Dynamic of landscape energetic characteristics based on remote sensing data

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Abstract

Methodological challenges in studing of the spatial and temporal variations in energy conversion on the basis of information-thermodynamic approach have been solved using the remote sensing techniques by the example of southern taiga landscapes of Valdai Hills. Demonstrated the possibility of evaluating the main components of the energy balance of ecosystems (gross evaporation, production, thermal scattering, accumulation) as an open thermodynamic system, which maintain its structure through the conversion of solar energy. Analysis of the ratio of thermodynamic variables for the different types of landscapes shows that the flow of energy absorbed by the surface, redistributed to balance components by various mechanisms, and it depends on the structure of the redistribution system expressed through the nonequilibrium. Nonequilibrium of solar energy transformation is determine in the first instance by the costs of energy in the synthesis of biological products and exergy of the solar radiation is little impacted – the cost of energy to evaporation. Invariance of energy conversion by landscape as a whole and generalized types of landscapes is estimated. The ability to maintain energy absorbed invariants, exergy and temperatures in the taiga landscapes forms a naturally determined series, wich emulate succession: meadows - falls - deciduous forests - coniferous forest; anthropogenic objects possess the weakest auto regulation ability. Raised bogs contrary to forests, which carrying out moisture transport from the soil into the atmosphere, keep high heating of the territory and preserve precipitation in the subsurface runoff, while maintaining the level of biological production, comparable to coniferous forests.

Introduction

The function of live substance in biosphere is a transformation of space energy, mainly solar energy, in a “producing earth energy” – electrical, chemical, mechanical, thermal etc. (Vernadsky, 2004) The radiation of sun activates live substance, transferring it into the state principally different relative a inorganic matter. In this special state live substance is able to concentrate and redistribute energy in biosphere, transforming it to energy, which is “free in terrestrial sphere and capable to work”. The transformation of solar energy occurs in primary thermodynamic field of biosphere. Under transformations of solar energy in field of live substance the specific inherent chemical combinations are generated. In thermodynamic field these combinations are unstable, and disintegrating they give energy back to biosphere. By this in going from thermodynamic field of live substance in field of inorganic matter substance becomes a source of free energy, breaking its balance in that way.

In the second part of XX century the concept of exergy was introduced in thermodynamics. Exergy is a maximal beneficial work, which can be taken in contact of working solid and environment till they find a balance (Shargoot, Petela, 1968). Like energy, exergy is measured in joules, often it is expressed as a power (in watts). Quantity of exergy is defined by nonequilibrium and structure by a system that transforms energy – just this property makes constructive application of exergy conception in thermodynamics of live substance. At the close of XX century the concept of exergy was introduced in ecology (Jorgensen, Mejer, 1982; Kay, Schneider, 1992; Kay, Fraser, 2001). The new direction of research has been formed; it was named “exergy analysis of systems”.

Generally, exergy flows are in accordance to main energy flows (Wall, Gong, 2001). According to thermodynamics notions whole energy that comes to ecosystems is consumed for useful work: output creation, water evaporation, heat dissipation (we can speak about environment temperature maintenance), internal energy accumulation and maintenance. Exergy is an incoming energy part, which is possible to make useful work in system maintenance in non-equilibrium state with low entropy. Ecosystem useful work becomes apparent in water cycle maintenance and intensification in biosphere and bioproductivity ensuring. Another part of absorbed energy comes to system self-energy increase.

In classical thermodynamics internal energy relates to molecules motion (heat exchange) and chemical links (internal energy). In an ecosystem internal energy can relate to different species individuals interactions and system parts with its internal structure maintenance, with energy accumulation inside system in partly closed exchange cycles. Apparently internal energy in ecosystem also can relate with soil formation processes, in particular with carbon accumulation and with carbon content maintenance in balance. During transformation process exergy turns into energy, which is incapable of useful work – bound energy (heat energy with high entropy), and comes out from ecosystem (Jorgensen, Svirezhev, 2004). In that way maintenance of organization (order) in ecosystem is conditioned on entropy dissipation in environment in the process of energy transformation.

