Abstract: Methodological challenges in studying 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. This method demonstrated the possibility of evaluating the main components of the energy balance of ecosystems (evapotranspiration, 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, depends on the structure of the redistribution system expressed through the nonequilibrium. Nonequilibrium of solar energy transformation is determined in the first instance by the costs of energy in the synthesis of biological production 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, wích 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.

Key words: landscape, remote sensing, energy conservation, thermodynamic approach

Introduction

The function of live substance in biosphere is a transformation of space energy, mainly solar energy, in “producing the earth energy” – electrical, chemical, mechanical, thermal etc. (Vernadsky, 2004). The radiation of sun activates live substance, transferring it into the state principally different from 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 – field where living matter exist, which consists of essentially the same chemical elements as non-living matter, but their state of organization is entirely different. For that reason, a different thermodynamic field must be associated with the biotic component of the biosphere, in which exist multitudes of compounds that are unstable outside of it. Equilibrium properties of chemical reactions that occur in living organisms are determined by the properties of this field and are substantially different from those carried out in a laboratory. Under transformations of solar energy in field of live matter the specific inherent chemical combinations are generated. In thermodynamic field these combinations are unstable, and while disintegrating they give energy back to biosphere. By this cycle of transformation from thermodynamic field of live matter to the field of inorganic matter becomes a source of free energy, breaking energy balance in that way.
In the second part of XX century the concept of exergy was introduced in thermodynamics. Exergy is a maximal useful work possible during a process that brings the working body into equilibrium with environment (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 of a system that transforms energy – even just this property makes constructive application of exergy concept to thermodynamics of live substance. At the close of XX century the concept of exergy was introduced in ecology (Jørgensen, 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 flow in accordance to main energy flows (Wall, Gong, 2001). According to thermodynamics notions, all of the 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 transform in useful work for system maintenance in non-equilibrium state with low entropy. Ecosystem useful work becomes apparent in water cycle maintenance and ensuring intensification in bioproductivity. Another part of absorbed energy comes to system amount of 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 (Jørgensen, Svirezhev, 2004). In that way maintenance of organization (order) in ecosystem is conditioned on entropy dissipation in the process of energy transformation.

Ecosystem exergy – thermodynamic variable that reflects relation between structure and energy transformation and makes possible to identify particular qualities of system functioning as a result of particular system structure. Measuring of Exergy and active surface heat flow (temperature) gives an estimation 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 degree of nonequilibrium 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 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 application. In particular several Jørgensen’s and Svirezhev’s works are devoted to development of these ideas (Jørgensen, Svirezhev, 2004). Performing full analysis of thermodynamics applications in ecology based on enormous empiric material authors develop “preliminary fourth law of thermodynamics”: its main point says that maintenance of live substance state and related ecosystems are determined by exergy flow. The fourth law of thermodynamics is offered to explain growth and development in ecological systems. Growth is interpreted like systems extension in size, and development – like organization complication.

Three growth paths are possible (Jørgensen, 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 amount feedbacks mechanisms (proper development).

Finally, live substance criterion function is determined as exergy growth, i.e. ability to perform useful work. Even if above formulated positions are viewed like hypothesis, determination of its validity on real systems can be viewed like an important problem area in ecology. Full analysis of trophic and specific ecosystem structure, which makes possible to validate this hypothesis in formal way is unsolved problem. Therefore it is natural to compare energy flows structure and exergy transformation in ecosystem with 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 performed on the basis of remote sensing multispectral data which contain measurement of solar radiation reflected from surface, field measurements of land cover characteristics, digital elevation models, which indirectly reflects redistribution of water and mineral nutrition elements in landscape.

During last 20 years remote sensing information is used for assessment of energy aspects of ecosystem functioning: methods for energy and heat balance components calculation are already developed (Chemin, 2003; Ma et al., 2003 etc.); as are the 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 also being being solved. All this constitutes methodic ground for wider analysis.

Reflected solar radiation spectral structure, comparing to solar radiation coming to elementary surface unit (pixel), provides a mean 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 allow to calculate shape parameters, defining water and heat redistribution for different hierarchy levels and to estimate its influence on the solar energy transformation through vegetation.

This approach using remote sensing 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 hypothesis of vegetation cover maximizing exergy, is true, some supertemporal invariant should exist, that keeps similarity of solar energy transformation at least during vegetative period. Invariance can be measured through estimation of energy balance components similarity in different moments of time. Obviously, these measurements 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 usefulness of thermodynamic approach on the base of remote sensing data to ecosystem functioning research. In current report, we measure thermodynamic variables on landscape level changes in time and also tested hypothesis of exergy growth in process of vegetative cover development.

