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# Energetics of Forest Biomes

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## ABSTRACT

Forest energetics is the study of the mechanisms and general rules in forming and transferring energy or energy-containing materials within and between forest ecosystems. Understanding the spatial and temporal pattern of ecological energetics of forest biomes is important for the study of forest ecosystems, forestry planning and forest management at large scales. Currently this research area is receiving great attention because of the interest for strategic transition to biofuel or bioenergy. More and more field observations about forest biomass and productivity from different forest biomes all over the world have been conducted during the last decades, and it is time to generate some principles about the energetics of forest biomes. Based on the recent literature, the main indices to characterize forest energetics are summarized. The concepts in forest energetics could be used to analyze some system properties. The general emergent properties of forest energetics across biomes, such as the complexity and simplicity, are revealed. The possible underlying mechanisms are evaluated, some implications of forest energetics are also reviewed and the possible directions for future research are suggested. The study of energetics of forest biomes will shed new light on (forest) ecology.

**Keywords:** ecological energetics, energetics indices, energetics principles, forest ecosystems and biomes

## CONTENTS

## INTRODUCTION

Solar energy is the ultimate energy source for the biosphere and directly supports most natural ecosystems within the biosphere, although other energy sources, such as wind, rain, and water flow, may be important for many ecosystems (Odum 2001). The focus on energy flow in ecosystems stemmed from the pioneer work of Lindeman (1942) who drew particular attention to the transfer of energy from one part of an ecosystem to another, and followed by the Odum brothers (EP and HT). EP Odum (1968) suggested that ecoenergetics is the core of ecosystem analysis. HT Odum (1971) studied energy flow across trophic organization of aquatic systems and tropical rain forest ecosystems by models of electrical circuitry and use of the analogue computer. Gates (1968) commented that ecology must be understood from the standpoint of energy flow, organism temperature, diffusion theory, chemical rate processes as well as modern molecular biology. Many other plant and animal ecologists have focused on energy, its measurement in ecosystems and implications for ecological theory (Watt 1968; Jordan 1971). Ecosystems and their components are subjected to detailed analyses and by predictive models as scientists try to understand their operation and complexity. Wiegert (1976) outlined the development and principles of ecological energetics. Achievements and challenges in forest energetics were commented by Reiners (1988). Based on all these relevant concepts, forest energetics could be considered as the study of mechanisms and general rules in forming and transferring energy or energy-containing materials within and between forest ecosystems.

The ratio of gross primary productivity to incident solar energy is generally less than 2% and the efficiency of net primary productivity (NPP) is even less than 1% (McIntosh 1974). There is a great potential to increase the capture of solar energy by forests. One of the main goals of traditional forestry is to increase forest growth through silviculture practices. Studying energy allocation in different components of forest ecosystems could provide us understanding of ecosystem dynamics and also great implications for forest management (e.g., Reiners 1972; Wiens and Nussbaum 1975). However, forest ecosystems can provide not only timber and wood products for society, but also their ecological services, such as carbon storage, oxygen output and flooding controlling. The indirect values from forests are usually far more than the direct one of supplying timber and wood products. Long term time series of major forest ecosystems dynamics in the world were collected through the International Biological Program (IBP) during that time, which was created by UNESCO to conduct environmental research on a global scale with a particular emphasis on monitoring undisturbed ecosystems. The large amount of carbon stored in the forests (including soils) makes global forests extremely important to climate change. The net exchange of $CO_2$ between terrestrial ecosystems and the atmosphere is the balance of two major processes: NPP and heterotrophic respiration. NPP is an important parameter in the global carbon estimate because it can be validated with

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field measurements and can be compared between ecosystems (e.g., Day and Monk 1977; Gower 2001). Forests were considered to reduce the amount of carbon dioxide in atmosphere through increases in biomass and organic matter accumulation. These opportunities include increasing forest coverage, increasing productivity of existing forest lands, reducing forest burning and deforestation, increasing biomass production and utilization, planting trees in urban environments, as well as increasing use of wood in durable products. The relationships between forest growth, NPP or carbon accumulation and environmental conditions were intensively studied by field data and modeling (e.g., Graumlich *et al.* 1989; Goulden *et al.* 1998). Furthermore, the debates on the relationships between biodiversity and productivity also broaden our knowledge about forest energetics.