Ecosystem exergy – thermodynamic variable that reflects relation between structure and energy transformation and makes possible to class particular qualities of system functioning like a result of system structure. Measuring of Exergy and active surface heat flow (temperature) gives an estimate of energy transformation, and difference between absorbed energy and exergy reflects internal energy changes. The higher exergy system is, the further it is from equilibrium state with local entropy upper limit. This distance and nonequilibrium degree can be evaluated by corresponding entropies difference, more properly by Kullback’s entropy that reflects information or order increase in non equilibrium system relative to equilibrium. Structure, order or information maintain system in stationary non equilibrium state with local entropy producing local minimum and determine system capability to produce the work.

In ecology and biology notions about exergy are essentially extending an area of modern nonlinear thermodynamics ideas application. In particular Jorgensen’s and Svirezhev’s monograph is devoted to these ideas development (Jorgensen, Svirezhev, 2004). Performing full analysis of thermodynamics ideas application in ecology and basing one self on spacious empiric material authors develop “preliminary fourth law of thermodynamics”: its main point says that state maintenance of live substance and ecosystems related to it is determined by exergy flow. The fourth law of thermodynamics is offered it to explain growth and development in ecological systems. At that growth is interpreted like systems extension in sizes, but development – like organization or systems multiply increase.

Three growth paths are possible (Jorgensen, Svirezhev, 2004):

1) through biomass or biological structure growth (proper growth);

2) through structure complexity increase, i. e. components number and feedbacks number in trophic structure(growth with development elements);

3) through information increase, i. e. organization level, including feedbacks mechanisms number (proper development).

Finally, live substance criterion function is determined like exergy growth, i.e. ability for useful work. Even if above formulated positions are viewed like hypothesis, its validity determination on real systems exploration basis can be determined like an important problem area in ecology. Full analysis of trophic and specific ecosystem structure, which makes possible to realize this validity determination in formal way is undecidable problem. Therefore its natural to compare energy flows structure and exergy transformation in ecosystem to some easy observed and measurable functionally important elements of ecosystem structure with direct and indirect appreciation of ecosystem provision with water and mineral nutrition elements. That comparison can be realized on the basis of remote multispectral satellites measuring of solar radiation reflected from surface, field measurements of vegetative cover characteristics, digital elevation models, that indirectly reflects water and mineral nutrition elements redistribution in landscape.

In last 20 years remote information is used for assessment of ecosystem functioning energy aspects: methods for energy and heat balance components calculation are elaborated (Chemin, 2003; Ma et al., 2003 ect.); and methods of ecosystem state evaluation on the basis of reflection abilities (Vygodskaya, Gorshkova, 1987); climate and biophysical processes models are also constructed on this basis (Ma et al., 2003; projects BOREAS and SEBAL), applied problems are being solved. All this affords methodic ground for its application area widening.

Reflected solar radiation flow spectral structure, comparing to solar radiation coming to elementary surface unit, gives a possibility to estimate energy balance components, exergy and heat radiation in the moment of measuring. Vegetation and soil characteristics, measuring in sample allows to research the character of relations between energy balance components and landscape structure in relevant territorial unit. Digital relief model make possible to calculate its shape parameters, defining water and heat redistribution, for different hierarchy levels and to research its influence solar energy transformation through vegetation.

This approach using remote information, has essential restrictions. The most important one: solar radiation flow measuring is possible only in cloudless days; which for many globe regions is relatively rare event. Accordingly we can analyse only episodic measurements including time lag of few seconds in specific day time and season. But if functioning vegetative cover hypothesis, maximizing exergy, is true, some supertemporal invariant should exist, that keeps similarity of solar energy transformation at least during vegetation period. Invariance measure can be every measure of energy balance components fields similarity, measuring in different moments of time. Obviously, this measure can be rated like landscape exergy efficiency estimation.

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Materials and methods

Described approach was adjusted to landscape of south taiga forests on moraine sediments in Central Forest State Nature Biosphere Reserve (south-west part of Valdai Hills, Russian plain). Reserve territory with survived quasi-native fir forests, spacious peat bog massives, recent forest windfalls, bushing abandoned agricultural lands, meadows and cuts of different ages in buffer area, gives a unique possibility to evaluate thermodynamic approach informativity on the base of remote sensed data to ecosystem functioning research. In current report, we rated thermodynamic variables on landscape level and ecosystem basic types changes in time and also tested hypothesis of exergy growth it process of vegetative cover development.

