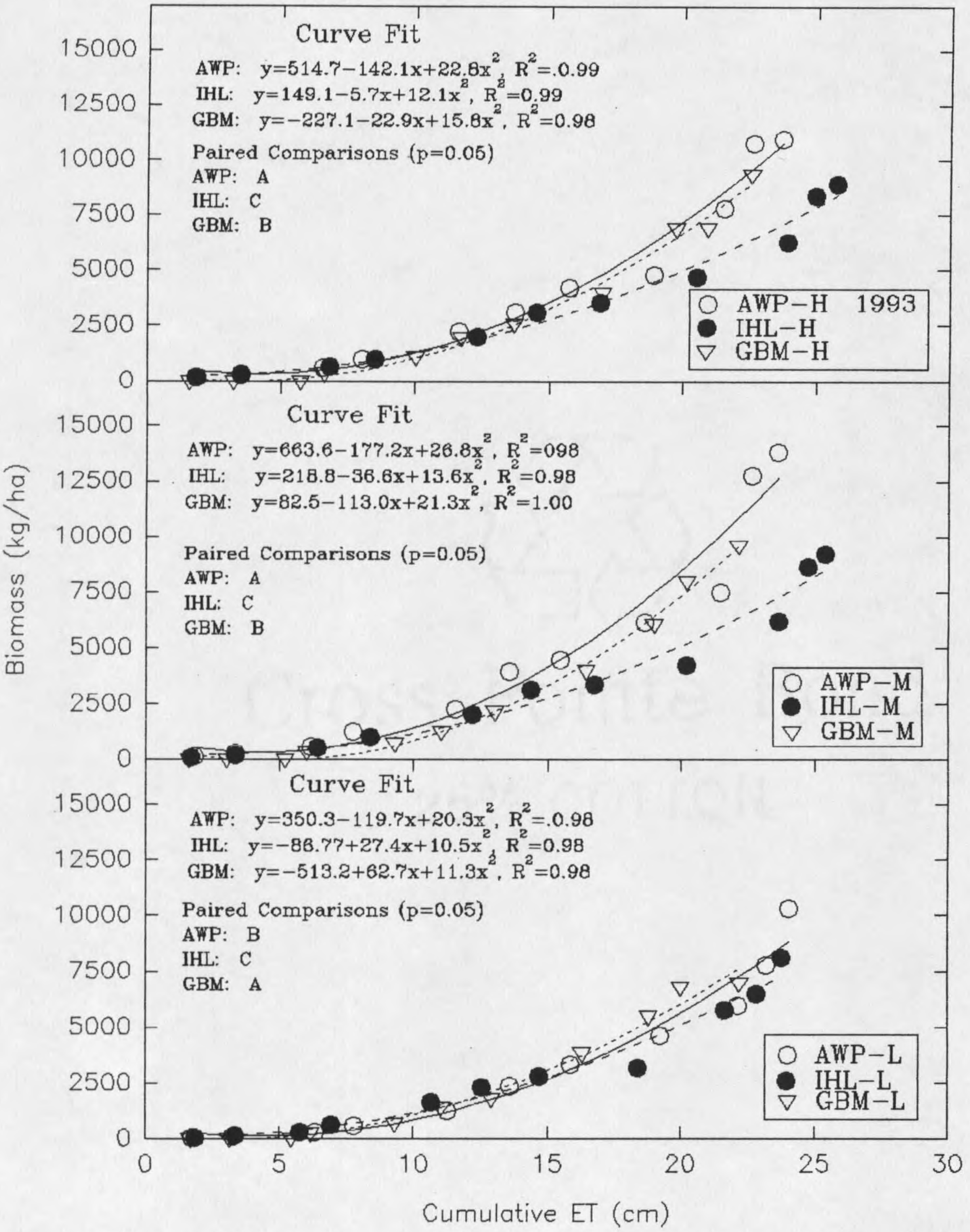

Fig. 26. Canopy biomass accumulation vs. ET regressions for 1993. Comparisons of AWP, IHL and GBM at each seeding rate.