During recent years, with the limitation of petroleum and natural gas at worldwide, there has been a growing interest in the use of biomass or bioenergy as a substitute of traditional fossil fuels for energy production and also protection of the living environment. Bioenergy means energy derived from organic materials – living plants and plant components. Forests are increasingly being considered as a potential source for biofuels. Without doubt, this shifting strategy is putting the research of forest energetics into a new perspective. If we intend to use forests to influence the global carbon cycle, it at least requires us to understand the full carbon cycle implications of our actions and to find out the most efficient options and the options that are most consistent with other forest management and social objectives (Schlamadinger and Marland 1996). The bioenergy strategy in forestry will require us to know more about biological characters of tree species and potential effects of different practices (such as harvest residues) on forest ecosystems (Kimmins 1997; Bens and Hüttl 2001; Roberts *et al.* 2005; Chen 2007), and it has triggered a more in-depth discussion of opportunities and challenges (e.g. Cook *et al.* 1991; Hill *et al.* 2006).

## SOME RATIOS RELATED WITH FOREST ENERGETICS

NPP and biomass are the most frequently used indices to quantitatively describe and compare forest ecosystems and their energetic properties. Several other ratios which could be used for ecosystem and biome energetics are summarized here.

(1) $E_p$: progressive efficiency, which is the ratio of assimilation by two adjacent trophic levels (Lindeman 1942). There was an early interest in $E_p$ values in natural ecosystems, which resulted in the poorly supported but still widely quoted estimate of $E_p \approx 10\%$. It was considered as a measure of ecosystem maturity (Lindeman 1942; Margalef 1968), but it is scale dependent (Strayer 1991). Odum (1969) mentioned the production/respiration ratio, which is the production for unit carbon cost in respiration. Having a similar meaning, NPP/GPP is the ratio of an organism's net primary production divided by gross primary production. It can measure the fraction of total carbon incorporated into biomass and may vary across plants and forest biomes accross temperature gradients (Chambers *et al.* 2004).

(2) Biomass/unit energy flow: Odum (1969) predicted that this value would increase with forest succession. Because biomass usually increases with age of a forest, Chen and Li (2005) used NPP/total annual radiation to estimate radiation use efficiency for forest biomes and indicated the areas with higher radiation use efficiency in China.

(3) Gross primary productivity/respiration: it is considered that gross primary productivity exceeds the rate of total community respiration in an early successional stage so that this ratio is more than 1.0 (Odum 1968, 1969). This ratio decreases to 1.0 in a mature or climax system. The ratio is said to describe successional stages and is related to developmental trends in succession; as this ratio decreases to 1.0, the total biomass of a community or system should increase, species diversity should increase, species should have narrower niches, mineral cycling should be slower and more nutrients be absorbed into biomass; in addition, a larger fraction of the available energy should be directed to ecosystem maintenance (McIntosh 1974).