Different seasons multispectral scanner images were used in current work for energy balance valuation (tab.1); used scanner devices are: Thematic Cartographic Scanner (Landsat 5 TM), and Extended Thematic Cartographic Scanner (Landsat 7 ETM+).

Table 1. Main used Landsat scene parameters

Scene parametres / Date	Surveing systems	Unical scene number (ID)	Scene coordinates (left overhead corner)	Time	Sun altitude
March (22.03.2001)	Landsat 7ETM+	7182021000304650	56°55'16"N, 32°18'10"E	11:38	32.72°
April (27.04.2000)	Landsat 7 ETM+	7182021000011850	56°55'12"N, 30°42'37"E	11:45	46.28°
May (03.05.1990)	Landsat 5 TM	4181021009012310	56°55'00"N, 32°15'34"E	10:28	45.00°
June (20.06.2002)	Landsat 7 ETM+	7182020000217150	58°19'26"N, 31°27'05"E	11:41	53.87°
September (27.09.2000)	Landsat 7 ETM+	7181021000027150	56°55'00"N, 32°15'34"E	11:38	31.02°

Landsat satellites multispectral scanners make possible to estimate reflected radiation in bands with wavelength 450 – 2350 μm, spatial resolution 28.5 x 28.5 m, surveing channels 1 – 5, 7 and temperature channel 10120 – 14500 μm with resolution 57 x 57 m – sixth band, including thus the most spectrum part of solar radiation. Survey is realised in seven spectral bands, corresponding to main atmosphere window regions (atmosphere spectral windows), that ensures optimal display of surface energy characteristics for waves with length corresponding to maximal perception of acting surface. Concepts of solar energy in different spectrum parts correlation with vegetation and underlying surface properties make grounds to physical sense intepretation of reflected solar radiation multispectral measurings. Generally, scanner system is adopted to present information about solar light flows most important for vegetation, but it can't reproduce total reflected solar energy flow, that inevitably understates constant and reflected solar radiation a little.

Solar radiation reflected by active surface is calculated throw converting recount of original Landsat images brightness values, that are received in digital numbers (DN), proportional to incoming to sensor radiation quality, in energy unities – energy flow in time unit – watt per m^2 accordingly to standard transformations, described in corresponding instructions (www.landsat.usgs.gov). As a result we find reflected radiations values in Wt/μm, of every spectrum band, per m^2, i.e. $Wt/m^2\mu m$. So as to find solar radiation reflectance from surface, in every band these values are to multiply by average value of corresponding wavelength. Reflected energy general flow equals every band flow sum. Solar radiation income valuates by solar constant for every spectral band. Solar constant for total spectrum is admitted usually like 1360 Wt/m^2. At the average 1000 Wt/m^2 comes in to surface when serenity. This value is admitted as standard in engineering calculation. Solar variation by solar constant is valuated considering sun altitude in the valuation moment (tabl. 1) and distance from earth for cloudless sky. Calculation of thermodynamic variables – absorbed solar radiation (B), solar constant and reflecting radiation entropy, Kullback's entropy and exergy – was realized by methods offered by Jorgensen and Svirezhev (2004), for six spectral diapasons corresponding to surveying channels (bands 1 – 5, 7).

Difference between reflected energy in red and near infrared diapasons – vegetation productivity index (VI) can be used for valuation of immediate exergy expenditure on biological production. More widespread Normalized Difference Vegetation Index (NDVI) differs from VI by two channels normalization relatively it sum. Good weakly nonlinear connection with net primary production is showed for this index in many works (Cramer et al., 1999; Puzachenko, Sankovsky, 2005).

Next thermodynamic variables were valuated: Eint – incoming solar energy, Wt/m^2; Eout – reflected solar energy, Wt/m^2; A – albedo; B – absorbed solar energy, Wt/m^2; K – Kullback's entropy, nit; Sint – incoming energy flow entropy, nit; Sout – reflected energy flow entropy, nit; Ex – solar radiation exergy, Wt/m^2; U – internal energy (increment), Wt/m^2; TW – heat flow coming from surface, Wt/m^2 T – active surface temperature, ^oC; STW – bound energy, Wt/m^2nit; VI – productivity index, Wt/m^2.

