The influence of soil matric pressure on the acidity and cation composition of soil solutions extracted by different methods

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Abstract. From the samples of gradually drying (beginning from the field moisture capacity, FMC) soddy-podzolic sandy loam soil (Albic Retisol (Loamic, Ochric)) contaminated with Zn were isolated the soil solutions (SS) by centrifugation, while from the other samples of the soil, moistened to FMC, various energy fractions of the SS were pressed using a hydraulic press. The acidity of the centrifuge solutions extracted from the soil of the experiment variant with the cultivation of plants (“barley”) was, on average, 1 pH higher than on “bare fallow”, and decreased with decreasing soil moisture content. The acidity of the solutions extracted from the soils of the “bare fallow” variant in the same range of soil moisture content practically did not change. It was also found that in more acidic solutions from the “bare fallow” variant the content of Ca, Mg, Mn, Zn and K was 2.4 – 6.9 times higher than the content of these metals in solutions from the “barley” variant. The positive correlation between pF and pH was clearly observed for the pressed solutions from the soils of both variants. Concentrations of Ca, Mg, Sr, Ba, Zn, K and Na in successively pressed fractions of SSs from more acidic soil of the “bare fallow” variant, on average, 3.0 – 8.4 times exceeded their concentrations in similar fractions of solutions of the “barley” variant and showed an inverse correlation with soil moisture (pF value).

1. Introduction

Soil solution is a liquid phase of the soil, is in constant contact with the solid and gas phase, and, in addition, it binds the flow of matter and energy between the above phases of the soil and living matter. Soil solutions are the most important component of biogeocenoses, as they perform a number of important functions [1]: biogenic information, transformation and transport.

Numerous data suggest that the liquid phase of the soil is energetically heterogeneous [1-7]. Some researchers considered the differences in the chemical composition of soil solutions obtained by various methods (use of vacuum, pressure, or centrifugal force) to the energy heterogeneity of various fractions of soil moisture [1, 4, 8, 9]. Heterogeneity of solutions depends on the initial moisture of the object, as well as its hydrophilicity and ion exchange ability.

Among heavy metals (HM), Zn deserves special attention for a number of reasons: it belongs to substances of the 1st hazard class (GOST 17.4.1.02-83); Zn is one of the most common man-made pollutants; it is an important trace element, vital to all forms of living organisms, including plants. Zn is also one of the most biologically available elements - the content of mobile fraction in soil can reach 70% [10]. In addition, as a vital element in small quantities, Zn can have toxic effects on organisms when accumulated in high concentrations [10].
The aim of the work was to study the relationship between the capillary-sorption pressure of soil moisture and chemical composition, as well as the acidity of various energy fractions of soil solutions extracted by centrifugation and pressing in the range of productive moisture for sod-podzolic sandy loam soil contaminated with Zn.

2. Methods

The objects of the study were soil solutions that were extracted from sod-podzolic sandy loam cultivated soil (Albic Retisol (Loamic, Ochric)) contaminated with Zn, after the end of the vegetation experiment with multiple rotation (a total of 4 cycles of 30 days) test-culture of barley (*Hordeum vulgare* L.) varieties Zazersky-85. Physical and chemical parameters of soil were determined by conventional methods [11, 12]. They are given in [13].

Zn (aqueous nitrate solution) was applied to the soil in the amount of 100 mg/kg, after which nutrients were added in the form of aqueous solutions of salts (NH$_4$NO$_3$, KH$_2$PO$_4$, K$_2$SO$_4$) so that the final concentration of nutrients was N$_{300}$, P$_{100}$ and K$_{100}$. Plastic vessels with a volume of 5.5 dm$^3$ with a double bottom (the first of which was perforated for free flow of gravitational moisture) were used as vegetation vessels. Plants of each rotation were grown in the field (when moistened with precipitation) for 30 days, after which plant samples were collected for investigate the removal of micro- and macronutrients from the soil.

The soil from the vegetation vessels-lysimeters was selected at a moisture content equal to the lowest water-holding capacity after the end of the growing experiment. Soil solutions were isolated by centrifugation and pressing methods using a hydraulic press.

In the first case, centrifuge cups with liners (where wet soil was placed) made of Teflon (PTFE) were used. The inserts have a perforated bottom. The appearance of the entire construction is shown in figure 1.