(4) NPP/biomass (or P/B): this index provides a measure of the energy input necessary to support unit biomass; it is well known for its fundamental 'macroscopic' character of ecosystems (Margalef 1968); and it is dimensionally equal to the reciprocal of the mean energy residence time (MacArthur in Leigh 1965) and the rate of entropy production (Johnson 1988). P/B ratio has been widely used in aquatic production research and management (Kerr and Dickie 2001). Odum (1969) predicted that it would decrease from high to low with community succession and it could be used to measure ecosystem maturity. Chen (2006) confirmed that it decreased with increasing age across Chinese forest biomes in which most forests could reach maturity in about 100 years. Kutsch *et al.* (1998) indicated that when ecosystems become mature, they have a lower P/B ratio, higher biomass, higher total entropy production, and higher complexity. Ecosystems tend to evolve to the lowest ratio of P/B and maximum resilience, and the P/B ratio can also reflect the resilience of ecosystems. When ecosystems have a higher resilience, they can respond very quickly to a perturbation (Cropp and Gabric 2002). After a reduction of its biomass under a disturbance, forest ecosystems can rapidly increase the P/B ratio to its steady-state level. Schneider (1988) observed this behavior in ecosystems subjected to perturbation (pollution) which moved them away from their steady state by reducing the biomass of the system. When the natural ranges of variability of different forest types in China were carefully considered, Chen (2006) suggested that it is possible to use this ratio as an indicator to measure naturalness or wildness for forests, which is commonly used to describe a contrast with urban, domesticated, or industrial environments, but is hard to define and quantify. Since this index is related to ecosystem functions (maturity and resilience), it may provide information to quantitatively describe restoration of forest ecosystems. Restoration of a forest ecosystem requires the recovery of not only its structure but also its function or service. Restoration may be considered successful only if the P/B ratio of a recovered forest is close to a threshold (e.g. its original value or the average value of this forest type). The P/B ratio may also describe risk of forest fires, because the occurrence and severity of wild-fires was originally viewed from climate and the influence of weather factors on fuel moisture, but with little attention from an energetics perspective. Holling (1992) indicated that in the succession of forest ecosystems, the tightly bound accumulation of biomass and nutrients becomes increasingly connected, unless the bound energy is properly released (such as thinning), otherwise, it can be suddenly released by forest fires. Mutch (1970) indicated that the bound energy level can set the stage for potential flammability, but moisture-content of plant communities determine fire seasons or burning peaks. Based on the forest's energy value, more suitable reforestations can be carried out to prevent forest fires or their spreading. The basic idea is to create forest (or tree) strips with low energy value (such as *S. scoparius* Link, *P. radiata* D., *P. sylvestris* L., and *C. sativa* Miller) and flammability as natural fire-breaks (Núñez-Regueira *et al.* 1999).

Whittaker and Woodwell (1972) considered that its reciprocal (biomass/NPP) is more useful and it represents the "turn-over time". The higher this ratio, the lower the turnover-time or higher cycling ability of forest ecosystems. It is a relative measure of energy flux (the energy input per unit time necessary to support unit energy in the biomass) and the smaller the ratio the greater the energy flux. Then, if a forest is kept at a higher cycling ability or lower turnover time after thinning or disturbances, it would need less time to recover and can supply sustainable timber and services. Chen (2006) found that there existed a relationship between biomass/NPP ratio, stand age and stand density for the mixed coniferous and broad-leaved Korean pine forests in

China; the ratio increased dramatically at the forest age of 50 years and the stand density around 2,000 n $ha^{-1}$. This result may be useful for designing ecologically sound thinning or selective logging. Traditional forest thinning is aimed at stand density to reduce tree competition, to enhance forest health, and to gain some social and economic benefits, but emphasizes less detailed information of stand age that should be maintained after thinning or selective logging.

## SOME PRINCIPLES RELATED WITH FOREST ENERGETICS

The principles of energetics, as general statements about energy flows and transformation, include the first four laws of thermodynamics, although the precise position of the laws of thermodynamics within the principles of energetics is still under debate. Here they are briefly listed. More explanations are paid to the last three principles of energetics, which were proposed by HT Odum (Cai *et al.* 2004; Hall 2004; Tilley 2004; Cai *et al.* 2006).