For energetic characteristics average measures are calculated on all territory and for basic ecosystems types: overgrown ponds, coniferous forests, deciduous, windfalls, peat bogs, meadows, overgrown lands and recent cuts (fig 1).

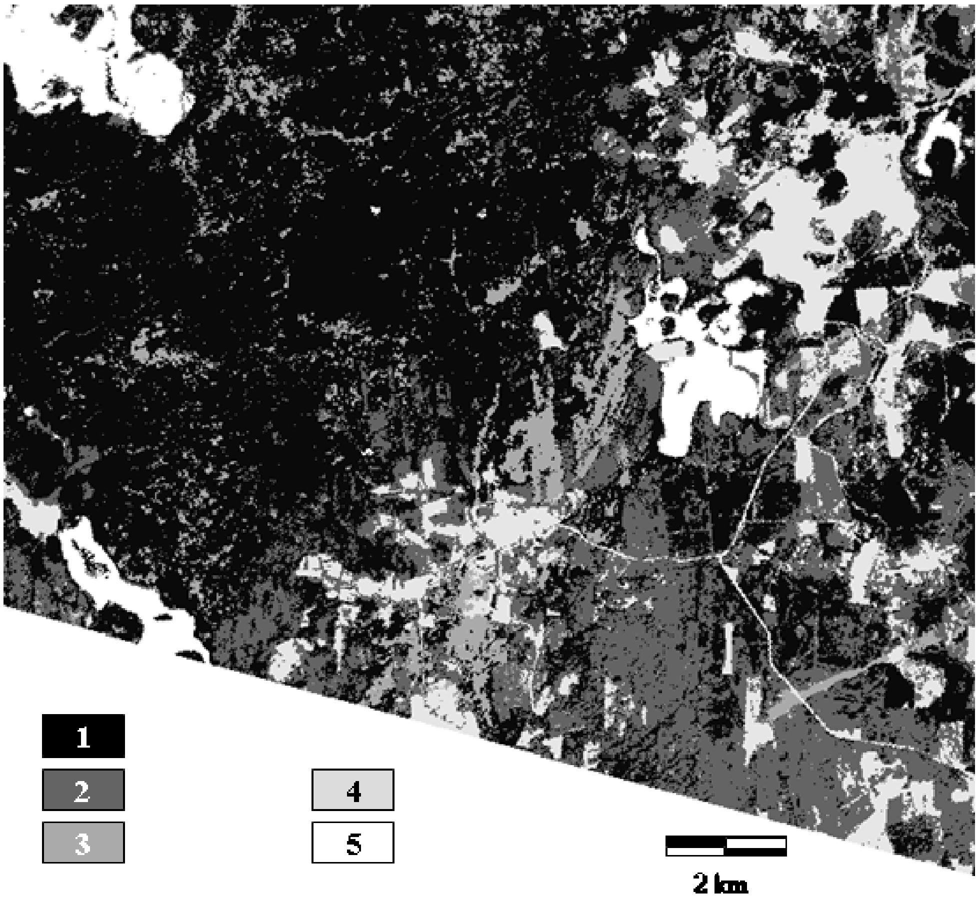

Figure 1. Generalized landcover types: 1 - coniferous forests, 2 - deciduous forests, 3 – windfalls and cuttings, 4 - meadows and wastelands, 5 - peatbogs.

Results

The seasonal change of thermodynamics variables is logically expected (tab. 2): entropy of system that transforms solar energy is minimal in summer in period of maximal vegetation cover biological activity; at the same time Kullback's entropy and biological production level are maximal. Exergy and bound energy value, either as surface temperature, are maximal in spring and summer, and minimal in March in the presence of snow cover and very high albedo.

Table 2. The seasonal course of landscape thermodynamic variables for the whole studied territory.