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

<table>
<thead>
<tr>
<th>Date</th>
<th>Surveying systems</th>
<th>Unical scene number (ID)</th>
<th>Scene coordinates (left overhead corner)</th>
<th>Time</th>
<th>Sun altitude</th>
</tr>
</thead>
<tbody>
<tr>
<td>March (22.03.2001)</td>
<td>Landsat 7ETM+</td>
<td>7182021000304650</td>
<td>56o55'16''N, 32o18'10''E</td>
<td>11:38</td>
<td>32.72°</td>
</tr>
<tr>
<td>April (27.04.2000)</td>
<td>Landsat 7 ETM+</td>
<td>7182021000011850</td>
<td>56o55'12''N, 30o42'37''E</td>
<td>11:45</td>
<td>46.28°</td>
</tr>
<tr>
<td>May (03.05.1990)</td>
<td>Landsat 5 TM</td>
<td>4181021009012310</td>
<td>56o55'00''N, 32o15'34''E</td>
<td>10:28</td>
<td>45.00°</td>
</tr>
<tr>
<td>June (20.06.2002)</td>
<td>Landsat 7 ETM+</td>
<td>71820220000217150</td>
<td>56o19'26''N, 31o27'05''E</td>
<td>11:41</td>
<td>53.87°</td>
</tr>
<tr>
<td>September (27.09.2000)</td>
<td>Landsat 7 ETM+</td>
<td>7181021000027150</td>
<td>56o55'00''N, 32o15'34''E</td>
<td>11:38</td>
<td>31.02°</td>
</tr>
</tbody>
</table>

Survey is performed 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 correlation of solar energy in different
Spectrum parts with vegetation and underlying surface properties make grounds to interpretation of reflected solar radiation in terms of ecosystem functioning. Generally, a scanner system is adopted to present information about parts of spectrum most important for vegetation, but it can’t reproduce total reflected solar energy flow. Thus, constant and reflected solar radiation is a little understated.

Solar radiation reflected by active surface is calculated through converting of original Landsat images brightness values, which are received in digital numbers (DN), proportional to incoming amount of radiation, to energy units – energy flow in time – watt per m², accordingly to standard transformations, described in corresponding instruction (www.landsat.usgs.gov). As a result we see reflected radiation values in Wt·μm⁻¹, of every spectrum band, per m², i.e. Wtm⁻²·μm⁻¹. To calculate solar radiation reflectance from surface in each band, these values should be multiplied by average value of corresponding wavelength. Reflected energy general flow equals the sum of every band flow. Solar radiation income evaluated through solar constant for every spectral band. Solar constant for total spectrum is admitted usually as 1360 Wtm⁻². At the average 1000 Wtm⁻² comes in to surface at noon. This value is admitted as standard in engineering calculation. Variation of solar constant is evaluated considering sun altitude in the valuation moment (tab.1) and distance from earth with assumption of 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 computed: Ein – incoming solar energy, Wtm⁻²; B – absorbed energy, Wt/m²; Ex – solar energy exergy, Wtm²; A – albedo; K – Kullback’s entropy, nit; Sint – incoming energy flow entropy, nit; Sout – reflected energy flow entropy, nit; U – internal energy (increment), Wtm²; TW – heat flow coming from surface, Wt/m²; T – active surface temperature, °C; STW – bound energy, Wt/m²·nit; VI – productivity index, Wt/m². Average measures of energetic characteristics are calculated for entire territory and for separate land cover types: overgrown ponds, coniferous forests, deciduous, windfalls, peat bogs, meadows, overgrown fields and recent cuts.

Results

The seasonal change of thermodynamics variables is logically expected (table 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, bound energy value and 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

<table>
<thead>
<tr>
<th>Month</th>
<th>Ein</th>
<th>B</th>
<th>Ex</th>
<th>U</th>
<th>K</th>
<th>Sout</th>
<th>STW</th>
<th>T</th>
<th>VI</th>
</tr>
</thead>
<tbody>
<tr>
<td>March</td>
<td>757.25</td>
<td>567.88</td>
<td>345.34</td>
<td>214.2</td>
<td>0.065</td>
<td>1.503</td>
<td>8.34</td>
<td>-4.75</td>
<td>7.34</td>
</tr>
<tr>
<td>April</td>
<td>1032.84</td>
<td>939.19</td>
<td>725.21</td>
<td>201.48</td>
<td>0.092</td>
<td>1.605</td>
<td>12.48</td>
<td>16.10</td>
<td>19.23</td>
</tr>
<tr>
<td>May</td>
<td>1013.36</td>
<td>937.39</td>
<td>750.19</td>
<td>175.00</td>
<td>0.093</td>
<td>1.605</td>
<td>12.19</td>
<td>15.55</td>
<td>16.09</td>
</tr>
<tr>
<td>June</td>
<td>1175.93</td>
<td>1056.87</td>
<td>818.06</td>
<td>226.41</td>
<td>0.267</td>
<td>1.412</td>
<td>12.41</td>
<td>24.00</td>
<td>48.99</td>
</tr>
<tr>
<td>September</td>
<td>726.94</td>
<td>660.73</td>
<td>467.03</td>
<td>182.39</td>
<td>0.114</td>
<td>1.559</td>
<td>11.39</td>
<td>10.17</td>
<td>17.34</td>
</tr>
</tbody>
</table>