- Zeroth principle of energetics: if two thermodynamic systems A and B are in thermal equilibrium, and B and C are also in thermal equilibrium, then A and C are in thermal equilibrium.
- First principle of energetics: the increase in the internal energy of a system is equal to the amount of energy added to the system by heating, minus the amount lost in the form of work done by the system on its surroundings. This means that energy is neither created nor destroyed, but may transform from one type to another.
- Second principle of energetics: the total entropy, which is the quantitative measure of that kind of spontaneous process, of any isolated thermodynamics system tends to increase over time and approach a maximum value. This law indicates that energy of all kinds in our material world disperses or spreads out if it is not hindered from doing so.
- Third principle of energetics: as a system closes absolute zero of temperature all processes cease and the entropy of the system closes to a minimum value (or zero) for the case of a perfect crystalline substance.
- Fourth principle of energetics: HT Odum considered maximum power as the fourth principle of energetics. He also proposed the maximum empower principle as a corollary of the maximum principle to describe the propensities of evolutionary self-organization. The earliest thinking of this law was in HT Odum's PhD dissertation (Odum 1950), this idea was believed to be influenced by Lotka's (1922a, 1922b) work on system energetics and stability, and Charles Darwin's theory of natural selection. Odum (1971) pointed out that Lotka developed Darwin's evolutionary law (such as natural selection) into a general energy that "maximization of power for useful purposes was the criterion for natural selection". He reformulated Lotka's principle as the "maximum power principle". After HT Odum (1996) elaborated his emergy-based system dynamics and hierarchical organization, he finalized his restatement of the 4th law as the "maximum empower (emergy per time) principle". He continually indicated that the "maximum empower princeple" could work as a guide for human society in its struggle to self-organize to create new social customs, cultural norms and ecological ethics to match fossil-fuel-based technological power for a more mutually powerful fit with nature, given a future downturn in energy availability (Odum and Odum 2001).
- Fifth principle of energetics: HT Odum (1996) proposed the 5th principle as "Energy flows of the universe are organized in an energy transformation hierarchy. The position in the energy hierarchy is measured with transformities". Three factors were considered to contribute to energy hierarchies: (a) there is no 100% efficiency in energy transformation (2nd principle) so that products have less available energy than the sum of their "reactants"; (b) system processes maximize power (4th principle); and (c) products from processes in self-sustaining systems must posses some potential ability to have the input energy flows of great quantity. The transformity is defined as the ratio of total energy required of one form to the energy available of another form, then, it increases along the energy hierarchy. He used this principle to explain the organization of ecological food webs that predators "paid" for the energy they captured from prey by providing services to the ecosystem, otherwise, predators would be a net drain on the ecosystem and never selected.
- Sixth principle of energetics: Odum (2000) considered this as the sixth principle "Material cycles are hierarchically organized in a spectrum measured by emergy per mass that determine mass flows, concentrations, production processes, and frequency of pulsed recycle". "The coupling of the biogeochemical cycles to the energy transformation hierarchy explains the skewed distribution of material with concentration. When self organization converges and concentrates high quality energy in centers, materials are also concentrated by the production functions". Basically, he pointed out that for a material to become more concentrated in its carrier or on the landscape, more emergy (embodied energy) is required per gram of material.

The above principles constitute powerful concepts, definitions, and tools for investigation of energetics of forest ecosystems (or biomes) at all scales, framing a system's behavior and sustainability within the biosphere's driving forces and evolutionary pattern. Other scientists also have similar concepts from different perspectives. Jørgensen (1992) suggested a new "law" that a system receiving a throughflow of high-quality energy will use it to move away from thermodynamics equilibrium; the organization that obtains the highest storage of high-quality energy will win. However, all these principles need to be further tested in the energetics of forest ecosystems and biomes. Some may be supported while others may not always be right (e.g., Smith and MacMahon 1981). Månsson and McGlade (1993) argued that many of the ecological studies that have adopted the ideas from Odum's work have not been aware of some of the fundamental problems underlying this approach. They introduced an alternative concept which could be constructed for use as a numeraire in an energy-centered ecological theory or paradigm. They examined what is meant by material accessibility and energy stocks and flows with respect to traditional food web and food chain theories, and related these to the evolutionary dynamics of ecosystems. They indicated that the various forms of energy bound up in essential ecosystem processes make a formidable obstacle to obtaining an operational definition of a general, aggregated available-work concept, a prerequisite for the system approach of Odum and others. They also showed that the prototypical derivations of the "maximum power principle", and its interpretation, are contradicted to both empirical data and models on many scales, thereby it is impossible for the "maximum power principle" as a general principle of ecological evolution. They further pointed out the fundamental problem of describing ecosystems in a framework with a one-dimensional currency.