Month	Thermodynamics characteristics								
	Ein	B	Ex	U	K	Sout	STW	T	VI
March	757.25	567.88	345.34	214.2	0.065	1.503	8.34	-4.75	7.34
April	1032.84	939.19	725.21	201.48	0.092	1.605	12.48	16.10	19.23
May	1013.36	937.390	750.19	175.00	0.093	1.605	12.19	15.55	16.09
June	1175.93	1056.87	818.06	226.41	0.267	1.412	12.41	24.00	48.99
September	726.94	660.73	467.03	182.39	0.114	1.559	11.39	10.17	17.34

Ein – incoming solar energy, Wt/m^2; B – absorbed energy, Wt/m^2; Ex – solar energy exergy, Wt/m^2; U – internal energy (increase), Wt/m^2; K – Kullback's entropy, nit; Sout – reflected energy flow entropy, nit; TW – heat flow from active surface, Wt/m^2; T – active surface temperature, C; STW – bound energy, Wt/m^{2}nit, VI – vegetation index, Wt/m^2.

Correlation of three basic variables: absorbed radiation, exergy and temperature (heat flow) – represents well specificity of ecosystems basic typological states functioning in different seasons (fig. 2). In March all forestless snow covered territories absorbed solar radiation minimum, have minimal exergy and the lowest temperature. Solar radiation absorption, exergy and temperature grow from windfalls to coniferous forests. That state can be defined as initial. Territory clearing from snow cover results in sudden increase of solar energy absorption, at that absorption differences in different ecosystems types aren't significant in April and May. Generally absorption maximum is near open water surface, and absorption minimum is in the meadows. Exergy changes similar in different ecosystems, but its variation scale is essentially higher.