Vessels with soil of natural moisture after harvesting the last rotation were transferred to the laboratory conditions, additionally moistened with the amount of deionized water corresponding to the total moisture capacity (TMC) from the surface, and balanced the soil – soil solution system, allowing gravitational moisture to flow into the pallet several times and returning it back every day. After the excess of gravitational moisture as a result of evaporation from the soil surface ceased to form (it took several days), the soil vessels were covered with lids on top, left for another day to determine the value of FMC (WFMC = 25±2%(wt.)) and proceeded to the procedure of extraction of soil moisture by centrifugation or pressing with a hydraulic press.

![Figure 1. External view of the centrifuge PTFE buckets and liners with a porous bottom.](image)

In the second case, for pressing the soil solution, the installation shown in figure 2 was used. It consists of a hydraulic press with an exemplary pressure gauge, a thick-walled cylinder in which a wet soil sample is placed, stainless steel with a hole in the lower part of the cone surface for drainage of press soil solutions (PSS), covered with a two-layer grid (stainless steel, 0.1 mm), as well as a piston.
(stainless steel) with a groove for a U-shaped cuff of chemically resistant rubber lubricated with silicone vacuum grease.

**Figure 2.** Appearance of installation (a) and device (b, c) for pressing soil solutions.

In the first case, the combined sample was made up of 5-point samples obtained by injections to the entire depth of the soil layer in the growing vessel by the “envelope” method with a special stainless steel sampler. Wet soil in vegetative vessels-lysimeters gradually dried up in the air in the laboratory for 12 days to \( W = 10\% \), which corresponded to \( \approx 2 \) WP (wilting point). Simultaneously, quasi-equilibrium soil solutions were periodically extracted from it by centrifugation on a RS-6 centrifuge with a typical angular rotor RU 8×90 at \( n = 5500 \) rpm for 1 hour. The residual moisture in the centrifuged soil sample corresponded to the capillary-sorption pressure \( F = 12900 \) cm of water column, (pF = 4.11) [14], i.e., was close to WP (pF = 4.18) and was equal to 8.8±0.5\%. The repeats of the experiment (3 in total) were represented by combined samples taken from different vegetation vessels of the Zn\(_{100}\) variant.

The press soil solutions were successively pressed with a hydraulic press from each soil sample \( [W = \text{FMC (1 days)}] \), placed in a specially designed thick-walled stainless steel cylinder (figure 2) in the range of capillary-sorption pressures, \( F: 330\text{÷}28000 \) cm of water column (pF: 2.52÷4.45). Each combined soil sample was prepared in the same way as when the centrifuge soil solutions (CSS) were extracted (see above) from 5-point samples. The difference between this technique and centrifugation was the use of combined samples (corresponding to the repeats of the experiment - only 3), selected from the same vegetation vessel of the Zn\(_{100}\) variant. Concentrations of macro- and microelements, including Zn (by ICP-OES), and pH values were determined in the obtained soil solution samples.

### 3. Results and discussion

Changes in the acidity of quasi-equilibrium CSSs extracted from the soil variant “barley” in the soil moisture content range 10 – 25 % reached 1 unit of pH (6.0 \( \rightarrow \) 5.0), (figure 3). A close correlation between \( W_{\text{soil}}, \% \) (predictor) - pH (response function) was established for the soil of the “barley” variant: pH = 0.054W+4.50 (\( R^2 = 0.72 \)). Vice versa, the acidity of soil solutions extracted from the soils of the “bare fallow” variant in the same range of soil moisture content changed very slightly. The attempt to
reveal significant dependence of the $W_{soil}$ - pH failed ($pH = 0.013W+4.50; R^2=0.17; F(1,26)=3.95; p<0.057$).

Figure 3. The dependence of the acidity of the quasi-equilibrium centrifuge soil solutions from soil moisture.

In the whole range of the investigated moisture values, a decrease in acidity (by $0.5 – 1\ pH$) of the CSS extracted from the soil of the “barley” variant comparing to the solutions extracted from the soil of the “bare fallow” variant was observed. This difference in the acidity of the CSS is explained by the influence of test plants grown in one of the variants of the experiment. Instead of actively absorbed by plants $NO_3^-$ in the near-root zone (for small vegetative vessels as it can be considered the entire volume of the vessel [15]) there is a release of plant roots anions $OH^-$ or $HCO_3^-$[16].