Ein – incoming solar energy, Wt/m²; B – absorbed energy, Wt/m²; Ex – solar energy exergy, Wt/m²; U – internal energy (increase), Wt/m²; K – Kullback’s entropy, nit; Sout – reflected energy flow entropy, nit; TW – heat flow from active surface, Wt/m²; T – active surface temperature, °C; STW – bound energy, Wt/m²·nit; VI – vegetation index, Wt/m².
Correlation of three basic variables: absorbed radiation, exergy and temperature (heat flow) – represents specificity of ecosystems basic typological states functioning in different seasons (fig. 1). In March all forestless snow covered territories absorb minimum of solar radiation, 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 cleared from snow cover (due melting) show rapid increase of solar energy absorption, and absorption differences in different ecosystems types aren’t significant during April and May. Generally absorption maximum can be found near open water surface, and absorption minimum is located at the meadows. Exergy changes similarly in different ecosystems, but its variation scale is essentially higher.

Fig. 1. 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 value is, the less is heat flow. Correspondingly in March positive relation of exergy and temperature isn’t connected with active evaporation processes and corresponding heat outlay, but is connected 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 are observed 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. 2), which specify mechanisms, directing energy balance. In March, when biological activity is very low, Kullback’s entropy is minimal. Differences are insignificant in different ecosystems types. In spring entropy definitely grows for meadows and windfalls and in lesser degree for bogs and forests. Bogs, deciduous forests and ponds has nonequilibrium maximum; for these types low values of total entropy are typical. During 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. 1), also bogs are found in thermodynamics lethargy with maximum equilibrium under exergy minimum and heat flow maximum. In September all structural indexes almost completely repeat spring indexes.

Bound energy isn’t used in system at all and can be rated as its dissipative component. Internal energy interpretation for ecosystem is challenging, but on the assumption of general thermodynamics understandings, it can be defined 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 internal energy for structure’s maintenance. As water exergy is
maximal, but heat flow is minimal, in spring and autumn seasons bound energy production is minimal, and the most part of it goes to evaporation (fig. 1, 3). 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. During spring and autumn internal energy accumulation also takes place. According to exergy increase and internal energy reduction, internal energy is minimal in coniferous forests. Bogs are specific in dynamics of most thermodynamics variables. They are functioning in following way: in spring theirs bound energy is essentially lower, than in meadows, and is close to leaved forests, but an amount of free energy is little less, than in meadows. In autumn, during 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, this corresponds to relative minimum of exergy, heat flow and entropy maximum.

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 special functioning regime that principally differs from other ecosystems types of South Taiga landscape.
**Discussion**

Analysis of real measurements of thermodynamics space-time variance gives dual results in verification of theoretical notions. In consequence of succession elements “meadows - windfalls -leaved forest - coniferous forest” system increases an exergy and solar radiation absorption, decreases heat flow. Vegetation tries to provide at thermodynamics equilibrium between soil and atmosphere, maintaining maximal evaporation. 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 energy-based processes, formally described by 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, when approaching to thermodynamics equilibrium internal energy decrease results in balance loses; 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 thermodynamics equilibrium which is destructive for ecosystem. Against this, quite simple thermodynamics theory, absolutely different antiexergy strategy develops. It doesn’t aspire to provide thermodynamics equilibrium, but also avoids it, constantly accumulating organic matter from year to year.

**Conclusion**

Real system analysis on the basis of thermodynamics variables, on the basis of remote sensing data, represents that real correlation don’t correspond entirely within simple model, and exergy principle can’t be admitted as universally adequate for systems in question. Evaporation work is primitive, doesn’t demand high level of internal nonequilibrium, and accordingly don’t have exergy nature. Exergy makes sense only for that part of energy, which apply 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. Obviously, extended thermodynamics analysis of land cover functioning, promises perspectives for deeper understanding of ecosystems processes. Comparative functioning analysis of different types of ecosystems, arising in different evolution phases, can yield important information for understanding a general direction of ecosystem evolution.

**References**


Sandlerskiy R., Puzachenko Y.