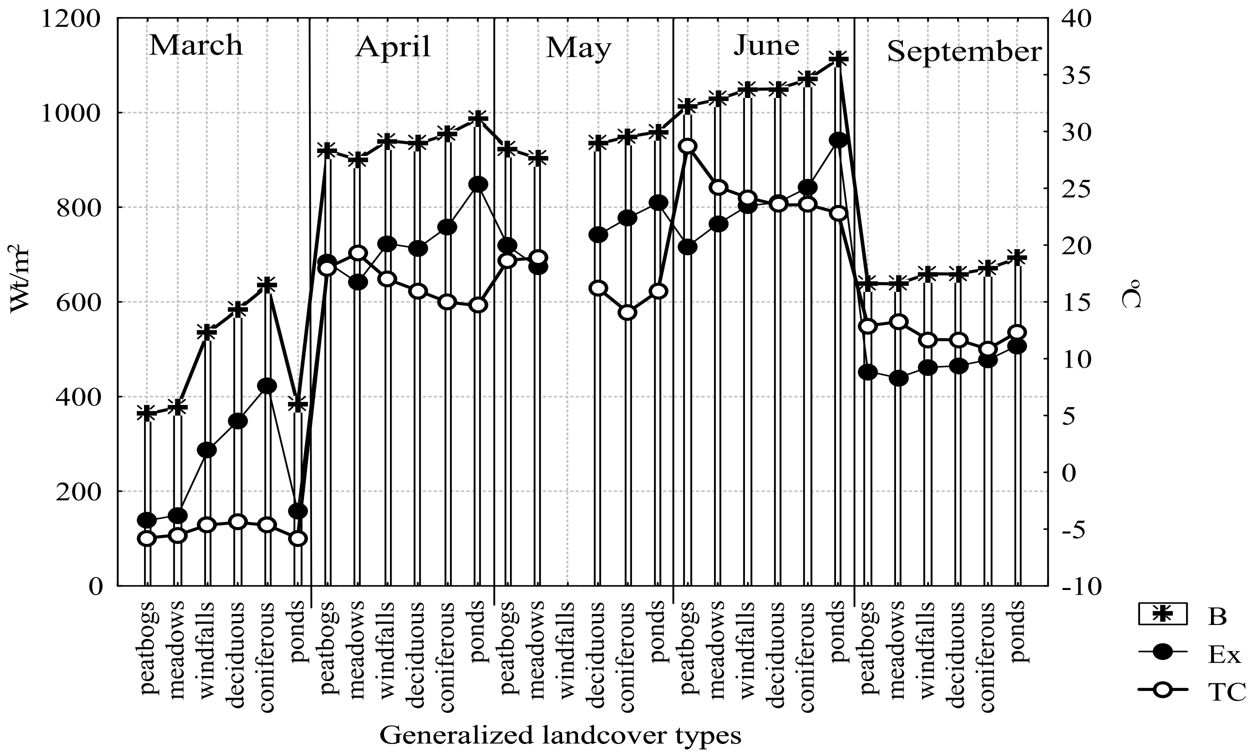

Figure 2. Absorbed radiation (B), exergy (Ex), surface temperature (TC) space-time variability

In contrast to March in this spring period according to thermodynamic model the more exergy is, the less heat flow activity is, the lower temperature is. Correspondingly in March positive relation of exergy and temperature isn't concerned with active evaporation processes and corresponding heat outlay, but it's concerned with physical heating, determined by heat capacity of phytomass. In June radiation absorption visibly grows, but exergy increase is a little less. However essential modifications feature in activity of different ecosystems types. In spring exergy in bogs was higher, than in meadows. In June absorbed radiation and exergy on bogs are minimal, but temperature is maximal. Open water and coniferous forests exergy is maximal (temperature is minimal). In autumn absorbed energy and exergy differs a little, but as in spring they are higher in bogs, than in meadows.

Reflected radiation entropy and Kullback's entropy, as nonequilibrium measure, demonstrate physically well interpretable correlations (fig. 3), specified mechanisms, directing energy balance.

In March, when biological activity is very low, Kullback's entropy is minimal, and total entropy is closed to minimum. At that their differences are insignificant in different ecosystems types. In spring entropy definitely grows for meadows and windfalls and a lesser degree for bogs and forests. Bogs, leaved forests and ponds has nonequilibrium maximum; for them low values of total entropy are typical. In summer in period of vegetation cover physical activity entropy of most ecosystems types' is minimal, but Kullback's entropy is maximal. According to it system has the most nonequilibrium state. At the same time ponds and coniferous forests are the closest to thermodynamics equilibrium, though they have exergy maximum (fig. 2), also bogs are found in peculiar thermodynamics lethargy with maximum equilibrium under exergy minimum and heat flow maximum. In September all structural indexes almost completely repeat spring indexes.