Figure 4. Hydrophysical characteristics of soil and chemical characteristics of pressed solutions.

We suggest that the observed dependence of $W_{soil} - pH$ for the studied soil variant “barley” is due to the joint action of the following factors: a) the heterogeneity of the pore space of soils; b) the effect of alkalinization of the soil absorbing complex (SAC) as a result of $NO_3^-$ uptake by the roots of plants.
effect of SAC alkalinization by root secretions of plants develops, starting with particles, “lining” the walls of larger capillaries and ending with the smallest capillaries, where the processes of mass transfer of dissolved cations are due to diffusion. In the process of soil drying (“Methods”), the proportion of soil solution fractions extracted by centrifugation from large capillaries will decrease, which is manifested in the form of a decrease in the pH value. Figure 4 presents: hydrophysical characteristics of the soil, i.e., the dependence of capillary-sorption pressure $F_{CS}$ (expressed in units pF) consistently pressed energy fractions of soil solutions from the moisture content of the studied soil (figure 4a), the share of energy fractions of soil moisture extracted in the range between successively increasing values of capillary-sorption pressure (expressed in pF units), (figure 4b) and chemical characteristics (acidity) of the solutions pressed from the soil (figure 4c).

For both “barley” and “bare fallow” variants, there was a distinct positive correlation between pF and pH. This effect (reduction of acidity of PSS with a decrease in residual soil moisture) is opposite to the effect observed when removing CSS – acidification of solutions with decreasing soil moisture. It can be caused by two possible reasons: a decrease in the concentration of positively charged hydrogen ions with an increase in the pressure module (pF) in accordance with the theory of insoluble volume (as well as other positive ions) [2, 4], as well as the process of respiration of soil microorganisms. In the last case, because the pressing of soil solutions was carried out in the air (and not in the environment of inert gas, for example, nitrogen), the release of CO$_2$ by microorganisms was not interrupted. The solubility of the released carbon dioxide increases with the increase of the pressure applied from the outside in the soil solution, and, therefore, the acidity and the extractive ability of the formed aqueous solution of carbon dioxide increases regarding the cations (primarily Ca) present in the SAC. Degassing of dissolved CO$_2$ and consequently the increase of pH value in PSS occurs after the soil solution is pressed. Such an effect is described in the scientific literature [2] and can serve as a source of distortion of the results of the cationic composition of PSS with a soil moisture decrease (in the direction of their overestimation).
The behavior of ions of various elements in the liquid phase of soils is determined not only by the characteristics of the solid phase of soils, but also by the physical and chemical characteristics of the ion forms of the corresponding elements, the most important of which are: the value of the electronegativity of the element (EE); its ion potential (IP) [10, 17]. In soil solutions, the content of the main macro- and microelements present in the form of cations was determined: K (0.82; 7.5), Na (0.93; 10.2), Ca (1.00; 19.2), Mg (1.30; 27.0), trace elements Mn(II) (1.55; 22.0) and Fe(III) (1.83; 44.8), as well as a trace element – Zn(II) (1.65; 24.1). The values of EE; IP are given in brackets [17].

As a result of the cationic composition of CSS data set analysis (including all 3 repeats of the experiment) for the “barley” variant, a pronounced inversely proportional relationship between the pH and the concentration of Ca, Mg and Zn present in the solution in the form of divalent ions was obtained (figure 5):

\[ [\text{Me}] = a \times \text{pH}_{\text{CSS}} + b \]  

\[ (R^2 = 0.34 – 0.47) \]

The significance of the relationship between the pH of the solutions (predictor) and the concentration of the examined cations (response function) was determined using the F-criterion, which is the ratio of the dispersion due to the regression dependence and the mean value of the dispersion caused by random deviations. \( H_0 \) (null hypothesis) stating the absence of dependence between the predictor and the response function, was rejected at the significance level \( p \) (figure 5). According to common practice in soil and agrochemical studies, \( H_0 \) is rejected at \( p > 0.05 \). For Fe, Mn, K and Na the dependence \( [\text{Me}] = f(\text{pH}_{\text{soil solution}}) \) was absent. All the noted regularities are in strict accordance with the theory relating the mobility of ion forms of elements with the ion potentials of the latter [17].