## COMPLEXITY AND SIMPLICITY IN FOREST ENERGETICS

The basic energy flow in forest communities or ecosystems across biomes includes energy intake, loss and utilizetion in maintenance and growth. These energetic processes link to radiation, water vapor, and exchange of carbon. The surface energy balance can be described by this equation (Schmid *et al.* 2000):

$$Q^* = Q_H + Q_E + Q_G + \Delta Q_S + Q_P$$

where $Q^*$ is the net radiation, $Q_H$ and $Q_E$ are the fluxes of sensible and latent heat, respectively. $Q_G$ is the soil heat flux, $\Delta Q_S$ is the heat storage change in canopy, and $Q_P$ is the energy fixed by photosynthesis. Studies of forest energetics usually concentrated on one or several factors (or their ratios) in the above equation, such as $Q_H$ and $Q_E$ are related to Bowen ratio. $Q_E$ of high-latitude ecosystems is less than from a freely evaporating surface and decreases late in the season. Evergreen coniferous forests have a canopy conductance half that of deciduous forests and consequently lower $Q_E$ and high $Q_H$ (Eugster *et al.* 2000). Latent heat can also be measured from xylem sap flow in trees, such as xylem sap flow and its relationships with environmental variables were investigated in an old *Larix gmelinii* (Rupr.) Rupr forest in Siberia (Arneth *et al.* 1996). The energy from photosynthesis also provides food for animals and insects. The dead bodies or litters on forest floors are decomposed to release energy for detritus food web and return nutrients to soil. Mean rates of decomposition vary from 200% per yr in rain forests, to 80% in temperate deciduous forests (Deshmukh 1986). Haines and Foster (1977) studied annual litter fall in a mature secondary Tropical Moist Forest in Panama and found that there were 583 g (2782 kcal) in leaves, 230 g (1049 kcal) in twigs and barks, and 174 g (716 kcal) in fine materials (trash). Sohlenius (1979) investigated carbon budget for nematodes, rotifers and tardigrades in a Swedish coniferous forest soil and indicated these annual values for this soil fauna: consumption 4.3, production 0.6, respiration 0.9, and defecation 2.8 g carbon $m^{-2}$. Forest floors could be regarded as nutrient pools, the regulation for water flux and plant reproduction as well as fuel for fires (Reiners and Reiners 1970). Wiens and Nussbaum (1975) gathered data from the Coniferous Forest Biome Program and indicated the magnitude and patterns of energy flow in breeding bird population in northwestern coniferous forests in central Oregon. Hairston and Hairston (1993) concluded that it is trophic structure that controls the ecological efficiencies, rather than energetics controls trophic structure. The detailed data of energy flow within different forests on earth could be found in IBP program, GCTE (global change and terrestrial ecosystems), or ecological network stations across nations, such as boreal forest of North America (BOREAS) (Sellers *et al.* 1997), Scandinavia (NOPEX) (Halldin *et al.* 1998), North America Arctic (ARCSS LAII Flux Study) (Weller *et al.* 1995), and Siberian forests (Schulze *et al.* 1995). Also there are long-term carbon flux networks FLUXNET (Baldochi *et al.* 1998) including Euroflux in Europen (Valentini *et al.* 1996), AmeriFlux in America (Wofsy and Hollinger 1997), as well as emerging networks in Australia and Asia. In addition, permanent forest plots (such as Forest Inventory and Analysis Program from the USDA Forest Service) in different countries may provide partial information.