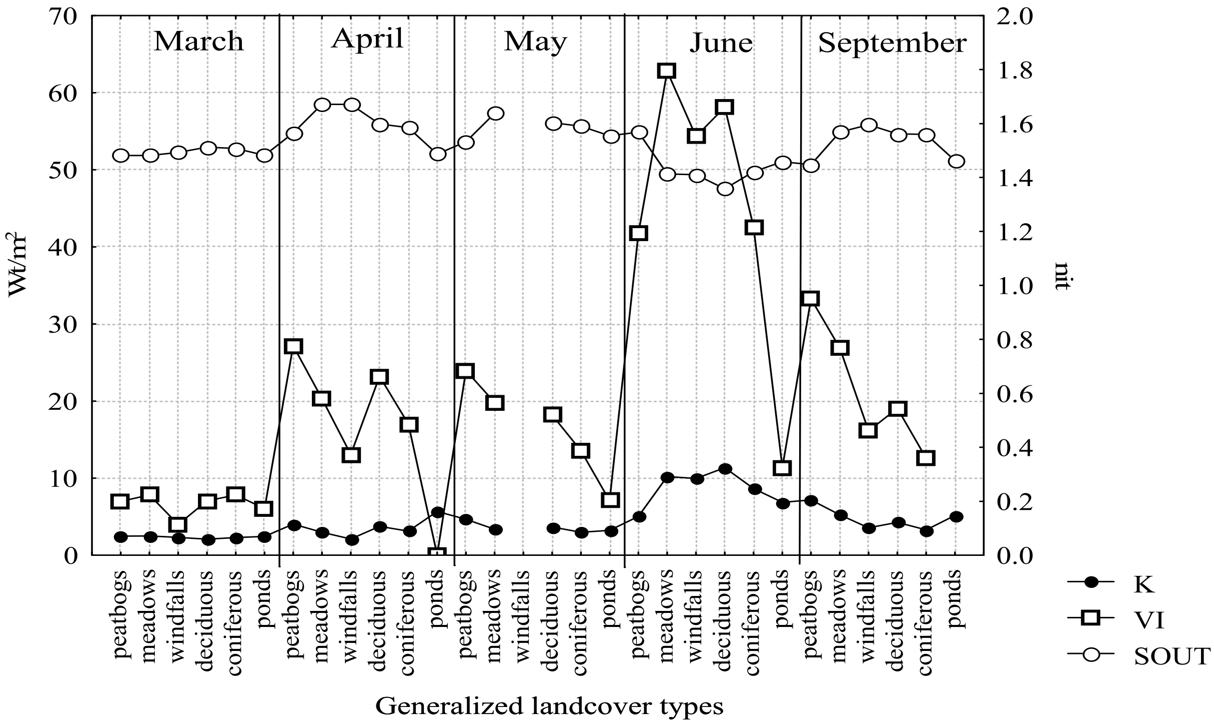

Figure 3. Kullback's entropy (K), reflected energy flow entropy (SOUT), vegetation index (VI) space-time variability

Bound energy isn't used in system at all and can be rated as its dissipative compound. Internal energy interpretation for ecosystem demands of special elaboration, but on the assumption of general thermodynamics understandings, it can be rated as energy that maintains structure. This interpretation has a confirmation in fact, that open pond water ensures internal energy minimum in all seasons of year. Apparently, "water" as system has a very simple structure, and there is no need in a lot of internal energy for structure's maintenance. As water exergy is maximal, but heat flow is minimal, in spring and autumns seasons bound energy production is minimal, and the most part of it goes to evaporation (fig. 2, 4). But in summer bound energy amount doesn't reach the minimum because of relatively large entropy. In spring and autumn maximal bound energy and internal energy are typical for meadows. There in this time exergy is minimal, and entropy is maximal, that, in spite of relatively high productivity, determines large output of bound energy. In that time internal energy accumulation also takes place. According to exergy increase bound and internal energies are reduced, at that internal energy is minimal in coniferous forests. Bogs are original in dynamics of most thermodynamics variables. They are functioning in that way, in spring theirs bound energy is essentially lower, than in meadows, and is closed to leaved forests, but free energy is little less, than in meadows. In autumn under maximal productivity these indexes for bogs are almost the same as for open water surface. Finally, in active vegetation period bound and internal energies maximum is typical for bogs, is corresponds to relative minimum of exergy, heat flow and entropy maximum.