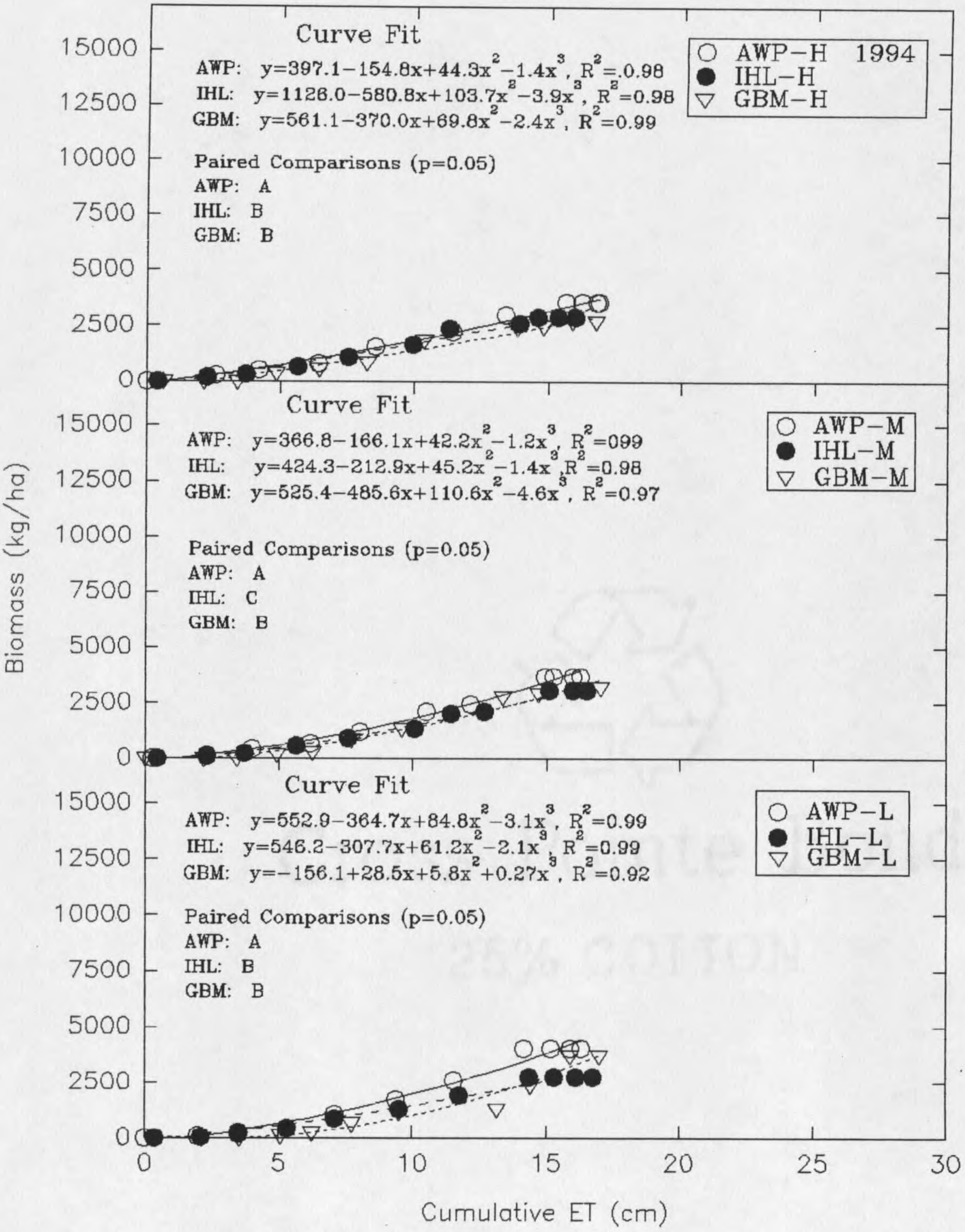

Fig. 27. Canopy biomass accumulation vs. ET regressions for 1994. Comparisons of AWP, IHL and GBM at each seeding rate.

In Terms of Biomass vs. ET

Austrian winterpea had highest WUE during both years (Figs. 26 and 27). The only exception to this occurring in the low seeding rate in 1993, where there was very little distinction between the three species and GBM eventually led in efficiency.

In 1993, differences between species did not become apparent until after approximately 15 cm of water use. In 1994, the growth cycle was almost complete by this point and there appeared to be very little distinction between the three species. However, AWP curves were generally not coincident at the 5% level with GBM and IHL curves.

Biederbeck and Bouman (1994) found similar results using a feed pea (*Pisum sativum* L.) and black lentil (*Lens culinaris* Medikus). The feed pea used water more efficiently in terms of dry matter production than did the black lentil. On the other hand, Wright (1993) found there was no significant difference in WUE in terms of biomass production between AWP, IHL and GBM in a wet year. However, in a dry year AWP and IHL had similar WUE, but significantly greater than GBM.

Within species comparisons between seeding rates (Figs. 28 and 29) reveal no distinctive trends between 1993 and 1994. In 1993, the medium rate had highest WUE for AWP and GBM, with IHL showing no difference between rates.