Mainly through the IBP in the early 1960s, NPP measurements and monitoring information have been acquired in many environmental conditions around the world, and comparisons of productivity and generalizations based on these appeared in the literature (e.g., Rodin and Bazilevich 1965), such as gross primary productivity varies greatly as ranging from 120 g/$m^2$/yr in desert to 6,700 g/$m^2$/yr in tropical forests. Some previous studies have shown significant NPP differences among terrestrial ecosystems (Whittaker and Niering 1975; Runyon *et al.* 1994). Lieth (1975) indicated that ecosystems at cold and high latitude are less productive than those at warm and low latitudes. Gower *et al.* (2001) indicated that for boreal forests the total (above- and belowground) NPP ranged from 52 to 868 g $C \cdot m^{-2} \cdot yr^{-1}$ and averaged 424 g $C \cdot m^{-2} \cdot yr^{-1}$, and there are poor correlations between the climate characteristics and aboveground NPP and total NPP, respectively. But they found a positive correlation between aboveground NPP and mean annual temperature and mean annual precipitation. There was also a significant inverse correlation between aboveground NPP and latitude, confirming that more northerly stands have a lower NPP. However, characteristics such as mean annual precipitation, mean annual temperature, and latitude inadequately represent important environmental factors controlling NPP, except at the continental to biome scale. Other studies suggest that seasonal distribution of precipitation, timing of soil thaw, nutrient availability, and cumulative growing season vapor pressure deficit influence the NPP of boreal forests (Linder and Axelsson 1982; Frolking *et al.* 1996; Frolking 1997). Also, soil type or topographic position influence NPP through fine root production and turnover (Ruess *et al.* 1996). Numerous studies suggested that the increasing atmospheric $CO_2$ concentration could increase forest productivity based on the results of short-term laboratory and field experiments, but the annual NPP since 1880 for four high-elevation forest stands in western Washington was significantly correlated with long-term variation in summer temperature and short-term variation in annual precipitation, and production was uncorrelated with atmospheric $CO_2$ concentration (Graumlich *et al.* 1989).

Although there are many examples of physiological adaptation and geographic variation in functional groups, it is still not clear if such evolutionary and ecological changes in organism traits could systematically alter large-scale ecosystem processes (Ackerly and Monson 2003). The divergences among species are emphasized at the population, community, and regional levels. At the biome level, traits such as photosynthetic rate and leaf longevity scale predictably with one another, largely irrespective of environment or phylogeny (Reich *et al.* 1997). There are some general trends related with energetics across forest biomes. Chen (2006) indicated that P/B ratios of Chinese forests decrease with increasing forest ages, and after 100 years most Chinese forests can reach a steady P/B ratio, and this may mean that most Chinese forests can reach their maturity in about 100 years. Even only using above ground data (most forest surveys provide this data) from Appendix B of Gower *et al.* (2001), it is still possible to find the trend of decreasing ratios of aboveground NPP/biomass for boreal forests (**Fig. 1**). This result may partially support that forest ecosystems evolve to the lowest ratio of NPP/biomass, higher biomass, maximum resilience, higher total entropy production, and higher complexity (Kutsch *et al.* 1998; Cropp and Gabric 2002). By using Reiners' (1972) information about structure and energetics of three Minnesota forests (oak forest, marginal fen, and cedar swamp), their aboveground P/B ratios were very similar and close to 0.0714. This means solar energy use efficiency is similar in different forest communities or ecosystems at similar ages within a biome.

Age-related changes in the total NPP and aboveground NPP of forests are a universal phenomenon (e.g., Sprugel 1985), but at a given geographic region, the change (i.e., decrease) in NPP during succession is of similar magnitude (Gower *et al.* 2001). When the ratios of NPP/biomass are compared in different forest stands across forest biomes, these ratios are very close to a fixed value of 0.1; also there is an allometric relationship between NPP/biomass and energy equivalents of body mass for all forest biomes (Chen and Li 2005). Valentini *et al.* (2000) indicated no trend in annual ecosystem GPP across European latitudes north of the Mediterranean. Furthermore, Kerkhoff *et al.* (2005) showed that variations in instantaneous rates of net primary productivity had little to no variation with latitude and growing season temperature. Soil decomposition rates accross a global-scale gradient in mean annual temperature were remarkably constant (Giardina and Ryan 2000). Niinemets *et al.* (1999) indicated that ecosystems at cold areas seemed to have lower temperature optima for photosynthesis and ecosystems at warm areas had higher temperature optima based on comparative ecophysiology of leaves. Baldocchi *et al.* (2001) found that the temperature optimum for ecosystem photosynthesis appear to change with mean growing season temperature, and this means that photoautotrophic processes may systematically vary across broad gradients. These ecosystem "invariants" are surprising because they are in contrast to the original paradigm. The specific energetic mechanisms behind the simplicity are still not clear. Enquist *et al.* (2006) tried to explain these phenomena by the metabolic scaling theory which claimed that quarter-power scaling is the 'single' most pervasive theme (West *et al.* 1997). However, its assumptions, underlying theory and