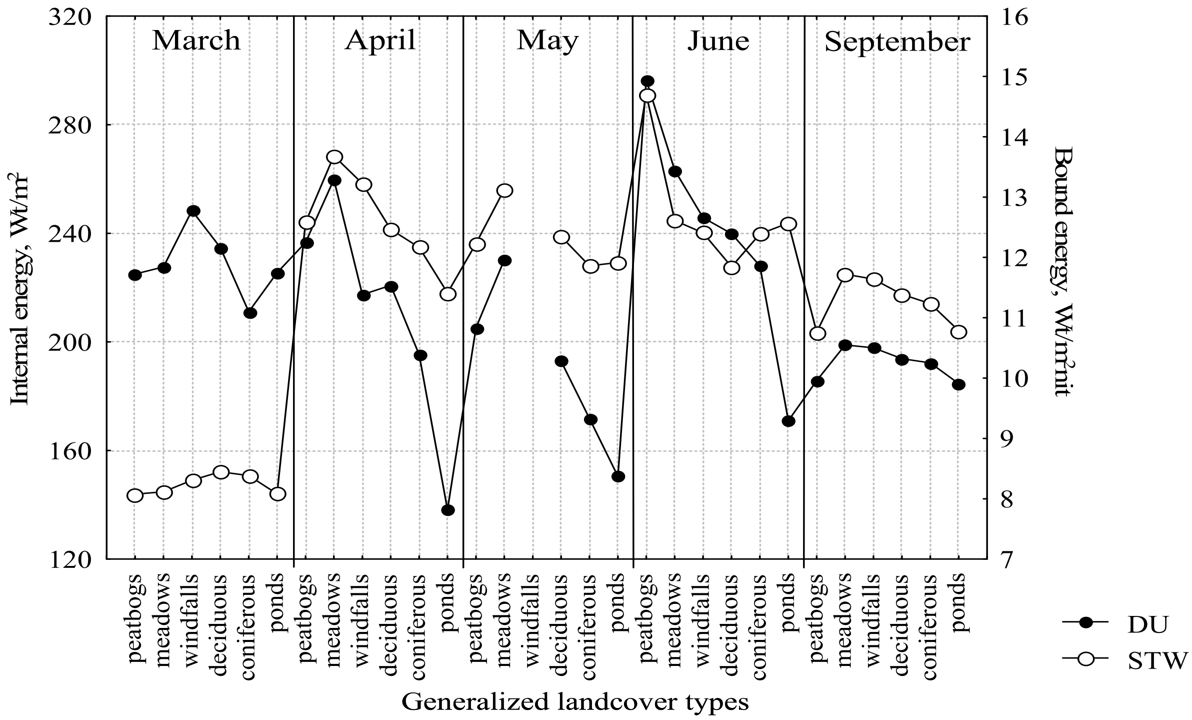

Figure 4. Internal energy increasment (DU), bound energy (STW), space-time variability

Thus, in sequence: meadow-forest-open water change of all thermodynamics variables reflects general scheme: meadows have minimal exergy, but maximal productivity, coniferous forests – maximal exergy and minimal productivity. But bogs have absolutely especial functioning regime that principally differs from other ecosystems types of concerned landscape of South Taiga.

Discussion

Real measurements analysis of thermodynamics space-time variance gives dual results in verification of theoretical notions. If we view consequence: meadows, windfalls, leaved forest, coniferous forest – like elements of succession, obviously we find unambiguous direction of system dynamic to exergy increase, solar radiation absorption increase, heat flow decrease. Vegetation aspires to provide at most possible maintenance of thermodynamics equilibrium between soil and atmosphere, maintaining maximal evaporation. At that the process doesn't comply with nonequilibrium increase: Kullback's entropy for coniferous forests is minimal in active vegetation time. Maximal Kullback's entropy is related with production, which is maximal in meadows and leaved forests and minimal in coniferous forests. Internal energy is also minimal in coniferous forests. In that way, two energybased processes, formally included in exergy, obviously are independent and managed by different mechanisms. The nonequilibrium maximum defines productivity maximum and evaporation minimum.

Development process, directed at evaporation maximization, is definitely entropic, whereas process, directed at biological productivity, is antientropic. The first submits to primary thermodynamics correlations and ecosystem motion in area of maximal thermodynamics equilibrium, the second submits to synthesis and biomass accumulation under evaporation decrease and some increase of heat flow. Obviously under approaching to thermodynamics equilibrium internal energy decrease results in balance lost; and ecosystem falls by one or another way and turns to repeat cycle of self-development. Difference in water partial pressures in soil and atmosphere fastens transition to destructive for ecosystem sphere of thermodynamics equilibrium. Against this quite simple thermodynamics theory absolutely different antiexergy strategy develops. It doesn't aspire to provide thermodynamics equilibrium, but also avoids from it, constantly accumulating organic matter from year to year.

Conclusion

Real system analysis on basis of thermodynamics variables, valuated by remote sensing, represents that real correlation don't keep within simple model, and exergy notion can't be admitted as universal conformably to concerned systems. Evaporation work is primitive, doesn't demand of high level of internal nonequilibrium, and accordingly don't have exergy nature. Exergy makes sense only for that part of energy, which comes to bioproduction process. Nonequilibrium and nonstationarity are absolutely necessary for this process realization.

Unfortunately exergy increase, proposed as fourth thermodynamics law, isn't a universal invariant in self-development process of complex system. Reality is essentially more complicated. At that obviously extended thermodynamics analysis of landcover functioning on the multispectral information basis, promises perspectives for deeper understanding of ecosystems processes. Under comparative analysis of ecosystems different types functioning, that are generated by plants taxa, arising in different evolution phases, it can give the important information for evolution general direction understanding.

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