It was not possible to establish a relationship between the pH value and the concentration of elements in soil solutions for “bare fallow” variant. During the experiment, it was not possible to determine the dependence of the content of the studied elements (Ca, Mg, Mn, Zn, K, Na and Fe) in CSS extracted from both the soil of the “bare fallow” experiment and the soil of the “barley” variant on moisture (figure 6). This figure shows data only for Ca, Zn, and K. However, they allow us to estimate the magnitude of variation in the resultant trait and the dependence absence of \( [\text{Me}]_{\text{soil solution}} = f(W_{\text{soil}}) \).

Also, for the variants of the experiment “barley” and “bare fallow”, the mean values and confidence intervals (\( p = 0.05 \)) of the concentration of the studied metals in quasi-equilibrium CSS for the entire range of soil moisture were established (figure 7). As can be seen from figures 6 and 7, the influence of different acidity factor has a significant effect on the mass fraction of Ca, Mg, Mn, Zn, K and Na, in CSS extracted from the “barley” and “bare fallow” variants. In the more acidic solutions of the “bare fallow” variant, Ca concentration, on average, was 2.5 times higher than the metal concentration in the solutions of the “barley” variant in the entire range of the investigated soil moisture. For Mg, Mn, Zn and K these values were 2.4, 6.9, 4.5 and 2.7 times respectively. The differences were significant at the significance level of \( p = 0.05 \). For Na, the ratio of the mean values of metal concentrations in the solutions of the experiment variants “bare fallow” and “barley” were equal to 1.4 and were unreliable at the level of significance \( p = 0.05 \). For iron, there were no differences in the mean values of metal concentrations in the solutions of the experimental variants. Thus, the acidity of quasi-equilibrium CSS has a significant impact on the chemical composition: with increased acidity, desorption into the soil solution of alkaline, alkali-earth elements and also microelements present in solutions in the oxidation state (+2) increases. Simultaneously, the solubility of elements present in the oxidation state (+3), for example, Fe(III) in the investigated range of pH values (4.5 – 6.0) did not change.

Another important factor contributing to the relatively low content of the studied elements in the soil solutions of the “barley” variant is the significant removal of some of them with the biomass of test plants during 4 rotations (K – up to 40%, Mg – 34%, Ca – 5%, Zn and Mn< 1% of the stock of available forms of their occurrence in the soil).
Figure 6. Dependence of the Ca, Zn, K content in a quasi-equilibrium centrifuge soil solutions on soil moisture

Possible causes of the obtained results are, first, the previously mentioned [1, 4] spatial heterogeneity of the chemical composition of quasi-equilibrium soil solutions due to the heterogeneity of the composition of the solid phase of the soil. Secondly, the peculiarity of the method used in this work for obtaining mixed samples for centrifugation, according to which point samples that made up the combined sample were taken daily from different parts of the vegetation vessel-lysimeter (and the same soil sample was not used to separate different energy fractions of the soil solution).

Figure 7. Concentrations of the studied metals in quasi-equilibrium soil solutions (\(X \pm \text{stds}_x\)) obtained by centrifugation (average values for the entire range of the investigated soil moisture: 10-25%)
It consists in the lack of dependence between of the content of basic macro- and microelements in CSS on soil moisture in a wide range of productive moisture. The key, from our point of view, is the fact that plants absorb water from the soil together with dissolved substances in the range of productive moisture from an unlimited volume and from all its available energy fractions. Therefore, the absence of dependence between soil moisture within the investigated part of the range of productive moisture and the concentrations of the main macro- and microelements in CSS for the reasons mentioned above, established in this work, significantly simplifies the solution of a number of problems on modeling the behavior of chemical elements in the soil – soil solution – agricultural plant system. It should be particularly noted that the result does not contradict the theory relating the composition of the fractions of soil solutions with the molecular energy of their interaction with the CDC.

Figure 8. Dependence of the cation composition of PSS on the pH value (“barley” variant).