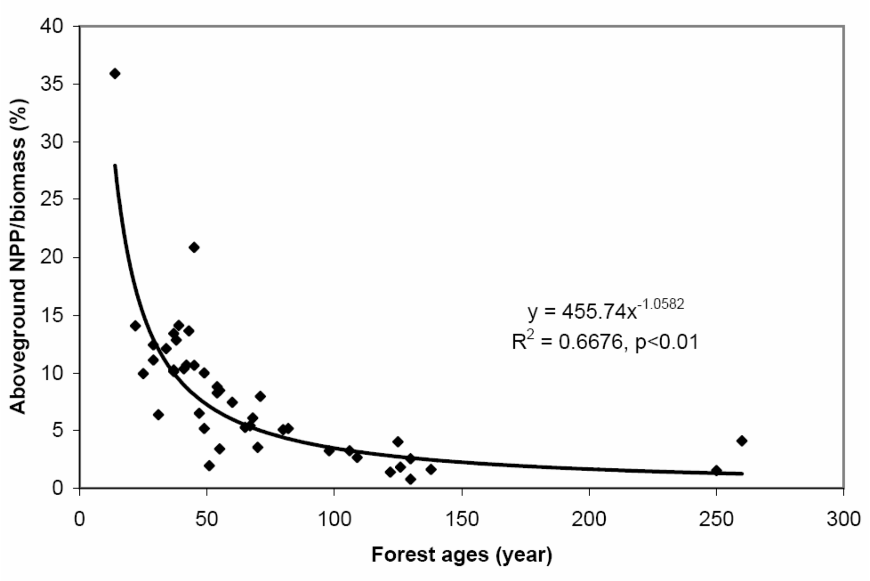

**Fig. 1** The aboveground NPP/biomass ratios of boreal forests decreased with forest ages (data from Appendix B of Gower *et al.* (2001).

broader implications of the quarter-power scaling model have all been fully contested (e.g., Dodds *et al.* 2001; Symonds and Elgar 2002; Chen and Li 2003; Ricklefs 2003; Li *et al.* 2004).

The relationships between available energy and the number of species are some of the major hot topics in recent biodiversity debates (Whittaker 1999; Gaston 2000). It is obvious that the number of species in different taxonomic groups (including microorganisms, trees, insects, mammals and primates) has a visible latitudinal gradient, decreasing from the tropics to the poles in both hemispheres (Rapoport 1982; Stevens 1989). Basing on observations, Gaston (2000) indicated a positive monotonic relationship between species richness and environmental energy, although the type of energy differs between taxonomic groups. Energy hypothesis is one of about 20 mechanistic explanations which have been suggested to describe the existing latitudinal distribution of species (Brown and Lomolino 1998). Actual evapotranspiration, a measure of latent heat flux, was found to describe well with the tree species diversity in North America and Great Britain (Currie and Paquin 1987). O'Brien (1998) found correlation-based models of relating species richness in vascular plants with potential and actual evapotranspiration, annual temperature and water deficit at a coarse spatial resolution on the global scale were very significant. However, it is necessary to have more accurate models to explain theoretically for the observed correlateons between climate and plant diversity (e.g., Venevsky and Veneskaia 2003).

## CONCLUSION

After decades of field data collection, comparison and integration, a deep understanding of forest energetics across species, communities, ecosystems and biomes is underway. No doubt, with the increasing data accumulation from the all kinds of forest ecosystems, especially with the advance in satellite images (e.g., MODIS) and micrometeorological techniques (e.g., eddy covariance), the energy flow and its dynamics at different levels of ecosystems could be recorded and further studied across different forests, although currently the cost of the system may limit its widespread use. Also, the current bioenergy policy provides a good chance to study forest energetics and carbon storage dynamics. In the near future, more studies will emphasize the mechanisms related to the principles of energetics, complexity and simplicity in the allometric scaling of energetics, ecosystem diversity, and their implications to forest management.

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