The data showing the dependence of the concentration of the studied elements Ca, Mg, Sr, K, Na in the PSS on the acidity of the latter and soil moisture for the “barley” variant are not presented, because there would not be detected any relationships between pH and [Me]_{PSS}. Dependences pH – [Me]_{PSS}, besides multidirectional, would be established only for Zn ([Zn]_{PSS} = -0.18pH+1.45, R^2=0.71) and for Mn ([Mn]_{PSS} = 8.51pH-46.8, R^2=0.45) (figure 8). The above is also true for dependencies pF – [Me]_{PSS} (figure 9): there is an apparent trend towards increasing concentration of Mn and descending the concentration of Zn in more strongly associated with soil matrix fractions of the soil solution.

Figure 9. Dependence of the cation composition of PSS on the value of pF (“barley” variant).
On the contrary, for consistently extracted PSSs of the “bare fallow” variant (more acidic), reliable inversely proportional dependences of the concentration of divalent elements Ca, Mg, Zn, Sr and Ba in quasi-equilibrium soil solutions on their pH value were obtained: 

\[ [\text{Me}^{2+}]_{\text{PSS}} = -a \times \text{pH} + b \] \( (R^2 = 0.34 - 0.78) \).

Figure 10. The dependence of the cation composition of PSSs from the pH value (the “bare fallow”) for individual samples.

Simultaneously, no such dependencies were found for K, Na and Mn. This may be due to the insufficient amount of data accumulated for statistical processing due to the high variation in the content of the metals studied in different pooled samples. This assumption is supported by the high correlation dependence of the cation composition of the PSS on the pH value for individual samples, including divalent and monovalent cations (figure 10).

On the contrary, for the sequentially extracted “bare fallow” variant PSSs, reliable inversely proportional dependences of the concentration of the studied elements in quasi-equilibrium soil solutions on the value of their pF were obtained: 

\[ [\text{Me}^{n+}]_{\text{PSS}} = -a \times \text{pF} + b \] \( (R^2 = 0.74 - 0.99) \) (figure 11).

Generally, the concentrations of divalent elements Ca, Mg, Sr, Ba and Zn in the energy fractions of soil solutions sequentially pressed from the more acidic soil of the “bare fallow” variant, on average, 4.0, 3.0, 3.2, 3.2 and 8.4 times, respectively, exceeded the concentration of metals in similar fractions of solutions of the “barley” variant. Mn stood out sharply from the general picture: its concentration in solutions extracted from the soil of both variants practically did not differ. Concentrations of monovalent K and Na in the fractions of press solutions of the “bare fallow” variant on average exceeded similar indicators of the “barley” variant by 3.9 and 3.0 times.
Figure 11. The dependence of the cation composition of pressed soil solutions from the magnitude of the capillary-sorption pressure (pF) - “bare fallow” variant.
4. Summary
The acidity of the centrifuge soil solutions extracted from the soil of the “barley” and “bare fallow” variants differed significantly (in the latter it was almost one pH unit lower), which is due to the influence of the biological factor, i.e., test plants grown in the “barley” variant. With a decrease in soil moisture (in the range of FMC – 2WP), the acidity of the solutions decreased: for the “barley” variant by 1 pH (6.0 → 5.0), for the “bare fallow” variant - slightly. In this case, we can only talk about a certain tendency to reduce the pH of the CSS with a decrease in soil moisture with fluctuations in individual pH values in the range of 4.5 – 5.0 units.

In soil solutions extracted from the soil variants “barley” and “bare fallow” a significant effect on the mass fraction of Ca, Mg, Mn, Zn, K and Na has a factor of different soil acidity. In more acidic solutions of the “bare fallow” variant, the concentration of the above elements, on average, was 1.4 – 6.9 times higher than the concentration of metal in the solutions of the “barley” variant in the entire range of the investigated soil moisture. For iron, there were no differences in the mean values of metal concentrations in the solutions of the experimental variants.

It was not possible to establish the dependence between the concentration of basic macro-and microelements in soil solutions within the investigated part of the productive moisture range (2 wilting point – FMC) on soil moisture, which is associated with the peculiarities of the used method of soil sampling followed by soil solutions extraction, and the fundamental properties of the heterophase “soil – soil solution” system – its spatial and structural heterogeneity.

The positive correlation between pF and pH was clearly observed for the pressed solutions from the soils of both variants. For the consistently extracted “barley” variant of the relationship between pH and [Me]_{PSS} for most of the studied elements (K, Na, Ca, Mg, Sr) could not be found. The above is also true for pF – [Me]_{PSS}. On the contrary, for the sequentially extracted “bare fallow” (more acidic) option, the reliable inversely proportional dependences of the concentration of divalent elements Ca, Mg, Sr, Ba and Zn in quasi-equilibrium PSSs on their pH were obtained. No such dependencies were found for Mn, K and Na. This may be due to insufficient data accumulated for statistical processing. Similarly, reliable inversely proportional dependences of the concentration of the investigated elements in quasi-equilibrium PSSs on the value of their pF were obtained for consistently extracted “bare fallow” option.

Concentrations of Ca, Mg, Sr, Ba, Zn, K and Na in successively pressed fractions of soil solutions from more acidic soil of the “bare fallow” variant, on average, were 3.0 – 8.4 times higher than the corresponding concentrations of metals in similar fractions of solutions of the “barley” variant. Mn stood out sharply from the general picture: its concentration in solutions extracted from soils of both variants practically did not differ.

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References
[1] Trofimov S Ya and Karavanova E I 2009 Liquid Phase of Soils: Tutorial on Some Chapters of the Course of Soil Chemistry (Moscow: University book) p 112
[2] Kryukov P A 1971 Soil Solutions (Novosibirsk: Publishing house “Science”) p 220 (in Russian)
[3] Voronin A D 1990 Energy concept of the soil physical state Pochvovedenie 5 7-19 (in Russian)
[4] Smagin A V, Sadovnikova N B, Kirichenko A V, Egorov Yu V, Vityazev V G and Bashina A S 2018 Dependence of the osmotic pressure and electrical conductivity of soil solutions on the soil water content Eurasian Soil Sci. 51 (12) 1440–51
[5] Marques R, Ranger J, Gelhaye D, Pollier B, Ponette Q and Goedert O 1996 Comparison of chemical composition of soil solutions collected by zero-tension plate lysimeters with those from ceramic-cup lysimeters in a forest soil Eur. J. Soil Sci. 47 407-17
[6] Giesler R, Lundstrom U S and Grip H 1996 Comparison of soil solution chemistry assessment using zero- tension lysimeters or centrifugation Eur. J. Soil Sci. 47 (3) 395-05
[7] Gallet C and Keller C 1999 Phenolic composition of soil solutions: comparative study of lysimeter and centrifuge waters Soil Biol. Biochem. 31 1151-60
[8] Zaitseva R I, Minashina N G and Sudnitsyn I I 1997 Concentration of Sodium Chloride Solutions in Pores of Various Size Eurasian Soil Sci. 30 (3) 284-89
[9] Karavanova E I and Timofeeva E A 2009 Chemical Composition of Solutions in Macro- and Micropores in the Upper Horizons of Soils in the Central Forest State Biosphere Reserve Eur. Soil Sci. 42 (12) 1357–63
[10] Kabata-Pendias A 2011 Trace Elements in Soils and Plants (London: CRC Press) p 505
[11] Pansu M and Gauthreyrou J 2006 Handbook of Soil Analysis. Mineralogical, Organic and Inorganic Methods ( Berlin Heidelberg: Springer-Verlag) p 995.
[12] ISO 22036:2008 Soil Quality - Determination of Trace Elements in Extracts of Soil by Inductively Coupled Plasma - Atomic Emission Spectrometry (ICP - AES)
[13] Anisimov V S, Anisimova L N, Frigidova L M, Dikarev D V, Frigidov R A, Korneev Yu N, Sanzharov A I and Arysheva S P 2018 Evaluation of the Migration Capacity of Zn in the Soil–Plant System Eurasian Soil Sci. 51 (4) 407–17
[14] Smagin A V, Sadovnikova N B and Ali M M B 1998 The determination of the primary hydrophysical function of soil by the centrifuge method Eurasian Soil Sci. 31 (11) 1237-44
[15] Lorenz S E, Hamon R E, Holm P E, Domingues H C, Sequeira E M, Christensen T H and McGrath S P 1997 Cadmium and zinc in plants and soil solutions from contaminated soils Plant Soil 189 21–31
[16] Barber S A 1995 Soil Nutrient Bioavailability: A Mechanistic Approach. 2nd edition (New York: John Wiley & Sons) p 384
[17] Sposito G 2008 The Chemistry of Soils. 2nd edition (New York: Oxford Univ.Press). p 329